The Sustained Global Ocean Observing System For Climate

FY2008

Annual Report

Climate Observation Division
NOAA Climate Program Office

NOAA, National Oceanic and Atmospheric Administration
www.noaa.gov

NOAA Climate Observation Division
www.oco.noaa.gov

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Ocean Climate Observation Program
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a. Ocean Climate Observation Program
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Projects and Web Sites

Ocean Climate Observation Program
FY 2008 Progress Report

Mike Johnson
Office of Climate Observation
February 20, 2009

Project Initiation Year: 2000

Project Summary:

NOAA's Ocean Climate Observation program is the core of the ocean sub-capability of NOAA's Climate Observations and Monitoring Program. The Ocean Climate Observation program also constitutes the backbone of the Global Component of the U.S. Integrated Ocean Observing System (IOOS). IOOS is the U.S. contribution to the international Global Ocean Observing System (GOOS), which is the ocean baseline of the Global Earth Observation System of Systems (GEOSS).

In 2003 the Project Office for Climate Observation (OCO) was established under the auspices of the Climate Program Office (CPO) to manage the Ocean Climate Observation program. It is the job of OCO to advance its multi-year *Program Plan for Building a Sustained Ocean Observing System for Climate*, which is updated annually. The intended outcome is a sustained global system of complementary *in situ*, satellite, data, and modeling subsystems adequate to accurately document the state of the ocean and to force climate models. The observing system is being put in place to meet climate requirements but it also supports weather prediction, global and coastal ocean prediction, marine hazard warning systems (e.g., tsunami warning), transportation, marine environment and ecosystem monitoring, and naval applications. Many non-climate users also depend on the baseline composite system that is nominally referred to as the Sustained Ocean Observing System for Climate.

The Sustained Ocean Observing System for Climate is a composite system-of-systems comprised of ten complementary sub-systems or networks (illustrated in Figure 1). The networks are managed by 22 distributed centers of expertise at NOAA laboratories, centers, joint institutes, universities and business partners. The "System" is centrally managed at the Office of Climate Observation. Specifically, OCO's tasks are to:

- Monitor the status of the globally distributed networks; report system statistics and metrics routinely and on demand;
- Evaluate the effectiveness of the system; take action to implement improvements through directed funding;
- Advance the multi-year program plan; evolve the *in situ* networks through directed funding;
- Focus intra-agency, interagency, and international coordination;
- Organize external review and user feedback; and
- Produce annual reports on the state of the ocean and the adequacy of the observing system for climate.

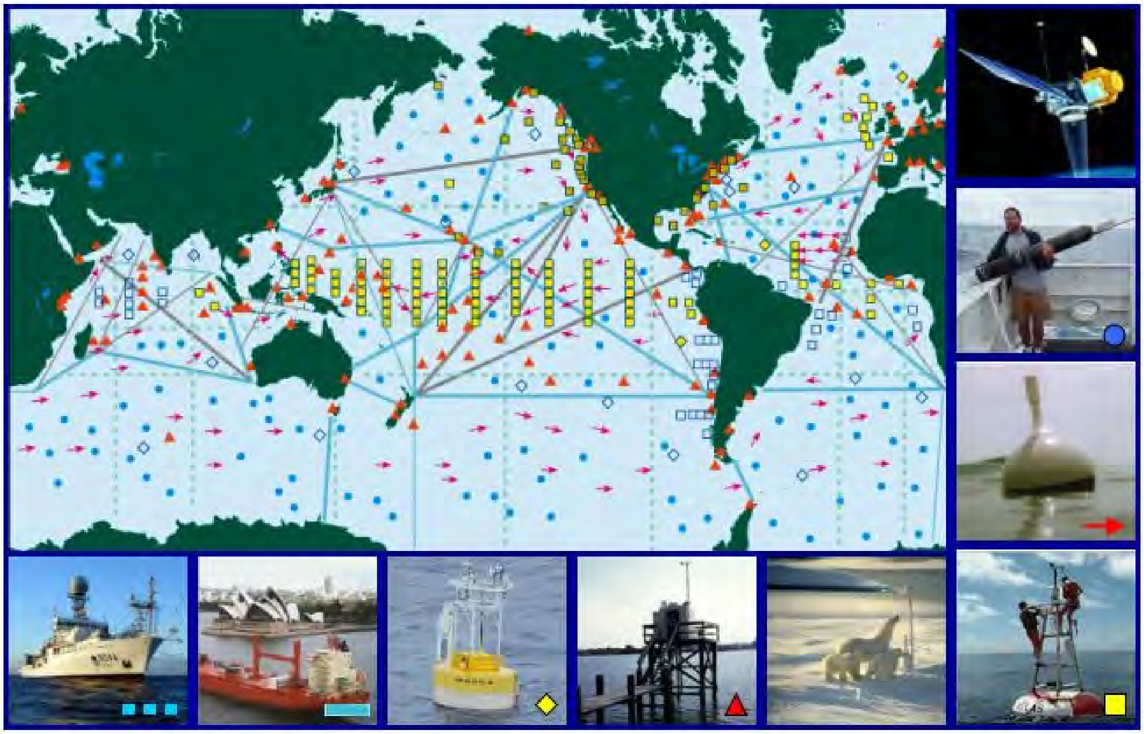

Figure 1. The Networks that make up the Sustained Ocean Observing System for Climate are (from lower left to upper right): Dedicated Ships, Ships of Opportunity, Ocean Reference Stations, Tide Gauge Stations, Arctic Observing Systems, Tropical Moored Buoys, Surface Drifting Buoys, Argo Profiling Floats, and Continuous Satellite Missions for sea surface temperature, sea surface height, surface vector winds, ocean color, and sea ice. Not illustrated are the Data & Assimilation Subsystems and Analysis Products.

The 22 distributed centers of expertise that are implementing NOAA's contributions to the system are at AOML, PMEL, ESRL, GFDL, JIMAR (University of Hawaii), JIMO (Scripps Institution of Oceanography), CICOR (Woods Hole Oceanographic Institution), JISAO (University of Washington), CIMAS (University of Miami), CICAR (Columbia University), CIFAR (University of Alaska), NCDC, NODC, NGDC, CO-OPS, OMAO, NDBC, NCEP, FSU (Florida State University), LSA, CLS America, and OCO. The contributions of these centers are summarized by the project managers in their individual reports, which are published each year in OCO's *Annual Report on the Ocean Observing System for Climate.*

Across the United States there are 46 Federal employees, and 81 non-Federal employees working to implement NOAA's contribution to the global ocean observing system. Within the OCO project office there are seven Federal employees, and two non-Federal employees.

Partnerships are central: A global observing system by definition crosses international boundaries, with potential for both benefits and responsibilities to be shared by many nations. All of the Ocean Climate Observation program contributions to global observation are managed internationally in cooperation with the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). The Ocean Climate Observation program sponsors nearly half of the observing system platforms in the global ocean, and provides approximately half of the funding needed to support JCOMM's technical infrastructure. OCO employees provide international leadership through active service in the JCOMM Management Committee, Expert Teams, and the Implementation Panels, and have held the office of JCOMM Observations Program Area Coordinator since 2002.

OCO also works cooperatively with other U.S. agencies, especially the National Science Foundation (NSF). The ongoing NSF-NOAA cooperative project for CLIVAR-ocean carbon surveys has proved to be an interagency-international-interdisciplinary success. NSF has initiated the Ocean Observatories Initiative (OOI), which will provide significant infrastructure in support of ocean climate observation; OCO is committed to working with NSF to jointly maintain climate reference stations at the OOI global ocean observatory sites.

Mission and Requirements: The mission of the OCO is to build and sustain a global climate observing system that will respond to the long term observational requirements of the operational forecast centers, international research programs, and major scientific assessments. The focus is on building the *in situ* ocean component. The top-level requirements are to:

- Document long term trends in sea level change;
- Document ocean carbon sources and sinks;
- Document the ocean's storage and global transport of heat and fresh water; and
- Document ocean-atmosphere exchange of heat and fresh water.

Deliverables: The ocean climate observing system must have the capability to deliver continuous instrumental records and analyses accurately documenting:

- Sea level to identify changes resulting from climate variability;
- Ocean carbon content every ten years and the air-sea exchange seasonally;
- Sea surface temperature and surface currents to identify significant patterns of climate variability;
- Sea surface pressure and air-sea exchanges of heat, momentum, and fresh water to identity changes in forcing function driving ocean conditions and atmospheric conditions;
- Ocean heat and fresh water content and transports to: 1) identify changes in the global water cycle; 2) identify changed in thermohaline circulation and monitor for indications of possible abrupt climate change; and 3) identify where anomalies enter the ocean, how they move and are transformed, and where they re-emerge to interact with the atmosphere; and
- Sea ice thickness and concentrations to identify changes resulting from, and contributing to, climate variability and change.

Present ocean observations are not adequate to deliver these products with confidence. The fundamental deficiency is lack of global coverage by the *in situ* networks. Present international efforts constitute only about 60% of what is needed. The *Second Report on* *the Adequacy of the Global Observing System for Climate in Support of the UNFCCC* concludes that “the ocean networks lack global coverage and commitment to sustained operations…Without urgent action to address these findings, the Parties will lack the information necessary to effectively plan for and manage their response to climate change.”

In response to the Second Adequacy Report, international GCOS produced the *Implementation Plan for the Global Observing System for Climate in support of the UNFCCC* (GCOS-92). GCOS-92 was published in October 2004. It has been endorsed by the UNFCCC and by the Group on Earth Observation (GEO). In particular:

1. The UNFCCC, Decision CP.10, “Encourages Parties to strengthen their efforts to address the priorities identified in the [GCOS] implementation plan, and to implement the priority elements …”
2. The *Global Earth Observation System of Systems (GEOSS) 10-Year Implementation Plan Reference Document* targets include: “Support implementation of actions called for in GCOS-92.”

OCO’s *Program Plan for Building a Sustained Ocean Observing System for Climate* is in complete accord with GCOS-92 and provides the framework for NOAA contributions to the international effort. In particular 21 of the specific actions listed in the GCOS-92 ocean chapter (pages 56-84) are being acted upon by the OCO program in cooperation with the implementation panels affiliated with JCOMM. These specific GCOS-92 actions provide the roadmap to guide annual work plans. GCOS-92 is accessible via link from the OCO web site: www.oco.noaa.gov -- click on “Reports & Products.” The work supported by OCO is directed toward implementation of this international plan and the projects are being implemented in accordance with the GCOS Ten Climate Monitoring Principles. The OCO-supported projects contributed 48% of the total international effort in 2008.

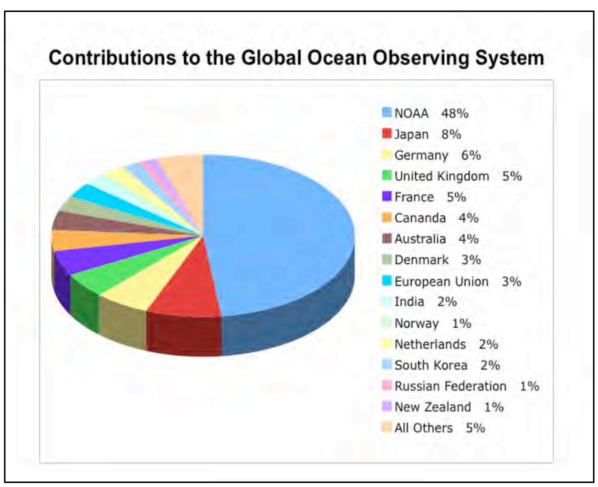

Figure 2: Relative contributions to the Global Ocean Observing System.

FY 2008 Accomplishments:

FY 2008 accomplishments are detailed in the individual Project Manager reports. Some highlights include:

- The international global ocean climate observing system overall advanced from 59% complete in 2007 to 60% complete in 2008. The annual reports of the Project Managers detail the specific advancements of the individual networks. Some highlights for 2008 included:
    - The Global Drifting Buoy array was maintained at its design strength of 1250 data buoys in service for the fourth continuous year since 2005, which enabled NOAA to meet its GPRA Performance Measure for reducing the error in global measurement of sea surface temperature.
    - The Argo profiling float array was maintained at its design strength of 3000 floats in sustained service for the second continuous year since 2007.
    - RAMA, the tropical moored buoy array in the Indian Ocean, progressed from 8 to 14 stations in operation.
    - Transition of the Indonesian Through Flow ocean reference station from NSF to NOAA funding was completed.
    - Transition of the Weddell Sea ocean reference station from CVP to OCO funding was initiated (to be completed in 2009).
    - Two NOAA-NSF CLIVAR/Carbon survey lines were completed, one aboard the NOAA RH Brown and the other aboard UNOLS.

- The Ocean Climate Observation program made the following contributions to the GCOS initial implementation targets for sustained global ocean observing system operations (as modified by JCOMM):
    - Tide gauge stations: 16% (the 2008 total international effort was estimated to 62%)
    - Surface Drifting Buoys: 49% (the 2008 total international effort was estimated to be 79%)
    - Tropical Moored Buoys: 64% (the 2008 total international effort was estimated to be 79%)
    - Ships of Opportunity: 24% (the 2008 total international effort was estimated to be 67%)
    - Argo Profiling Floats: 58% (the 2008 total international effort was at 100%)
    - Ocean Reference Stations: 14% (the 2008 total international effort was estimated to be 36%)
    - Ocean Carbon Networks: 25% (the 2008 total international effort was estimated to 43%)

- In addition to planned dedicated ship support, three research vessels were chartered to conduct annual climate observing system maintenance operations that were unexpectedly cancelled by the NOAA Ship RH Brown, which was recalled from field operations mid-season for emergency repairs due to mechanical and other problems:

- R/V Oceanus (WHOI): 15 days in support of the NTAS/MOVE ocean reference stations.
- R/V Cape Hatteras (Duke U): 10 days in support of the Western Boundary Time Series ocean reference station.
- R/V Antea (France, IRD): 33 days in support of the PIRATA North East Extension moored array.

- Woods Hole Oceanographic Institution released a global analysis of ocean evaporation from 1958 to 2006 at 1-degree resolution. This product, derived from blended satellite and in-situ ocean observations, is the first observationally-derived global dataset showing evaporation of water from the ocean, which is critical for addressing the issue of whether or to what extent the global hydrological cycle is intensifying as a consequence of climate change.

- The OceanSITES Global Data Assembly Center (GDAC) was established at NDBC for collection and distribution of a global set of Ocean Reference Station data and platform metadata.

- Two new daily 1/4° SST analyses were developed at NCDC: the AVHRR-only daily optimum interpolation (OI) from January 1985 to present and the AMSR+AVHRR daily OI from June 2002 to present. Both analyses use in situ data and use a satellite bias correction.

- CPC Extended the GODAS Monthly State of the Ocean briefing to include analyses of:
  1. Real time heat budget analysis for ENSO
  2. Estimation of Atlantic MOC with GODAS
  3. Validation of heat content variability in GODAS

- Twenty-one hurricane drifters were deployed in the paths of hurricanes Gustav and Ike in the Gulf of Mexico by the 53rd Air Force Reserve Squadron "Hurricane Hunters". The drifters measured winds, air pressure, surface temperatures and subsurface temperatures to a depth of 150m providing data for hurricane research and real-time data to NOAA's National Hurricane Center.

- Continuous measurements of pCO_2 were made at 8 ocean moorings to elucidate the magnitude and causes of temporal variability of ocean surface carbon uptake. Underway pCO2 measurements continued on board 12 ships to map the spatial variability of ocean surface carbon uptake. A key accomplishment in FY 2008 was the submission for publication of the OCO-sponsored Takahashi climatology of global ocean pCO_2, assembled from over 3 million measurements made internationally over a period of three decades.

- The NOAA-NSF CLIVAR/Carbon survey conducted two open-ocean transects making full-depth measurements of carbon, tracers, oxygen, nutrients, and physical oceanographic parameters. This international project conducts the only routine measurements sample below the depth of the ARGO array. Recent findings contribute to ongoing analyses of anthropogenic carbon uptake in the global oceans, and demonstrate warming of abyssal waters.

- OCO and GCC jointly funded work at PMEL and AOML to derive improved methodologies for retrieval of air-sea CO_2 fluxes from space-based measurements of sea surface temperature, winds, ocean color, and potentially other observables. The project draws upon in-situ measurements of pCO_2 made from ships of opportunity and from moorings, which are used to develop and calibrate regionally and seasonally dependent algorithms.

- OCO began cost-sharing with Office of the Oceanographer of the Navy for the maintenance of the GODAE server at Monterey, and worked in cooperation with the IOOS Program office to draft a NOAA-Navy MOU for long-term support of the GODAE server.

- A joint OCO-IOOS project was initiated to expand the Observing System Monitoring Center (web-based system management tool) to include U.S. regional observing systems as well and the international global system.

- A letter of intention was sent to the NSF Ocean Observatories Initiative for cooperative implementation of Ocean Station PAPA (northeast Pacific) as a joint ocean observatory and climate reference station.

- OCO submitted a NOAA report to the House of Representatives Committee on Appropriations on "Implementing the Sustained Global Ocean Observing System for Climate."

- The Sixth Annual System Review was held 3-5 September 2008 in Silver Spring and brought together 109 project managers, data users, advisors, and program managers both from NOAA and from other partner institutions to discuss the observing system's capability to deliver climate information about:
    - Rising Sea Level and the Ocean's Storage of Heat;
    - Ocean Circulation and Global Transport of Heat and Fresh Water;
    - Ocean Biogeochemistry;
    - The Ocean's Influence on Variability in Seasonal Temperatures, Precipitation, Sea Ice, and Extreme Events; and
    - User Requirements and Applications
- The Annual Review also served as a springboard to begin the year-long community-wide preparations for the international OceanObs'09 symposium, which will be held September 2009 in Venice.

Program Funding Summary

Ocean Climate Observation Funding History							
Network			**$ K**				
Expenditures	**FY 02**	**FY 03**	**FY 04**	**FY 05**	**FY 06**	**FY07**	**FY08**
Ocean Climate Observation Systems							
Tide Gauge Stations	670	710	970	1196	1177	1196	1196
Drifting Buoys	1699	2077	2769	3130	3427	3130	3169
Tropical Moored Buoys	3175	3175	3625	4360	3094	3329	2850
Ships of Opportunity	1960	1903	2487	2907	2776	2804	2678
Argo Profiling Floats	6749	9459	9835	9218	9108	9152	9201
Ocean Reference Stations	1712	2082	2998	2995	3958	5071	5747
Ocean Carbon Networks	1478	2204	2875	3521	3482	3181	3177
Arctic Observing System	1937	4659	3988	5325	5237	4031	4096
Dedicated Ship Time	0	626	523	92	542	378	1801
Data & Assimilation Subsystems	1286	1323	1487	1418	1331	1036	1229
CLS Argos Data Processing	813	480	1525	1408	823	1143	1590
Product Deliver, Analysis/Reanalysis	578	638	896	1982	2048	2572	2697
Institutional Infrastructure	1126	1175	1791	1878	1084	1591	1371
Total	**23183**	**30511**	**35769**	**39430**	**38087**	**38614**	**40802**
					38087	38614	40802
Program Income							
Ocean Observation					17657	18490	20741
Sustained Ocean Observations					5334	5389	5755
Argo					9758	9758	9758
Arctic					4927	3694	3995
Other					411	1283	553
Total					**38087**	**38614**	**40802**

Figure 4: System Funding Record

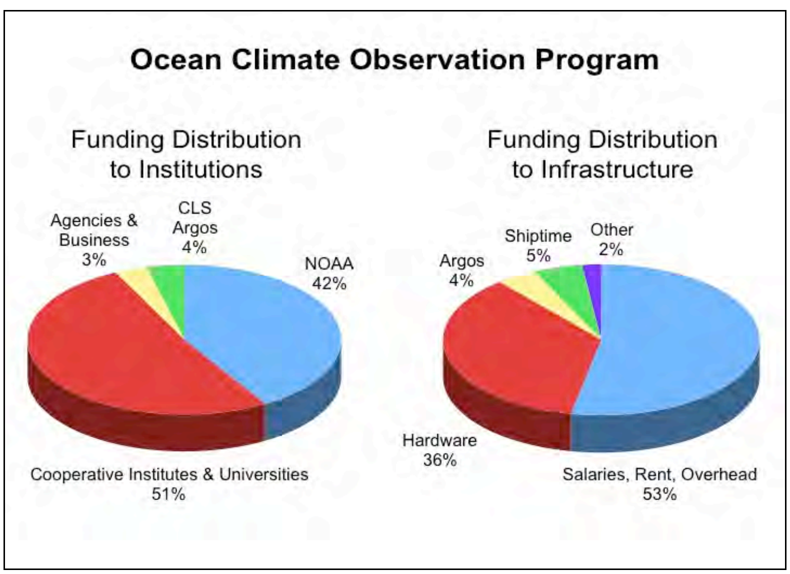

Figure 5: Program funding distribution.

FY 2008 OCO Annual Report
Projects and Web Sites

Project	Authors	Web Site
1. Tide Gauge Stations		
a. Global Sea Level Observations	Mark A. Merrifield	http://uhslc.soest.hawaii.edu
b. National Water Level Program Support Towards Building a Sustained Ocean Observing System for Climate	Stephen K. Gill, Chris Zervas, Lori Fenstermacher	http://tidesandcurrents.noaa.gov http://opendap.co-ops.nos.noaa.gov/content/
2. Drifting Buoys		
a. The "Global Drifter Program" - Drifter Measurements of Surface Velocity, SST, SSS, Winds and Atmospheric Pressure	Peter Niiler	http://tao-tc.ucsd.edu http://www.aoml.noaa.gov/phod/soto/gsc/index.php
b. Surface Drifter Program	Rick Lumpkin, Silvia Garzoli	http://www.aoml.noaa.gov/phod/dac/gdp.html
3. Tropical Moored Buoys		
a. Tropical Moored Buoy Array Program (PIRATA, Indian Ocean Array, Flux Reference Stations, Tropical Salinity, Engineering Development)	Michael J. McPhaden, Christian Meinig, Rick Lumpkin	http://www.pmel.noaa.gov/pirata/ http://www.pmel.noaa.gov/tao/ http://www.aoml.noaa.gov/phod/pne http://www.knmi.nl/scatterometer/ascat_osi_25_prod/ascat_app.cgi?cmd=buoy_validations&period=week&day=0&flag=no http://www.ocean-sci-discuss.net/5/77/2008/osd-5-77-2008.pdf
b. Development of a Next Generation Platform and Instrumentation for Continuous Ocean Observations (PICO)	Christian Meinig	http://www.pmel.noaa.gov/pico/
c. Tropical Atmosphere Ocean (TAO) Array	Landry Bernard, Michael McPhaaden	http://www.tao.noaa.gov/ http://www.pmel.noaa.gov/tao/ http://www.ndbc.noaa.gov/hurricanes/2008/ike/ http://www.oscar.noaa.gov http://www.knmi.nl/scatterometer/ascat_osi_25_prod/ascat_app.cgi?cmd=buoy_validations&period=week&day=0&flag=no http://www.ocean-sci-discuss.net/5/77/2008/
4. Ocean Reference Stations		
a. Ocean Reference Stations	Robert A. Weller, Albert J. Plueddemann	http://www.oceansites.org/ http://uop.whoi.edu/projects/ http://www.ndbc.noaa.gov http://uop.whoi.edu/techdocs/technotes.html
b. Western Boundary Time Series in the Atlantic Ocean	M. Baringer, C. Meinen, and S. Garzoli	http://www.aoml.noaa.gov/phod/wbts/
c. Flux Mooring for the	Meghan F. Cronin,	http://www.pmel.noaa.gov/OCS/

	North Pacific's Western Boundary Current: Kuroshio Extension Observatory (KEO)	Christian Meinig, Christopher L. Sabine	http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/ http://uskess.org http://usclivar.org/Organization/wbc-wg.html
d.	Southern Ocean Modern Observations/ Weddell Sea Moorings	Arnold L. Gordon, Bruce Huber	http://www.ldeo.columbia.edu/res/div/ocp/projects/corc.shtml
e.	Monitoring the Indonesian Throughflow in Makassar Strait	Arnold L. Gordon, R. Dwi Susanto	http://ioc3.unesco.org/oopc/
f.	Meridional Overturning Variability Experiment	Uwe Send	
g.	Integrated Boundary Current Observations in the Global Climate System	Uwe Send, Russ Davis, Daniel Rudnick, Peter Niiler, Bruce Cornuelle, Dean Roemmich	
h.	Glider Sampling of the Solomon Sea	William S. Kessler	http://spray.ucsd.edu/
i.	High Resolution Climate Data From Research and Volunteer Observing Ships	Christopher W. Fairall	http://www.esrl.noaa.gov/psd/psd3/synthesis/ http://www.usclivar.org/hlat.php http://saga.pmel.noaa.gov/Field/icealot/
j.	Assimilation, Analysis and Dissemination of Pacific Rain Gauge Data: PACRAIN	Mark L. Morrissey, Susan Postawko, J. Scott Greene	http://pacrain.evac.ou.edu/ http://sparce.evac.ou.edu/ http://srdc.evac.ou.edu http://www.pi-gcos.org/ http://pacrain.evac.ou.edu/pacusers.html http://pacrain.evac.ou.edu/changes.html http://gcmd.nasa.gov/records/GCMD_ATOLL_RAIN_PACIFIC.html http://dss.ucar.edu/datasets/ds484.0/ http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php
5. Ships of Opportunity			
a.	High Resolution XBT Transects	Dean Roemmich, Bruce Cornuelle, Janet Sprintall, Glenn Pezzoli	http://www-hrx.ucsd.edu http://www.brest.ird.fr/soopip/
b.	Ships of Opportunity Program (SOOP). Volunteer Observing Ships: Expendable Bathythermograph and Environmental Data Acquisition	Gustavo J. Goni, Molly O. Baringer, Silvia L. Garzoli	http://www.aoml.noaa.gov/phod/goos

Program		
c. Ships of Opportunity	Robert A. Weller, Albert J. Plueddemann	http://uop.whoi.edu/projects/VOS/vos.html
6. ARGO Profiling Floats		
a. The Argo Project	Dean H. Roemmich, Russ E. Davis, Stephen C. Riser, W. Brechner Owens, Silvia L. Garzoli, Gregory C. Johnson	http://www.argo.ucsd.edu http://argo.jcommops.org http://www.usgodae.org/ http://www.ifremer.fr/coriolis/cdc/argo.htm http://www.argo.ucsd.edu/FrBibliography.html http://www.argo.ucsd.edu/FrUse_by_Operational.html http://sio-argo.ucsd.edu http://xriley.whoi.edu/~argo/ http://flux.ocean.washington.edu/argo/ http://floats.pmel.noaa.gov http://www.aoml.noaa.gov/phod/argo/index.php
7. Ocean Carbon Networks		
a. Global Repeat Hydrographic/CO_2/Tracer Surveys In Support of CLIVAR And Global Carbon Cycle Objectives: Carbon Inventories And Fluxes	Richard A. Feely, Rik Wanninkhof, Christopher Sabine, Gregory C. Johnson, Molly Baringer, John Bullister, Calvin W. Mordy, Jia-Zhong Zhang	http://www.pmel.noaa.gov/co2/co2-home.html http://www.aoml.noaa.gov/ocd/gcc/co2research/ http://www.carboncyclescience.gov http://ushydro.ucsd.edu/ http://www.clivar.org http://www.clivar.org/carbon_hydro/ http://www.globalcarbonproject.org/ http://www.ioccp.org http://cchdo.ucsd.edu/data_access?ExpoCode=33RO20071215 http://www.aoml.noaa.gov/ocd/gcc/clivari6s/
b. Surface Water pCO_2 Measurements from Ships	Rik Wanninkhof, Richard A. Feely, Nicholas R. Bates, Frank J. Millero, Taro Takahashi, Gustavo Goni	http://www.aoml.noaa.gov/ocd/gcc/ http://www.pmel.noaa.gov/co2/uwpco2 http://www.bios.edu/Labs/co2lab/ http://www.ldeo.columbia.edu/CO2 http://www.aoml.noaa.gov/phod/tsg/index.php http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/LDEO_home.html http://www.ldeo.columbia.edu/~david/duck-rabbit/so_gasex
APPENDIX. Underway CO_2 Measurements aboard the RVIB Palmer and Data Management of the Global VOS Program	Taro Takahashi	http://www.ldeo.columbia.edu/res/pi/CO2/ http://www.bios.edu/Labs/co2lab/ http://www.oceansites.org http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/LDEO_home.html www.ldeo.columbia.edu/CO2
c. High-Resolution Ocean And Atmosphere pCO_2Time-Series Measurements	Christopher L. Sabine, Francisco Chavez, Nicholas R. Bates	http://www.pmel.noaa.gov/co2/moorings/ http://www.oceansites.org/
8. Arctic Ocean Observing System		
a. Arctic Sea Ice Thickness Observations	Jacqueline Richter-Menge, Donald Perovich, James	http://imb.crrel.usace.army.mil/ http://www.arcus.org/search/seaiceoutlook/index.php http://www.artic.noaa.gov

		Overland and Humfrey Melling	
b.	RUSALCA: The Pacific Gateway to the Arctic – Quantifying and Understanding Bering Strait Oceanic Fluxes	Rebecca Woodgate, Ron Lindsay, Tom Weingartner and Terry Whitledge	http://psc.apl.washington.edu/BeringStrait.html
	APPENDIX Cruise Report for Bering Strait Mooring Project 2008, RUSALCA 2008	Rebecca Woodgate, Kathleen Crane, Mikhail Zhdanov, Kevin Wood, Vladimir Smolin, Terry Whitledge	http://psc.apl.washington.edu/BeringStrait.html http://www.arctic.noaa.gov/aro/russian-american/
9. Ocean Analysis and Data Assimilation			
a.	In situ and Satellite Sea Surface Temperature (SST) Analyses	Richard W. Reynolds	http://www.ncdc.noaa.gov/oa/climate/research/sst/sst.html
b.	Development of Global Heat and Freshwater Anomaly Analyses	Gregory C. Johnson, John M. Lyman, Josh K. Willis	http://oceans.pmel.noaa.gov/
c.	Ocean Heat and Freshwater Content Variability Estimates	Sydney Levitus	http://www.nodc.noaa.gov/OC5
d.	Evaluating the Ocean Observing System: Performance Measurement for Heat Storage	Claudia Schmid, Gustavo Goni	http://www.aoml.noaa.gov/phod/soto/ghs/
e.	Quarterly reports on the state of the ocean: Meridional heat transport variability in the Atlantic Ocean	Molly Baringer, Silvia Garzoli, Gustavo Goni, Carlisle Thacker, Rick Lumpkin	http://www.aoml.noaa.gov/phod/soto/mht/
f.	A Fifty-Year Analysis of Global Ocean Surface Heat Flux	Lisan Yu and Robert A. Weller	http://oaflux.whoi.edu http://apdrc.soest.hawaii.edu/w_data/air-sea3.htm http://dss.ucar.edu/datasets/ds260.1/
g.	Climate Variability in Ocean Surface Turbulent Fluxes	Mark A. Bourassa, Shawn R. Smith, Eric Chassignet	http://www.coaps.fsu.edu/RVSMDC/FSUFluxes/ http://www.coaps.fsu.edu/RVSMDC/SAC/ http://www.cpc.ncep.noaa.gov/products/CDB/
h.	Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses	Pingping Xie, John Janowiak, Phillip Arkin	http://www.cpc.ncep.noaa.gov/products/global_precip/html/web.shtml ftp://ftp.cpc.ncep.noaa.gov/precip
i.	National Water Level Program Support Towards Building a Sustained Ocean Observing System for	Stephen K. Gill, Chris Zervas, Lori Fenstermacher	http://tidesandcurrents.noaa.gov http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml http://tidesandcurrents.noaa.gov/sltrends/sltrends_global.shtml http://opendap.co-ops.nos.noaa.gov/content/

FY 2008 OCO Annual Report
Projects and Web Sites

i.	National Water Level Program Support Towards Building a Sustained Ocean Observing System for Climate	Stephen K. Gill, Chris Zervas, Lori Fenstermacher	http://tidesandcurrents.noaa.gov http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml http://tidesandcurrents.noaa.gov/sltrends/sltrends_global.shtml http://opendap.co-ops.nos.noaa.gov/content/
j.	Evaluating the Ocean Observing System: Surface Currents	Rick Lumpkin and Gustavo Goni	http://www.aoml.noaa.gov/phod/soto/gsc/ http://www.aoml.noaa.gov/phod/altimetry/
k.	Global Carbon Data Management and Synthesis Project	Christopher L. Sabine, Richard A. Feely, Steve Hankin, Rik Wanninkhof, Tsung-Hung Peng, Alex Kozyr, Robert Key, Frank Millero, Andrew Dickson	http://cdiac3.ornl.gov/waves http://cdiac.ornl.gov/oceans/home.html http://ferret.pmel.noaa.gov/OCDMS/
l.	Optimal network design to detect spatial patterns and variability of the ocean carbon sources and sinks from underway surface pCO_2 measurements	Joellen L. Russell, Colm Sweeney, Anand Gnanadesikan, Richard A. Feely and Rik Wanninkhof	
m.	Observation-Based Quantification of Seasonal to Interannual Changes in Air-Sea CO_2 Fluxes	Rik Wanninkhof, Richard A. Feely, Christopher L. Sabine and Kent Hughes	http://www.aoml.noaa.gov/ocd/gcc http://ioc3.unesco.org/ioccp/Synthesis.html http://www.aoml.noaa.gov/ocd/gcc/movieloop.html
n.	Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon	Keith B. Rodgers and Anand Gnanadesikan	
o.	A Web Site for NCEP's Global Ocean Data Assimilation System: Data Link, Model Validation and Ocean Monitoring Products	Yan Xue	http://www.cpc.ncep.noaa.gov/products/GODAS/
p.	Enhanced Ocean Climate Products from NCEP	Stephen J. Lord	
q.	Ocean Data Assimilation Research at GFDL	Tony Rosati, Brian Gross	

10. Data Management			
a.	Observing System Monitoring Center (OSMC)	Steven Hankin, Kevin J. Kern, Ted Habermann	http://www.osmc.noaa.gov
b.	OceanSites: An international project to build a coordinated global network of multidisciplinary deep-ocean timeseries observatories	Bill Burnett, Uwe Send and Robert A. Weller	http://www.oceansites.org ftp://data.ndbc.noaa.gov/data/oceansites ftp://ftp.ifremer.fr/ifremer/oceansites
c.	U.S. Research Vessel Surface Meteorology	Shawn R. Smith, Mark A. Bourassa, Eric Chassignet	http://samos.coaps.fsu.edu/
d.	World Ocean Database Project	Sydney Levitus	
e.	Ocean Data Management at NCDC	Huai-Min Zhang	http://www.ncdc.noaa.gov/oa/rsad/blendedseawinds.html http://www7.ncdc.noaa.gov/CDO/CDOMarineSelect.jsp http://www.ncdc.noaa.gov/oa/climate/vosclim/vosclim.html

1. Tide Gauge Stations

a. UHSLC GCOS Tide Gauge Stations

b. National Water Level Program Support Towards Building A Sustained Ocean Observing System For Climate

University of Hawaii Sea Level Center

Mark A. Merrifield
University of Hawaii, Honolulu Hawaii

1. PROJECT SUMMARY

The University of Hawaii Sea Level Center (UHSLC) collects, processes, analyzes, and distributes tide gauge data from around the world in support of climate and oceanographic research. The UHSLC focuses on the collection of high frequency measurements that are available in near-real time usually via the Global Telecommunications System (GTS). The center complements the Permanent Service for Mean Sea Level (PSMSL), which is the primary archive for historic monthly-averaged time series of sea level. Data are provided to the UHSLC from ~ 450 stations maintained by 65 international agencies. In addition, the UHSLC directly assists host countries in the maintenance and operation of 60 stations. The UHSLC is an active contributor to the Intergovernmental Oceanographic Commission Global Sea Level Observing System (GLOSS), and participates in operational and scientific oversight through the GLOSS Group of Experts. The UHSLC is primarily concerned with the implementation of the Global Climate Observing System (GCOS) sea level network, a subset of GLOSS designated as being of high importance for climate research.

The UHSLC distributes near real-time and historic data directly from its host web site, http://uhslc.soest.hawaii.edu, through a dedicated OPeNDAP server, the Pacific Marine Environmental Laboratory Climate Data Portal, the National Ocean Partnership Program (NOPP) sponsored National Virtual Ocean Data System (NVODS) project, and the NOAA Observing Systems Architecture (NOSA) geospatial and geospatial metadata databases. The center also collaborates with NOAA's National Oceanographic Data Center (NODC) to maintain the Joint Archive for Sea Level (JASL), which is a quality assured database of hourly sea level from an expanded set of global stations.

UHSLC datasets are used in conjunction with operational numerical models, for the calibration of satellite altimeter data, the production of oceanographic products, and research on interannual to decadal climate fluctuations and short-term extreme events. UHSLC station data are made available directly to the Pacific Tsunami Warning Center and the Japanese Meteorological Agency for tsunami monitoring, as well as to various national tsunami warning agencies. Over the years the UHSLC has participated in national and international programs including NORPAX, TOGA, WOCE, GODAE and CLIVAR.

2. ACCOMPLISHMENTS

2.1. Tide Gauge Operations

The UHSLC assists with the operation and maintenance of 60 tide gauge stations in collaboration with local operators (Figure 1). All of these stations transmit data via the GOES, Meteosat, or GMT satellites. The transmission cycles have historically been between 1 to 3 hours of 2 to 6 minute averaged data; however, we are in the process of switching all stations over to 5 to 15 minute transmissions of 1 to 3 minute averages, with even higher rates at major tsunami generation zones. Of the 60 UHSLC stations, 48 contribute to the GLOSS Core network, and 46 to the GCOS network. 11 are equipped with co-located GPS, and 21 are within 5 km of a continuous GPS reference site. The UHSLC shares responsibility for the sites with local operators, which lowers our costs by reducing travel for our technicians while raising the reliability of the stations and the data quality. At most locations, on-site personnel perform regular maintenance, tide staff measurements, and provide security. UHSLC's role has been to provide spare parts as needed, to visit the sites on 1-3 year intervals to repair and upgrade components and to ensure the proper operation of the station, to trouble-shoot problems as they arise in coordination with local operators, and to quality assess the datasets. In the long-term, we provide training on station operation and maintenance with the aim of eventually transferring full responsibility of the station to local agencies.

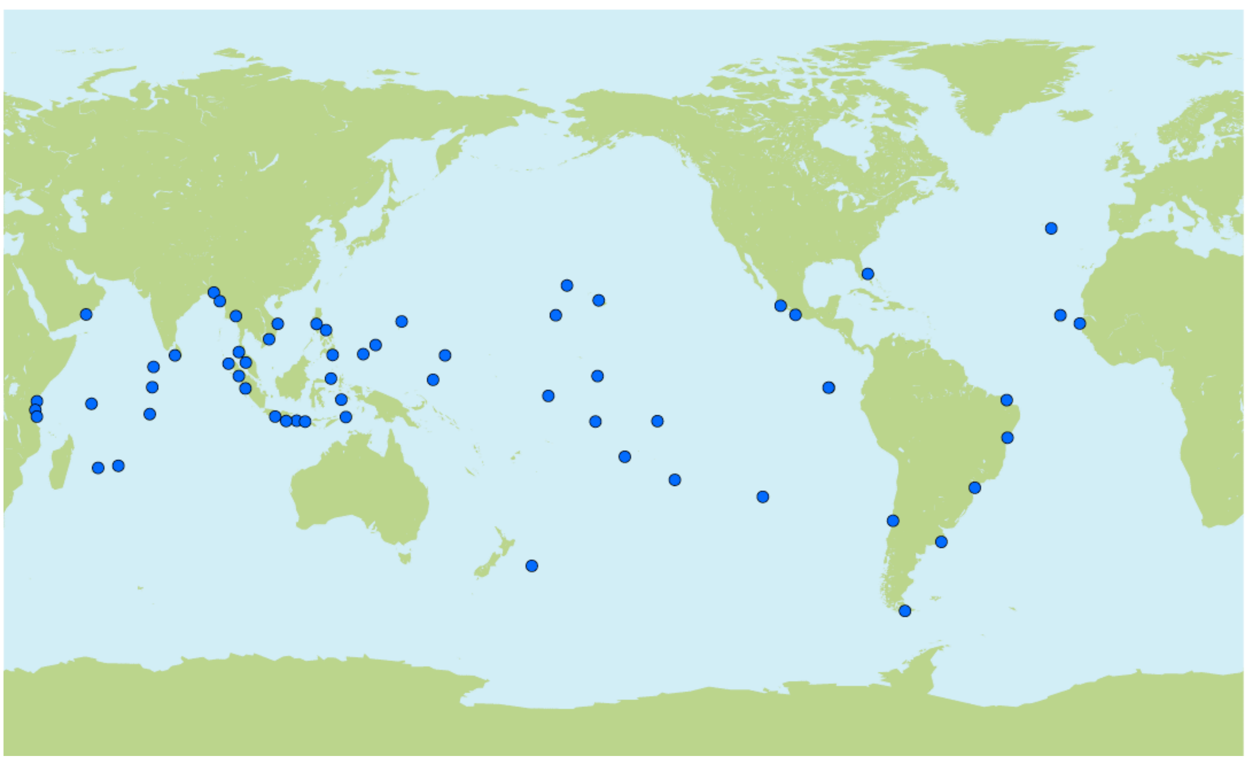

Figure 1. Tide gauge stations operated and maintained with assistance from the UHSLC.

New station installations and upgrades of existing OCO stations during FY2008 are listed in Table 1. The Intergovernmental Oceanographic Commission (IOC) provides supplemental funding for the maintenance of tsunami capable stations in the Indian Ocean. Our ability to tsunami upgraded stations at low costs to the co-sponsor was due to our core operational support provided by OCO. In turn, our involvement in this implementation benefited the aims of the global sea level network and OCO by ensuring that all stations are suitable for sea level monitoring as well as tsunami warning. All are equipped with open-air radar sensors, and most feature a backup float gauge or acoustic sensor, for stable and accurate long-term measurements. Most of these sites are either in the GLOSS Core Network or they will be proposed as new additions to the network at the next GLOSS meeting. In addition, we intend to recommend many of these sites as replacements for nearby GCOS stations that have a low probability of becoming operational.

Table 1. Station maintenance visits by UH technicians during FY2008. The stations in italics represent new installations.

Station	**Country**	**Date of Visit**	**Co-Sponsor**
Pointe La Rue	Seychelles	2007/12	IOC
Gan	Maldives	2007/12	
Hanimaadhoo	Maldives	2007/12	
Male	Maldives	2007/12	IOC
Johnston Island	USA	2008/1	
Baltra	Ecuador	2008/2	
Santa Cruz	Ecuador	2008/2	
Ponta Delgada	Portugal	2008/3	
Port Louis	Mauritius	2008/3	IOC
Rodrigues	Mauritius	2008/3	
Salvador	Brazil	2008/4	
Fortaleza	Brazil	2008/4	
Padang	Indonesia	2008/6	IOC
Sabang	Indonesia	2008/6	IOC
Sibolga	Indonesia	2008/6	
Cilicap	Indonesia	2008/6	
Benoa	Indonesia	2008/9	IOC
Langkawi	Malaysia	2008/9	IOC
Lembar	Indonesia	2008/9	
Bitung	Indonesia	2008/9	
Ambon	Indonesia	2008/9	
Saumlaki	Indonesia	2008/9	

2.2. Dataset Holdings

The Joint Archive for Sea Level (data latency: 1-2 years) is a collaborative effort between the National Oceanographic Data Center (NODC), the World Data Center-A for Oceanography, and the UHSLC. A NOAA Liaison officer supported by National Coastal Data Development Center (NCDDC) helps maintain the JASL. The JASL consists of a quality assured database of hourly sea level time series from stations around the world. We consider this to be our research quality database, complementary to the monthly averaged data maintained as PSMSL. In the past year, the UHSLC increased its JASL holdings to 12,113 station-years, including 6,979 station-years at 234 GLOSS sites.

The UHSLC maintains a fast delivery database (data latency: 1 month) in support of various national and international programs (e.g., GODAE, CLIVAR, GLOSS, GCOS). To ensure active participation and coordination with the international community, the database has been designated by the IOC as a component of the GLOSS program. The fast delivery data are used extensively by the altimeter community for ongoing assessment and calibration of satellite altimeter datasets. In particular, fast delivery data are used for monitoring the latest JASON altimeter and for the tie between JASON, TOPEX/Poseidon, ERS, and GEOSAT satellites. The fast delivery sea level dataset now includes 239 stations, 210 of which are located at GLOSS sites, and 127 at GCOS sites.

We consider a fully operational network to have near real-time reporting capability. We post the most recent 5 days of data from 186 stations as part of our near-real time website (http://ilikai.soest.hawaii.edu/RSL/). At most of these sites, the data are also available for direct download. Real-time data are received via a number of transmission channels. For example, data from UHSLC operated stations are received at the data center within minutes of transmission using the geostationary meteorological satellite system and the GTS. Data from the U.K. stations are received via email and updated within hours of transmission. NOAA CO-OPS data are obtained via the GTS and a backup download from their web site. Data from Chile and other countries that use the GOES are acquired via the GTS and also downloaded from the GOES web site.

As part of the JCOMM SLP-Pac, the UHSLC operates a Specialized Oceanographic Center that produces sea surface topography maps (monthly) and diagnostic time series (quarterly) for the Pacific Ocean. This activity is a continuation of one of the earliest examples of operational oceanography. The analysis includes comparisons of tide gauge and altimeter sea surface elevations that are available at our web site (http://ilikai.soest.hawaii.edu/uhslc/products.html).

The center produces CD-ROMs that mirror the UHSLC web site. These CDs are distributed with the JASL annual data report, shared with all data originators, and sent to other users upon request. Over 100 were distributed again last year.

2.3. GCOS Network Status

The UHSLC is working with GLOSS and international partners to bring the 170 stations in the GCOS network into full operational mode, which means having all stations report high quality data in near-real time, with the majority of stations having vertical datum control via GPS or DORIS. The status of the GCOS network is summarized in Figure 2. In the past year, we've added approximately 17 new GCOS stations into the near-real time data stream, so that 60% of the network is at that capability (72% are at Fast Delivery status or better). We estimate that 77 of the GCOS stations have nearby (< 10 km) GPS or DORIS platforms. Immediate implementation plans for the GCOS network are described in the FY2009 work plan.

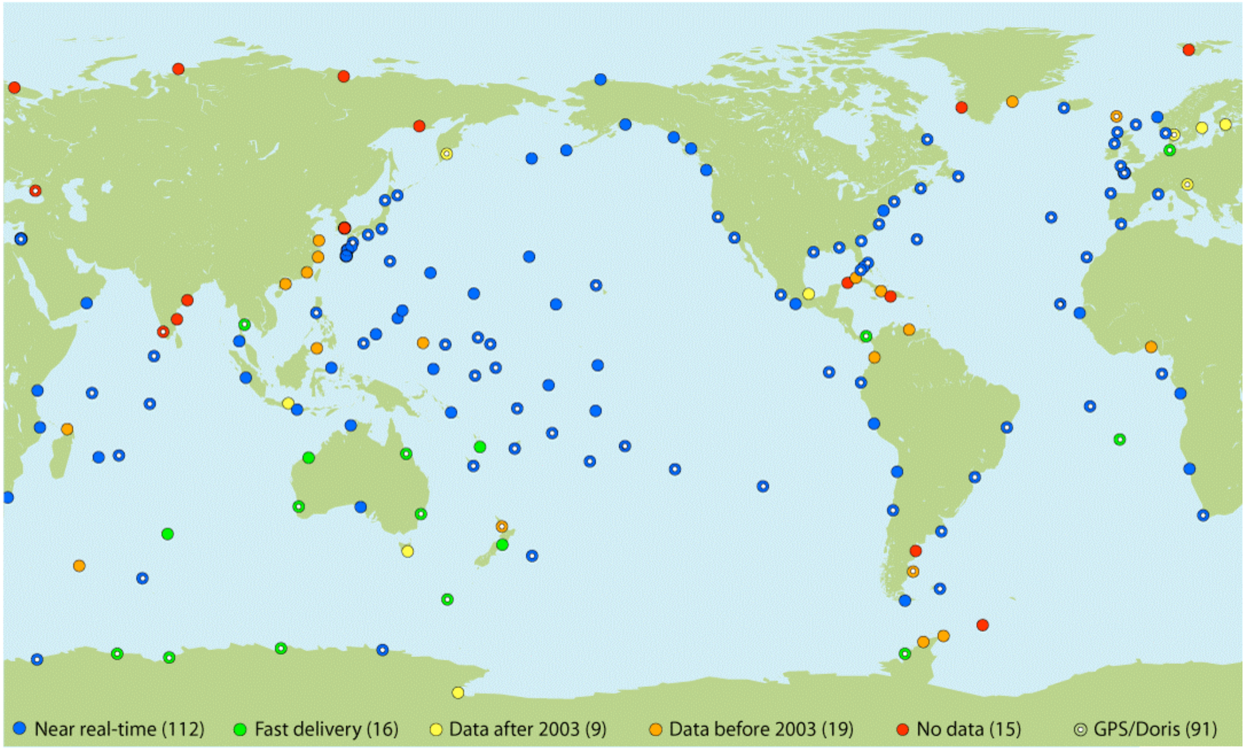

Figure 2. Summary of GCOS station data availability at UHSLC as of November 2008. The data must be sampled at one hour period or shorter. "Near real-time" are typically received within 1 hour, "Fast delivery" within 4-6 weeks.

2.4. Research Highlights

Research during FY08 focused on annual reporting of sea level, extreme events, and sea level rise estimates.

We completed a study documenting the relative importance of storms and tides in determining extreme water levels at tide gauges. Hourly time series from 157 tide gauge stations were used to specify global patterns of extreme coastal water levels, defined as values that exceed the 98 percentile of daily maximum hourly data above the annual mean level or each station, the extreme water levels were separated into tidal and non-tidal residual components using least squares fitting. Annual averages of the extremes and their tidal and residual components were used to define locations where high water levels are determined primarily by the tides (30% of all stations), by storms and other non-tidal processes (27%), and a mix of tides and storms (43%). The resulting spatial patterns of the tidal and residual components were compared to global estimates of tidal range and storm activity.

Tide gauge data were used to document a recent increase in the rate of global sea level rise. Linear trends over 15 year time segments were computed for each tide gauge record, averaged over latitude bands, and combined in an area weighted global mean. The uncertainty of the global trend was specified as a sampling error plus a random vertical land motion component. Corrections for land motion were considered based on altimeter-tide gauge trend differences. The average global sea level trend prior to 1990 is 1.56 ± 0.67 mm/yr, in agreement with previous estimates of 20^{th} century sea level rise. After 1990, the global trend increases steadily to a current rate of 3.43 ± 0.47 mm/yr, matching estimates obtained from satellite altimetry. The trend increase is insensitive to the vertical land motion correction. The transition from pre- to post-1990 trends is distinct from decadal variations in global sea level, which have been reported in previous studies. The recent acceleration of global sea level is accounted for primarily by increased rates in the southern hemisphere. The sea level acceleration coincides with warming and freshening trends observed in the high to mid-latitude regions of the southern hemisphere oceans, suggesting that regional volume changes account for the acceleration.

We are in the final stages of specifying a global reference frame for determining vertical land motion at tide gauge locations. Michael Bevis at the Ohio State University is performing the global analyses of GPS time series, and UHSLC will compare these results to tide gauge rates. We intend to have maps of land rates at all available GCOS and GLOSS stations by the end of the coming year.

We took part in the fourth OCO contribution to the BAMS State of the Climate report, describing sea level patterns during 2007, and an update of global sea level rise estimates (Merrifield et al., 2008).

2.5. Conferences, Meetings, Expert Panels, and Working Groups

ADPC Regional Steering Committee meeting, ADPC Regional Technical Committee meeting. Bangkok, 24-26 January 2008

POL BGAN planning meeting, Liverpool, 12-14 February 2008

Meetings & workshop for ICG/IOTWS V, Putrajaya, 6 April - 10 April 2008

Instructor for Carribbean Training Course for Operators of Sea Level Stations, Mayaguez, 23 June - 27 June 6 2008

Second International Round Table Dialogue on Earthquake and Tsunami, Kota Kinabalu, 6 October - 9 October 2008

ICG/IOTWS WG2 planning, International Conference on Tsunami Warning, ICG/IOTWS WG2 Meeting, Denpasar, 11-15 November 2008

ADPC RIMES Regional Steering Committee meeting, ADPC RIMES Regional Technical Committee meeting, Bangkok, 24-26 November 2008

3. PUBLICATIONS AND REPORTS

Merrifield, M**.**, G.T. Mitchum**,** S. Gill and P. Woodworth, 2008: Sea Level *in* State of the Climate in 2007, Levinson, D. H., and J. H. Lawrimore, Eds., *Bull. Amer. Met. Soc.*, **89**, S1-S179, doi:10.1175/BAMS-89-7-StateoftheClimate.

Mitchum, G., S. Nerem, M.A. Merrifield and R. Gehrels, 2009: 20th Century Sea Level Change Estimates From Tide Gauges and Altimeters, Cambridge University Press (reviewed book chapter), in press.

National Water Level Program Support Towards Building A Sustained Ocean Observing System For Climate

Allison Allen, Stephen Gill, Chris Zervas, Carolyn Lindley, and Lori Fenstermacher
NOAA National Ocean Service, Silver Spring Maryland

1. PROJECT SUMMARY

The purpose of this document is to provide a progress report on a continuing program plan for sea level observations that is being implemented by NOAA National Ocean Service (NOS)'s Center for Operational Oceanographic Products and Services (CO-OPS) in support of the NOAA Climate Program Office Global Ocean Observing System for Climate. Two tasks have been identified for which CO-OPS is providing support:

> Task 1: upgrade the operation of selected National Water Level Observation Network Stations to ensure continuous operation and connection to geodetic reference frames.
>
> Task 2: operate and maintain water level measurement systems on Platform Harvest in support of calibration of the TOPEX/Poseidon and Jason-1 and Jason-2 satellite altimeter missions.

A third task, to develop and implement a routine annual sea level analysis reporting capability that meets the requirements of the Climate Observation Program, is described in a separate FY2008 Progress Report on Sea Level Change Analysis.

The fundamental URL's are:

http://tidesandcurrents.noaa.gov for access to all programs, raw and verified data products, standards and procedures, and data analysis reports and special reports.

http://opendap.co-ops.nos.noaa.gov/content/ for access to data through an IOOS web portal.

http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml for access to the latest NWLON sea level trends and monthly mean sea level anomalies.

http://tidesandcurrents.noaa.gov/sltrends/sltrends_global.shtml for access to the latest sea level trends and monthly mean sea level anomalies for a set of global sea level reference stations.

The Climate Operating Monitoring Principles employed by the Climate Program Office are very similar to those used by NOAA's National Water Level Program (NWLP). NWLP's backbone observation system is the National Water Level Observation Network (NWLON) is a long-term continuous operational oceanographic network which meets several of NOAA's mission needs for tides and water levels. The NWLP is an end-to-end program that is planned, managed, and operated to provide products that meet user-driven needs. The program is also comprised of continuous quality control, data base management, operational readiness, continuous developments in technology, and fully open web-site for data delivery. These data and associated sea level products are made available over the web-site for use by PSMSL, UHSLC, and the WOCE communities. $125k was provided in last year's (FY2008) budget request to accomplish the two tasks described below.

1.1. Tide Station Network

Task 1: Upgrade NWLON Remote Ocean Island Station Operations

There are several coastal and island NWLON stations critical to the Global Ocean Observing System for Climate. The operation and maintenance of the ocean island and the more remote stations of the National Water Level Observation Network (NWLON) has been increasingly difficult over time due to the slow abandonment of the facilities at which some of the stations reside and the resulting decrease in accessibility. Finding routine and/or cost-effective flights is becoming increasingly difficult; yet these stations require high standards of annual maintenance to ensure the integrity of their long term data sets. Annual maintenance is even more important, in light of the fact that corrective maintenance is logistically very difficult and expensive.

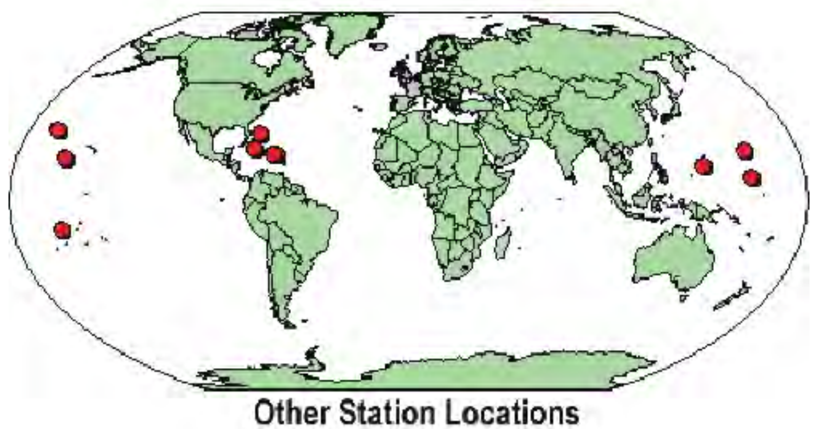

Figure 1. Ocean Island NWLON Station Map

Although operation of all of the long-term NWLON and GLOSS stations is important, the NOAA NWLON Ocean Island stations are being upgraded first with Climate Program office funding to ensure their continuous operation (NOS program funding and budget initiatives are used for operation of the coastal stations). These targeted funds are being used for travel costs and for upgrade to the data collection systems. The upgrades include high accuracy acoustic or paroscientifc pressure sensors and redundant Data Collection Platforms (DCP's) with equal capability to the existing primary systems. The station operations are also being systematically enhanced with GPS connections to geodetic networks followed by connection to CORS at selected sites. The following is a list of the ocean island NWLON stations (not including Hawaii) that have been considered in this category as priority for upgrade.

Table 1.

Station:	GPS Connection	Station DCP Upgraded
Guam	2008	2007
Kwajalein	2008	2007
Pago Pago	2008	2006
Wake	2008	2006
Midway	sched. 2009	2007
Adak	sched. 2009	sched. 2009-10
Bermuda	2008	2008
San Juan. PR	sched. 2009	*
Magueyes Island, PR	sched 2009	*
Charlotte Amalie, VI	sched. 2009	*
St Croix, VI	sched. 2009	*

***** DCP's at these stations have recently been upgraded using Base funding by CO-OPS.

Task 2: Satellite Altimeter Mission Support

Support for the TOPEX/Poseidon satellite altimeter mission began with installation of an acoustic system and a digibub system on Platform Harvest in 1992 (see Figure 2). System operations include provision of water level measurements relative to the satellite altimeter closure analysis reference frame for calibration monitoring (see B. Haines et al, Special Issue of Marine Geodesy, 2003 "The Harvest Experiment: Monitoring Jason-1 and TOPEX-Poseidon from a California Offshore Platform"). This station continues to support the Jason-1 and Jason-2 Altimeter Missions.

Figure 2. Platform Harvest Calibration Site at which the NOAA tide station is located.

CO-OPS' special support has included periodic vertical surveys on the Platform necessary to relate the water level sensor reference zeros (near the bottom catwalk) to the GPS reference zero (located up top at the helipad on the Platform). Continuous data are required to monitor effects of waves on the water level measurements and to ensure provision of data during the times of altimeter overflights every ten days. The original acoustic system was replaced by a digibub (bubbler/pressure) system prior to the Jason-1 altimeter launch.

The two digibub pressure tide gauge systems are collecting continuous water level data streams surveyed into the Platform and Satellite Orbit Reference frames. Funding is used cover travel, routine and emergency maintenance, and water level and ancillary sensor calibrations. Raw and verified 6-minute interval water level data are posted on the CO-OPS web-site.

2. FY2008 ACCOMPLISHMENTS

2.1. Task 1

Maintenance and upgrade of the ocean island NWLON stations continued in FY 2008. Redundant system upgrades were installed and GPS surveys conducted at Bermuda last year. The surveys included connections to reference benchmarks for the nearby Continuously Operating Reference System (CORS) (See Figures 3a and 3b).

Figure 3a. The tide station on the fuel pier at Bermuda.

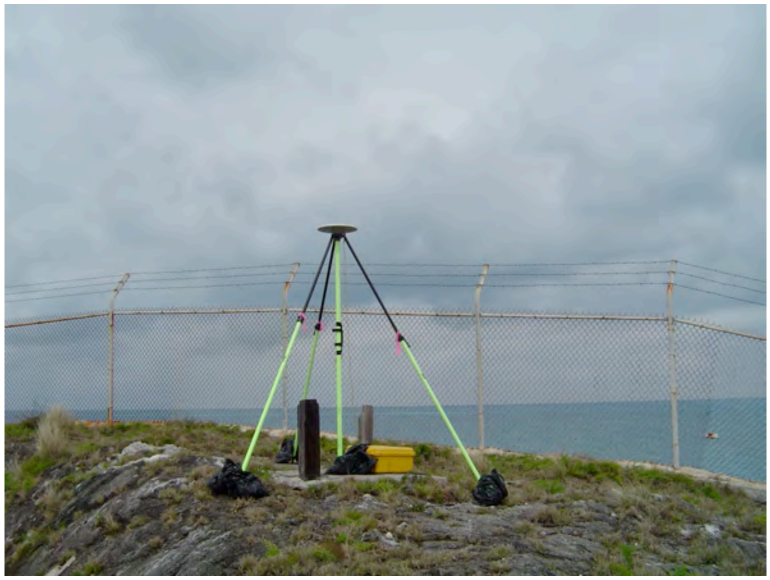

Figure 3b. A GPS survey being made on one of the tidal bench marks at Bermuda.

GPS survey connections have now been made at all remote ocean island stations except for Adak Alaska and the U.S. Virgin Islands (to be accomplished FY09). DCP's have been upgraded and redundant systems have been installed where required at all stations in Table 1. FY2008 funds were also used to continue upgrade of the sensors at remote island stations by purchasing high-accuracy paroscientific sensors to replace older technology pressure transducers and purchasing memory cards for the DCP's installed last year.

2.2. Task 2

Operation and maintenance of the Platform Harvest station (see Figure 2) continued over the past year. Coordination of activities continues with JPL. Two DCP's are operational and data from both are interchangeably used to obtain a continuous record when on DCP goes down. JPL continues to obtain the data at the time of every 10-day satellite crossover and provides periodic reports on the status of the verification project at Platform Harvest. The tide station has been reporting at intermittent intervals since September 1992, with near-continuous data since 2002 when the Climate Program Office funded a hardware upgrade. Figure 4 shows observed monthly mean sea levels for the period of record. The strong signal due to the annual variation in sea level is evident in the plot. The onset of the 1997 El Niño is also evident just prior to the gap in the data.

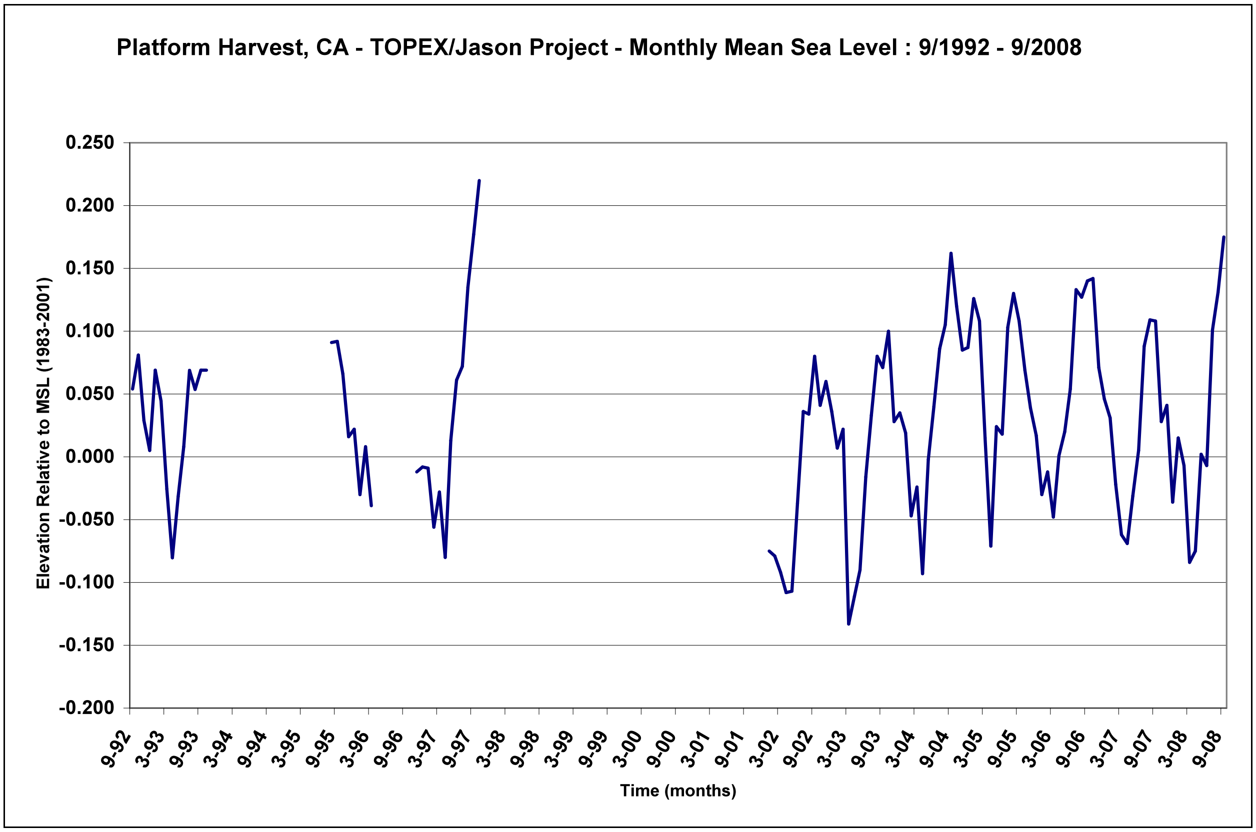

Figure 4. Platform Harvest Verification Site – Observed Monthly Mean Sea Level from the Tide Station from 9/1992 thru 9/2008.

3. PUBLICATIONS AND REPORTS

Results, analyses, and data products are routinely updated and reported on via the CO-OPS web site at: http://tidesandcurrents.noaa.gov/sltrends/sltrends.html. Derived sea level trends and related products are reported on in the companion *Progress Report for FY2008 Sea Level Change Analysis* being submitted by CO-OPS along with this progress report on the tide station network.

The original reference for the Platform Harvest operations is *Marine Geodesy, Volume 18, Numbers 1-2,* January-June 1995, Special Issue: TOPEX/POSEIDON Calibration/Validation.

For the most recent results of information from Platform harvest. See "Overview of the Calibration/Validation of OSTM/Jason-2 by Pascal Bonnefond and Bruce Haines at http://sealevel.jpl.nasa.gov/OSTST2008/agenda.html.

2. Drifting Buoys

a. The “Global Drifter Program” Drifter Measurements of Surface Velocity, SST, SSS, Winds and Atmospheric Pressure

b. Surface Drifter Program

The "Global Drifter Program"
Drifter Measurements of Surface Velocity, SST, SSS, Winds and Atmospheric Pressure

Peter Niiler
The Scripps Institution of Oceanography, La Jolla CA

1. PROJECT SUMMARY

1.1. Rationale

The principal scientific questions of the role of the ocean in climate change are how well can we describe or model the ocean circulation today and how well can these descriptions or models predict the evolution of future climates. Climate time scale changes in the sea surface temperature (SST) directly force changes in the air temperature and habitability conditions very large parts of the globe. On these interannual time scales SST depends on ocean circulation as well as air-sea interaction. A global array of drifters provide the operational instrumental data sets describing SST and ocean near surface circulation and evolution and these data are used for testing climate models and enhancing long-range weather prediction and interannual climate change.

Sensors that measure sea surface salinity (SSS) are now added to drifters and these SSS data are critical to determining the oceans' fresh water cycle and onset of deep-water renewals. Air pressures measured on drifters are assimilated into weather prediction models and are used by operational meteorological agencies to discern severe weather conditions over the oceans. Drifter pressure data also contribute significantly to the calculation of the inverted barometer effect on global sea level rise as measured from altimeters. Wind sensor and subsurface temperature chain data are used to improve prediction of tropical storms and hurricanes. Drifters designed and built within the *"Global Drifter Program"* (*GDP*) have proven to be reliable, autonomous platforms for obtaining climate and operational weather data from the global oceans.

1.2. Objectives of the " Global Drifter Program"

The "*Global Drifter Program*" (*GDP*) is the principal international component of the Joint Commission of Marine Measurements (JCOMM) *"Global Surface Drifting Buoy Array"*. It is a "Scientific Project" of the Data Buoy Cooperation Panel (DBCP) of World Meteorological Organization (WMO)/International Ocean Commission (IOC). It is a near-operational ocean-observing network that, through the Argos satellite system and the Global Telecommunication System (GTS), returns real time data on ocean near-surface currents, SST and air pressure (and winds, subsurface temperature - T(z), and SSS) and provides a data processing system for scientific utilization of these data. In addition to *GDP*, drifters are deployed by operational oceanographic and meteorological agencies and individual scientific research projects, whose data are utilized by *GDP*. In turn, *GDP* data are made available to operational users and scientists at large. Wind-sensors, salinity sensors and thermistor chains are added to SVP drifters, both on for specific operational and research requirements. The international protocols for these data exchanges and sensor additions are worked out each year by DBCP.

The scientific objectives of the *GDP*, and its operational and research partners, are:

1) Provide to GTS a near-operational, near-real time data stream of drifter position, SST, and sea level air pressure. GTS compatible data on winds, T(z) and SSS are also provided on operational basis when these sensors are mounted on the drifters.

2) Observe the 15m depth velocity on a global basis with 5.0° resolution and, jointly with satellite altimeter data, produce charts on the seasonal and interannual changing circulation of the world ocean at 0.5º resolution (Figure 1)

3) Develop and introduce into the drifter construction technological advances in sensors, electronics, power, methods of assembly and deployment packaging.

4) Provide enhanced research quality data sets of ocean circulation that include drifter data from individual research programs, historical data from instruments different from the Surface Velocity Program (SVP) Lagrangian Drifter and the corrected data sets for wind-produced slip of drifter velocity. To this end *GDP*:

- Provides to the coupled ocean-atmosphere climate modelers gridded, global data sets of SST, near surface circulation and dynamic topography for assimilation and the verification of the parametrized processes, such as wind-driven Ekman currents and spatial patterns of the seasonal circulation.
- Provides the Lagrangian data sets for the computation of single particle diffusivity, dispersal of ocean pollutants, the enhancement of models of fisheries recruitment and improvement of air-sea rescue.
- Obtains high-resolution coverage of ocean variability and time mean circulation in support of ENSO prediction model verification in the tropical Oceans and supports short-term research projects that require enhanced upper ocean velocity observations.

1.3. Required Drifter Observations and Status of Global Array

The 'required' global drifter array size by JCOMM is based on the need to maintain 1250 platforms that return instrumental observations of daily average SST (+/- 0.1^{0}C) over the global ocean at a 5º resolution, or the spatial scale of the error covariance function of the operational NOAA satellite infrared SST sensors (Figure 2). In the past 36 months the array has exceeded the 1250 required elements on more than half of the months, but more recently numbers have fallen below 1200. Surface pressure sensors are also supported by regional meteorological agencies based on regional needs, generally exceeding 500 elements. The number of drifters in the array is composed of the NOAA/*GDP* supported (85%), drifters deployed by principal investigators who have requested that their Argos Service costs be part of *GDP* contract. In turn, their data is included in the *GDP* real-time data that is placed on to the GTS. International oceanographic and meteorological agencies also deploy about 120 drifters per year.

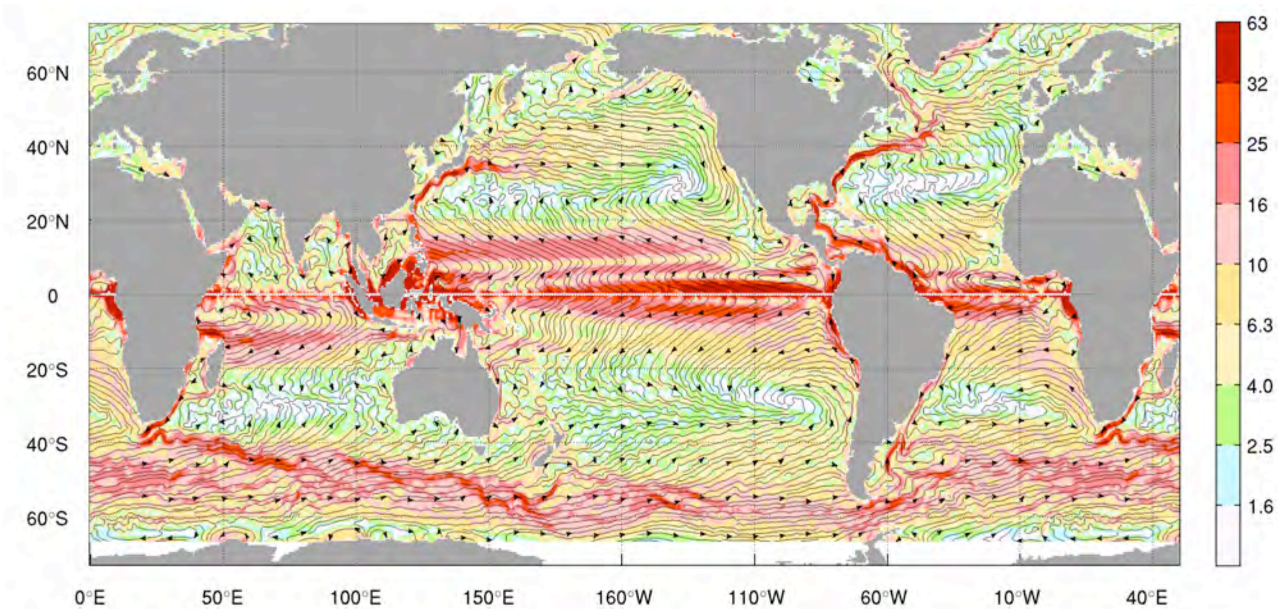

Figure 1. Mean streamlines calculated from a combination of drifter and satellite derived 15m-circulation at 0.50º resolution from data of October 1992 to December 2007. The choices of streamlines are made in an iterative fashion to cover the ocean at relatively uniform, several degree scale spatial density, giving the preference to the longest lines. Colors are magnitudes of the sum of the mean geostrophic plus Ekman velocity used to compute the streamlines, and units are cm/s. Note the "maelstroms" of circular convergent regions at 30ºN, 140ºW (a well known region of accumulation of plastic debris in the Northeast Pacific) and an heretofore unknown, but larger and more stable region at 30ºS, 90ºW.

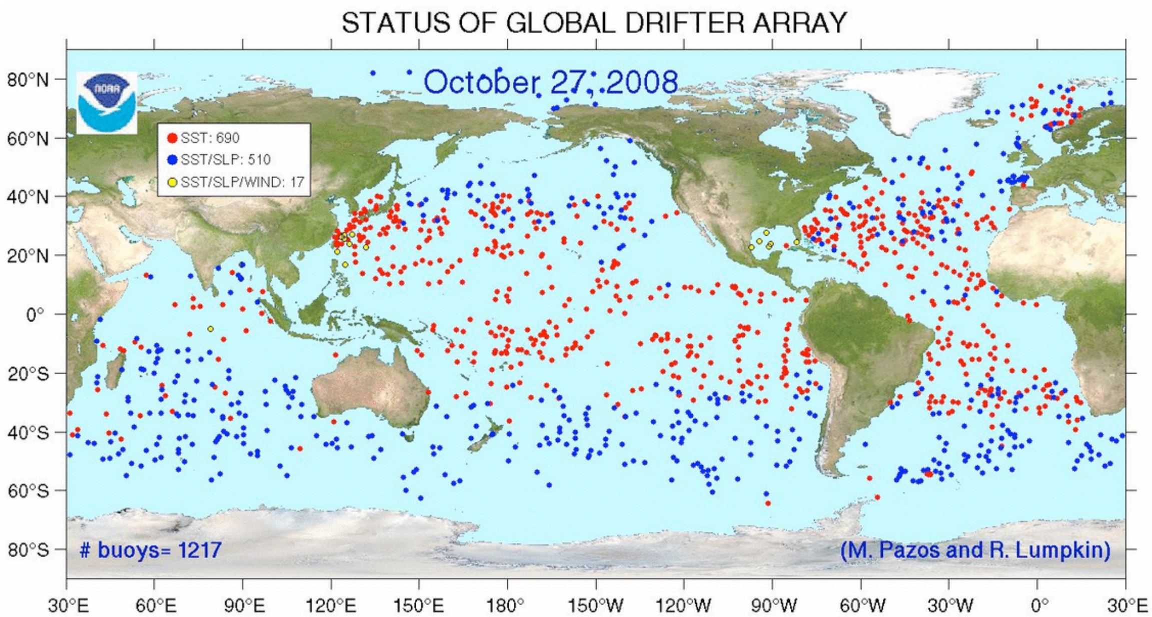

Figure 2. The JCOMM *Global Drifting Buoy Array* on October 13, 2008. Throughout the past 24 months the global array of SVP-B has exceeded 500.

On 27 October 2008, 1217 drifters were reporting to GTS and to the Atlantic Oceanographic and Meteorological Laboratory (AOML) *Drifter Data Center* (Figure 2). NOAA Climate Observations Program, funded to JIMO (910) and AOML (90) sufficient numbers of SVP drifters in FY'07, and with the contributions of drifters (100-120) from other national and international sources, the array was maintained from late 2005 to present date at a bit below the desired level. *GDP* /AOML is requesting additional drifters (143) to be funded to make up this gap.

1.4. Management

GDP reports every year on its activities relative to advances in technology in the DBCP "Technical Session" and its deployment plans and management in the DBCP "Plenary Session". *GDP* is managed according to the *"Ten Climate Monitoring Principles"* established by JCOMM. In these management tasks, the Principal Investigator of this proposal, Peter Niiler, assumes the responsibility for the coordination between the following entities:

• US manufacturers in private industry (*Technocean, Inc.* of Cape Coral, FL*; Clearwater, Inc*. of Watertown, MA*; Pacific Gyre, Inc.* of Oceanside, CA*)* who build the SVP, SVP-B, SVP-W and SVP-W-T(z) drifters according to closely monitored specifications. Internationally. Six private firms and several research laboratories build SVP drifters. Periodically, drifter construction manuals are upgraded and are posted on the DBCP website (e.g. 2005 the SVP-B Mini Construction Manual for which an upgrade is planned for 2009). As projected in the FY'09 budget, the price of the drifters, due to significant inflation in the past 18 month period, will be $100 per drifter more expensive than as these were in FY'08.

• Atlantic Oceanographic and Marine Laboratory (AOML) who carries out the deployments at sea, processes the data and archives these at MEDS, Canada, maintains the META file on the description of each drifter deployed and the maintains the *GDP* website.

• Technical staff of SIO, who assist in the supervision of aircraft deployments of drifters into hurricanes, place orders for the NOAA funded drifters, upgrade the technology, develop new sensors, enhance the data sets and maintain liaison with individual marine research programs that deploy SVP drifters.

• Supervision of cooperative arrangements with other NOAA and ONR, NSF and Internationally sponsored programs. *GDP* encourages principal investigators to purchase SVP – type drifters for their studies and make data from these drifters available on GTS to the international community. *GDP* also sends SVP drifters purchased by JIMO to be deployed in concert with the special projects to enhance the Lagrangian data sets.

This report from JIMO/*lGDP* addresses the progress of activities in FY’08 and proposes the activities for FY’09.

2. FY08 PROGRESS

In FY’08 NOAA Grants Office funding of the *GDP* through JIMO occurred in the third week of September 2008. This is a report of what was accomplished with both the FY’07 and FY’08 funding during the period of November 2007 – November 2008:

2.1. Summary of Drifter Acquisitions

With the FY’07 funds 910 drifters with SST sensors were manufactured and were delivered to AOML for deployment. With the FY’08 funds, 910 drifters were ordered in October 2008 and will be delivered to AOML for deployments during the calendar year 2009. With the FY’2008 funds, the composition of the drifter order in October 2008 to industry was:

a) A total of 620 SVP drifters were ordered from Clearwater Instruments, Inc Pacific Gyre, Inc. and Technocean, Inc. These are now being delivered to AOML for deployment.
b) A total of 270 SVP-B drifters were ordered from Clearwater Instruments, Inc., Technocean, Inc. and Pacific Gyre, Inc. These are now being delivered to AOML for deployment.
c) A total of 12 SVP-W wind-drifters (Minimet) and 8 SVP-W-T(z) wind and chain drifters (ADOS), fully rigged for air deployment, were ordered from Pacific Gyre, Inc. This is the third year that an industrial firm will build, calibrate and rig for air-deployment a full suite of hurricane drifters. All 20 units will be delivered the 53rd Air Force Reserve “Hurricane Hunter Squadron” at Keesler AFB before July

1, 2009. Dr. Rick Lumpkin and Dr. Eric Uhlhorn of AOML directing the design of the arrays that will be deployment for the 2009 Hurricane season.

In FY'08 JIMO has purchased 910 drifters and AOML purchased 140 drifters (from METOCEAN, Inc., Canada**), for total NOAA contribution of 1050 drifters to the JCOMM *"Global Surface Drifting Buoy Array".***

2.2. Sustained, Targeted Hurricane Deployments of Drifters

In 2008 Hurricane season targeted drifter deployments by the AF 53rd,Hurricane Hunter Squadron at Keesler AFB became fully operational. Ten training buoys and at least 20 operational drifters have been delivered by JIMO in years 2005, 2006, 2007 and 2008 to the 53rd. During this period, 75 of 77 deployed drifters provided data through Tropical Cyclone (TC) passages. The training buoys are used to maintain operational training exercises throughout the year for the 53rd flight crews for handling, storage, staging, loading and air-deployment of drifter packages.

Operationally, a drifter deployment plan is communicated from the National Hurricane Center/CARCAH in Miami to the 53rd Hurricane Hunter Squadron command at least 48 hours ahead of the expected deployment time. Final adjustments of the location of an array relative to the TC center are made 6 hours before the expected time of lift off of the 53rd C-130. In September 2008, successful operational deployments occurred in Hurricanes Gustav and Ike in the Gulf of Mexico (Figure 3).

With the assistance of ONR and NOAA/OAR, the combined *GDP* projects at JIMO and AOML have worked closely with the NHC and the AF 53rd Hurricane Hunter Squadron over the past five years to bring about a sustained ocean and atmosphere targeted observing system for Hurricanes and Typhoons. Crucial partners are also the US industrial firms of Pacific Gyre, Inc. and Clearwater Instruments, Inc. who build and maintain the store of drifters at Keesler AFB. This partnership is now sustained with funding of Minimet (SVP-W) and ADOS (SVVP-W-T) drifters through OCO/NOAA. In 2009 Hurricane season there will be 44 operational drifters stored in a Keesler AFB hangar.

2.3. Cooperative arrangements with ONR

In 2004 NOAA and ONR participated in a landmark study, CBLAST, of the effects of hurricanes on the ocean. With ONR continued support Jan Morzel (*Rosetta Consulting, Inc., Boulder CO*) has gathered all data acquired from dropsondes, drifters, floats, altimeters and scatterometers on to a website: http://tao-tc.ucsd.edu. ONR will continue to support this website for both hurricane and typhoon ocean data through 2011.

During the western Pacific Typhoon study, termed TCS-08, 24 *GDP* drifters were shipped to Andrews AFB in Guam, and under the direction of Mst.Stg.Rober E. Lee (retired) these were deployed in front of Typhoons Janghmi and Hagupit (23 of the 24 drifters that had been in storage for over 24 months deployed properly and produced data through passages of these storms: viz. Figure 4). **The objective of this ONR/NOAA cooperation is to maintain an ocean-air data set that can easily be accessed by scientists who wish to use it for improvement of coupled numerical models of Tropical Cyclones. By June, 2009, data sets from 9 hurricanes and typhoons will be in place in uniform easily accessible formats.**

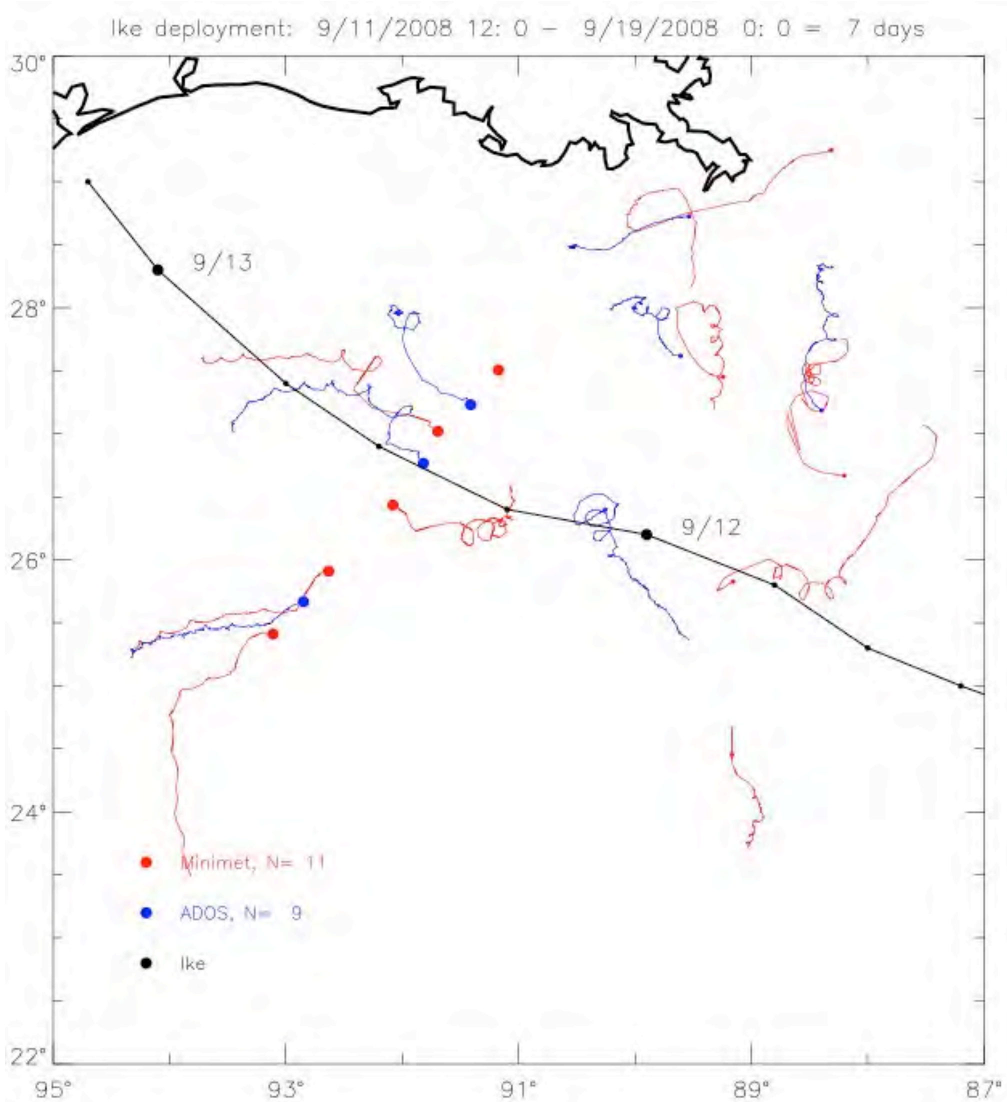

Figure 3. The drifter deployment pattern in front of Hurricane Ike in the Gulf of Mexico in September 2008 where red and blue dots mark the Minimet and ADOS drifter deployment locations. The red and blue lines are the subsequent 7-day tracks of drifters. Note that 9 drifters from the deployments in front of Gustav, 10 days before Ike, also observed the passage of Ike.

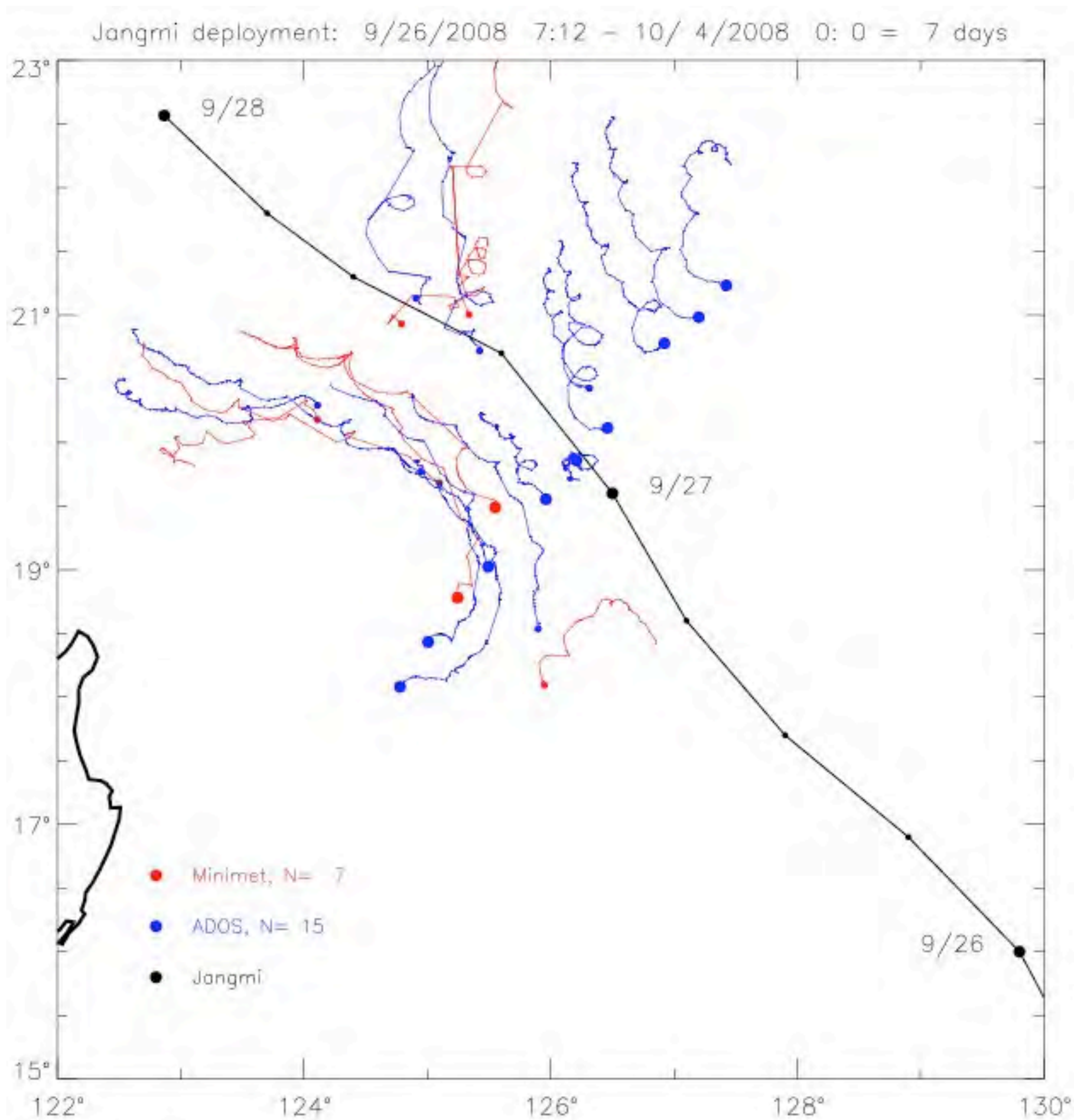

Figure 4. The drifter deployment pattern in front of Typhoon Jangmi in September 2008 in the western Pacific where red and blue dots mark the Minimet and ADOS drifter deployment locations. A total of 23 tracks appear because 12 drifters deployed in Typhoon Hagupit that passed over this region 6 days earlier were still sending good data.

2.4. Technical developments in drifter sensors

The temperature, air pressure wind direction and salinity sensors on drifters have worked reliable and produced data that has been possible to compare with other observations. The wind speed sensor, or WOTAN, that is based on ambient noise in the ocean cannot be interpreted in hurricane strength winds. In 2008, working with Pacific Gyre, Inc. we have installed a small Gill Acoustic Anemometer on the Minimet (SVP-W) and ADOS (SVP-W-TC) float (Figure 5). Calibration tests at sea are ongoing off San Diego during 11-15 November 2008 and we expect to place two of these drifters into the North Pacific in January 2009 for a longer deployment. These will be calibrated continuously with QSCAT over flight data.

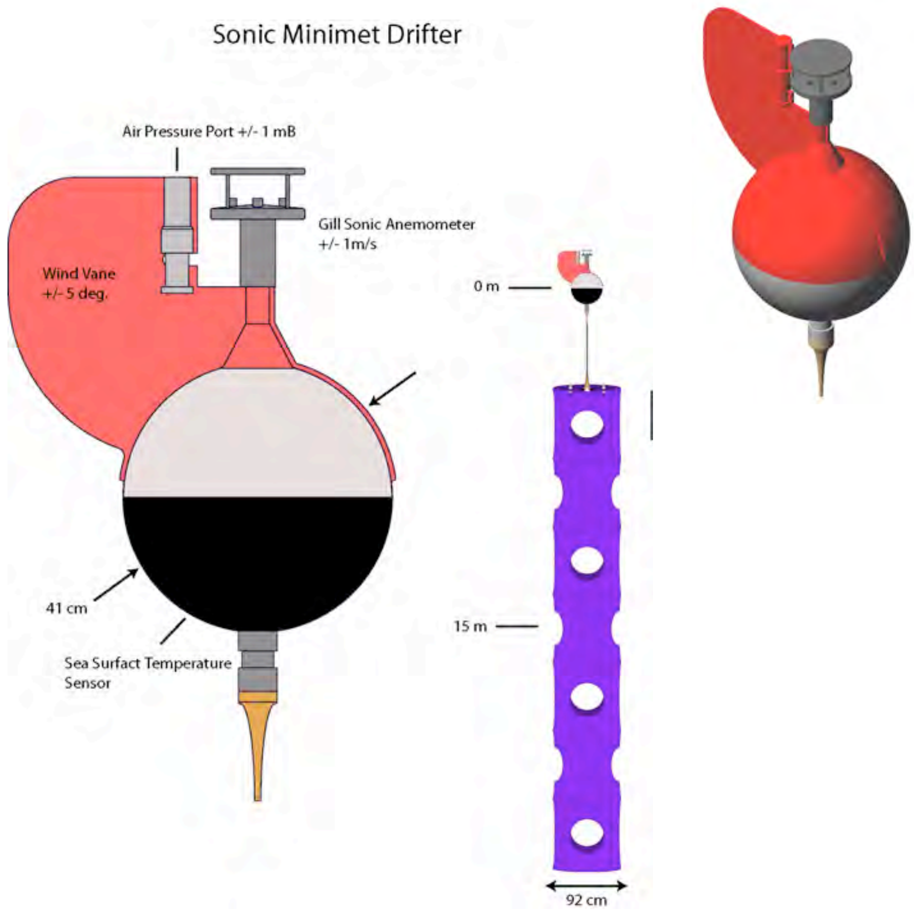

Figure 5. Schematics of the sonic Minimet drifter that is now in field tests off California next to NOAA/NDBC moored buoys. The digital controller within the surface float will integrate sample air pressure, tilt, compass direction and Gill anemometer wind speed at 1 sec intervals and record wind speed and direction measurements during conditions when the surface float is out of the water and level with the horizon. These conditionally sampled data will be averaged over 5 min periods once an hour and transmitted to Argos satellite system.

Two ADOS drifters that can be launched from a AXBT size hole in an aircraft fuselage have been assembled by Clearwanter Instruments, Inc. and tested in the laboratory conditions (viz: *GDP Report*, 2008 and Figure 6). We anticipate full at sea tests in early 2009.

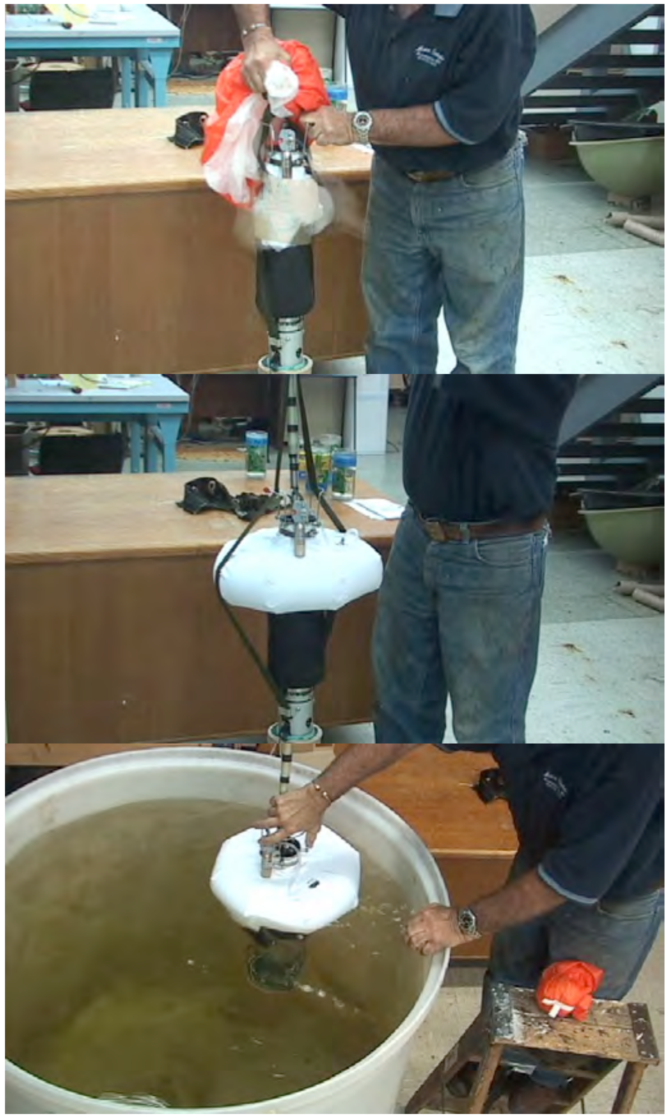

Figure 6. The sequence of laboratory photos showing the inflation of the floatation bladder for the ADOS drifter that is configured to be deployed from the AXBT launch holes in aircraft. A small parachute activates the inflation mechanism (note the orange and white cloth in upper panel). The bladder is a self-sealing inner tube that is used for ATVs and it is covered with fiber-enhanced sail cloth to prevent sea birds from puncturing the float. The entire ADOS drifter is packed in a cylindrical casing that is 4.5” in diameter and 36” long and automatically releases 150m of wire with 10 temperature and pressure sensors. At sea tests are planned for early 2009 off San Diego, CA. Releases from aircraft will occur in summer 2009.

2.5. Enhanced Data Sets and Publications:

Between December 2006 and November 2008, there were 25 requests for enhanced drifter velocity data sets. Dr. Yoo Yin Kim who works under the direction of P. Niiler as a Senior Statistician prepared and distributed these data. The drifter peer-reviewed publication list was upgraded in December 2006:
(http://www.aoml.noaa.gov/phod/dac/drifter_bibliography.html).

2.6. Meetings and Lectures

The following SIO personnel participated in the GDP presented lectures or attended the following organization meetings:

• Invited Lecturer at the workshop on "First CLIVAR Global Synthesis and Observation Panel Workshop on Ocean Velocity Measurements and their Application" December 5-7, 2007,La Jolla, CA: "Drifter Technology and Surface Circulation" (Peter Niiler)

• Invited Lecturer at the Keelung National Ocean University, Taiwan, March 20, 2008: "Observing Tropical Cyclones with Drifting Buoys" (Peter Niiler)

• AMS Conference on Tropical Meteorology, Orlando, FL. May 2, 2008: Drifting buoy deployments into Hurricane Dean, 2007 (Rick Lumpkin , NOAA/AOML, Miami FL; and P. P. Niiler and P. Black)

• Invited Lecture, OCO Meeting in Silver Spring, MD, June 3, 2008: "New Ocean Circulation Patterns from Combined Drifter and Satellite Dataz' (Peter Niiler)

• DBCP-XXIV, October 15-19, 2008 Cape Town, South Africa: "Operational deployments of drifting buoys into targeted Tropical Cyclones" (Luca Centurioni, Peter Niiler and Rick Lumpkin)

• DBCP-XXIV, October 15-19, 2008 Cape Town, South Africa: "The Global Drifter Program" (Luca Centurioni for: Rick Lumpkin and Mayra Pazos)

• Invited Lecture at the AGU Fall 2008 Meeting, San Francisco, CA December 17, 2008: "Equatorial Pacific vorticity and thermal energy balances determined from Lagrangian drifter observations" (Peter Niiler)

Surface Drifter Program

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1. PROJECT SUMMARY

The Surface Drifter Program is AOML's contribution to the Global Drifter Program (GDP), a branch of NOAA's Integrated Ocean Observing System, Global Ocean Observing System (IOOS/GOOS) and a scientific project of the Data Buoy Cooperation Panel (DBCP). The primary goals of this project are to maintain a global 5ºx5º array of Argos-tracked Lagrangian surface drifting buoys to meet the need for an accurate and globally dense set of in-situ observations transmitting in real time for weather forecast, and to provide a data processing system for the scientific use of these data that support short-term (seasonal-to-interannual, "SI") climate predictions as well as climate research. AOML's GDP responsibilities are to: (1) recruit ships and manage drifting buoy deployments around the world using research ships, Volunteer Observation Ships (VOS) and aircraft; (2) insure the data is placed on the Global Telecommunications System (GTS) for distribution to meteorological services everywhere; (3) maintain META files describing each drifter deployed, (4) process the data and archive it at AOML and at Canada's Integrated Science Data Management (formerly MEDS); (5) develop and distribute data-based products; (6) maintain the GDP website; and (7) maintain liaisons with individual research programs that deploy drifters.

The drifters provide sea surface temperature (SST) and near surface (mixed layer) currents. A subset of the drifters also measures air pressure, winds, subsurface temperatures and salinities. These observations are needed to (a) calibrate SST observations from satellites; (b) initialize global SI forecast models to improve prediction skill; and (c) provide nowcasts of the structure of global surface currents. Secondary objectives of this project are to use the resulting data to increase our understanding of the dynamics of SI variability, and to perform model validation studies, in particular in the Atlantic Ocean. Thus, this project addresses both operational and scientific goals of NOAA's program for building a sustained ocean observing system for climate.

2. ACCOMPLISHMENTS

The global drifter array became the first component of the IOOS that reached completion, with 1250 active drifters in September 2005. This number has since been maintained. During FY08, the drifter array averaged 1232 drifters, with a standard deviation of 48. The maximum size was 1312 (7 April); the minimum was 1152 (11 August). During the fiscal year, the Surface Drifter Program coordinated worldwide deployments of 1001 drifters (1023 in FY07), 880 (FY07: 859) funded by NOAA/OCO; 147 drifters were deployed in the Atlantic between 30ºN and 40ºS. AOML managed observations from 2113 unique drifters during FY08 (this is significantly greater than 1250, as some died while new ones were deployed to maintain ~1250).

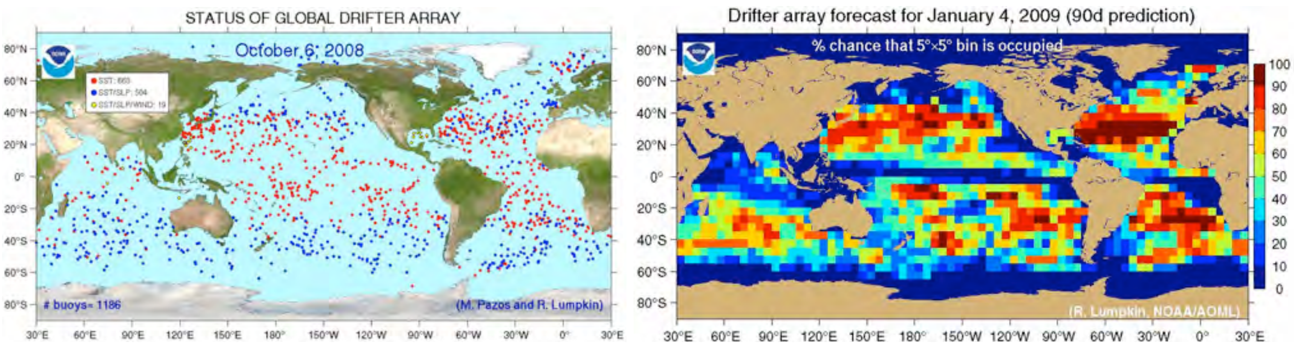

Figure 1. Global population of drifters on 6 October 2008 (array size 1186 drifters), and 90 day prediction of coverage (% chance that a 5ºx5º bin will have a drifter if no additional drifters are deployed in the interim).

The main challenge is now to increase the spatial coverage of the array while maintaining its size at 1250 drifters on average.

2.1. FY08 Deployment highlight: African Partnership Station (APS) Training

In March 2008, 28 participants from Ghana, Cameroon, and Nigeria boarded the U.S. Navy vessel HSV-2 *Swift,* where three days of training ensued from the port of Tema, Ghana. The ability of the US Navy to host the training aboard one of its vessels allowed for a novel "hands-on" experience which enabled participants to become familiar with the instruments, from which the data they are studying. The session was conducted as part of the US Naval Forces Africa Partnership Station (APS), which is an initiative in support of NOAA's climate research and ocean-observing efforts. During the three-day session, one Argo Float, three global drifting buoys, and 12 expendable bathythermographs (XBTs) were deployed from the HSV-2 *Swift* to gather temperature, salinity, and current measurements. The deployment of these instruments was an important step in understanding how to incorporate the data access training previously taught in Ghana and Belgium.

2.2. FY08 Deployment highlight: 2008 Hurricane drifters

On August 31 and September 11, the 53rd Air Force Reserve Squadron "Hurricane Hunters" deployed 21 GDP hurricane drifters in the paths of hurricanes Gustav and Ike in the Gulf of Mexico. These drifters, funded by OCO via JIMO, measured winds, air pressure, surface temperatures and subsurface temperatures to a depth of 150m. R. Lumpkin coordinated the deployments, in collaboration with P. Niiler (JIMO), E. D'Asaro (U. Washington), AOML's Hurricane Research Division (HRD), and NOAA's National Hurricane Center (NWS). The hurricanes moved over the drifters 24 hours after deployments. All drifters survived deployment to transmit data, and many of the Gustav drifters were subsequently hit by Ike. While the hurricanes passed over the arrays, R. Lumpkin interacted with AOML's HRD to coordinate WP-3D flights that measured the properties of the storms at drifter locations with dropwindsondes.

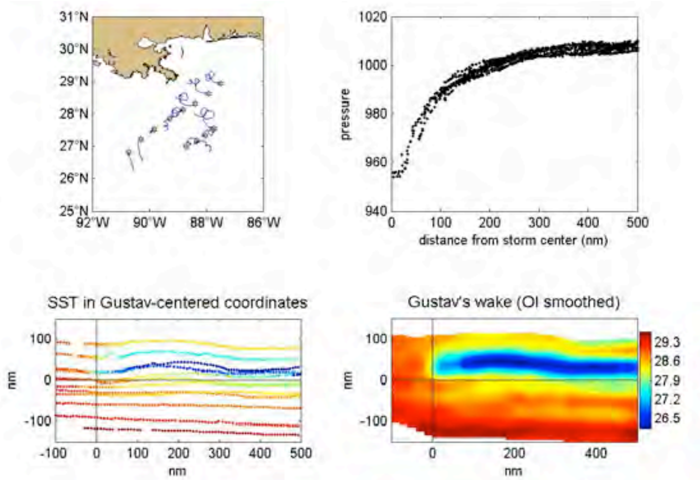

Figure 2. Drifter observations in hurricane Gustav. Upper left: deployment locations on 31 August 2008 (stars) and subsequent trajectories through 8 September. Upper right: measured air pressure as a function of distance from the storm's center. Bottom: surface temperature measurements in a frame of reference moving with Gustav (centered at 0,0), in which the array streaks from left to right.

2.3. Analysis of the drifter array

The number of drifters in the global array as a function of time is shown below. Since September 2005, the array size has fluctuated around 1250. Those fluctuations reveal a distinct seasonality, with peaks of 1300—1350 drifters in Boreal winter—spring and troughs of ~1150—1200 drifters in summer—fall. This pattern reflects seasonal variations in deployment opportunities, e.g., Southern Ocean deployments in February—March.

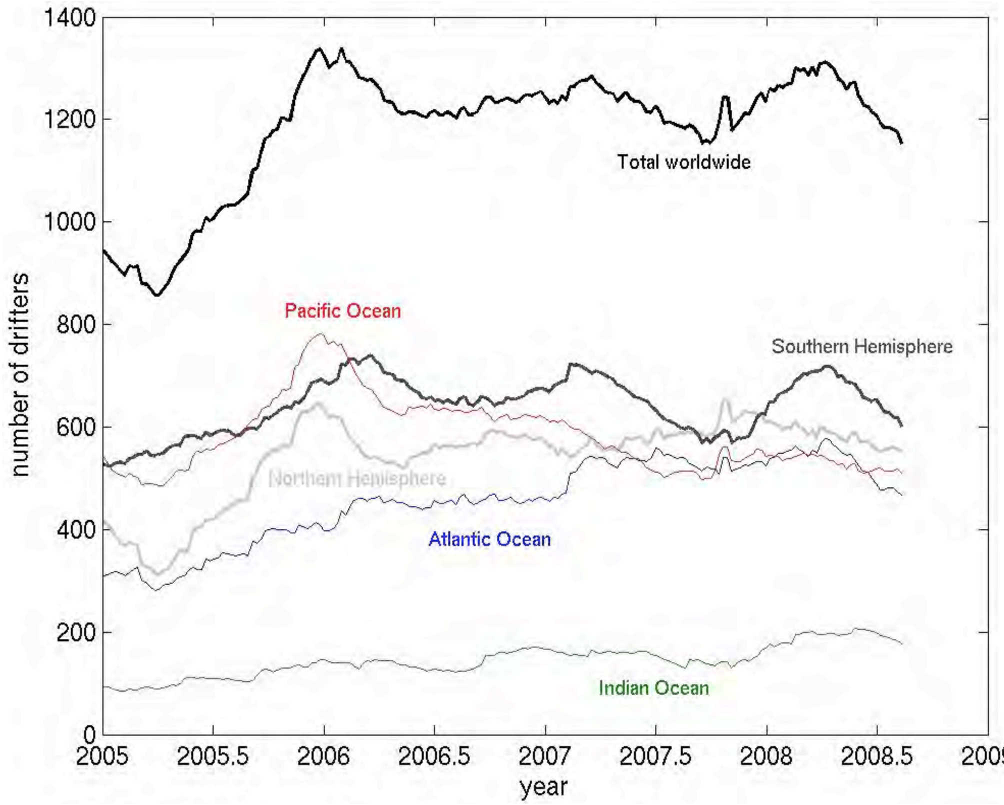

Figure 3. Size of global drifter array in regions. Atlantic/Indian divided at 25°E in the Southern Ocean, Atlantic/Pacific at 70°W in the Southern Ocean, Indian/Pacific at 125°E south of Timor.

The number of drifter deaths per month, per 1250 drifters, is shown in Figure 4. This is the number of drifters that must be deployed each month in order to maintain the array at 1250. In addition to short-term ups and downs, the death rate has generally increased over the last few years. Approximately 70 deployments were needed per month in September 2005 to maintain the array at 1250 drifters, while 90—100 deployments are now needed each month.

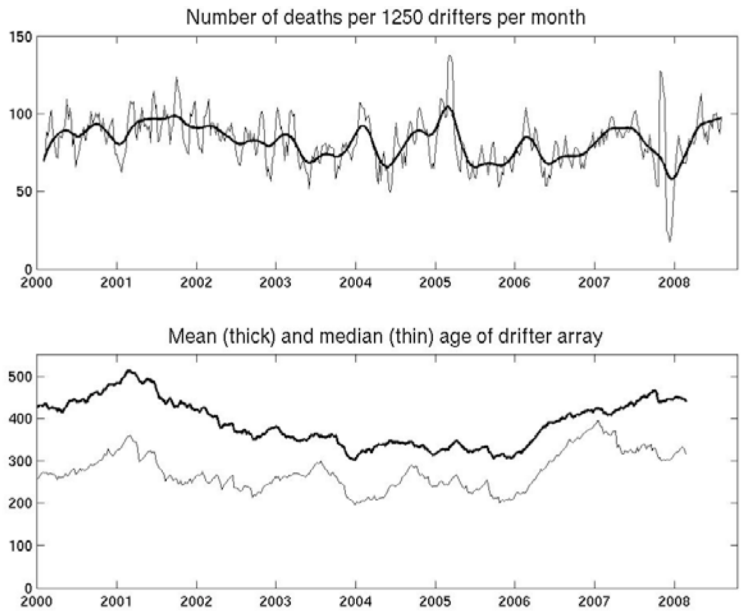

Figure 4. Number of drifter deaths per 1250 drifters per month (top) and the age of the global drifter array (bottom).

Why has the death rate increased? One major factor in setting the high death rate is the mean age of the array, also shown in Figure 4. During 2005, the size of the array increased dramatically as deployments were ramped up to meet the goal of 1250 drifters by September. This large influx of new drifters drove down the average age of the array to its lowest level in years. At the beginning of 2006, the median age of a drifter in the array was 200 days, far less than the operational lifetime of 450 days. After reaching the goal of 1250 drifters, fewer needed to be deployed to maintain that number. Thus, the mean age of the array began increasing after January 2006. The mean age is now near 450 days, e.g., the mean lifetime of a drifter, suggesting that the increase in death rate and array age should level off unless systematic engineering problems develop to reduce the mean age of the array while increasing the death rate.

What has been the impact of the increasing death rate? We have been responding to the increased death rate by a moderate increase in the number of deployments in the last few months. Thus, the number of drifters in the array has not substantially declined below the late Boreal summer minimum (c.f. Figure 3). However, our FY08 average deployment rate of 83 drifters per month is insufficient to maintain the array in the long term, in the face of 90—100 deaths per month per 1250 drifters.

What will be the impact of this increased death rate in the future? If we do nothing differently to address this, we can anticipate that there will be a shortfall of ~10 drifters per month to maintain the array. The array will grow to a peak of ~1245 drifters in mid-March 2009, then shrink to a minimum of ~1040 drifters by September 2009. The FY09 average size will be ~1165. Several strategies can be adopted to address this problem:

1) NOAA can fund an additional 10 drifters per month, at an additional cost of $160k per year (basic SVP drifters with SST and surface currents; operational partners will be invited to add barometers via the upgrade program). This strategy is offered in the FY09 Work Statement and Budget.

2) The Global Drifter Program can increase the pressure upon its international partners to share more of the load in their regions of interest. This strategy has been attempted in the past, for example to populate the tropical Atlantic with drifters, without major success. In many cases, a regional partner is a meteorological organization that is willing to fund barometer upgrades, but not the complete drifter. This strategy will certainly lead to regional gaps in the array in the short term.
3) The Surface Drifter Program can adjust deployment plans to place more focus on lowering the death rate. In short, we can trade off the 5°x5° resolution goal with the goal of maintaining 1250 drifters. There are ocean regions where drifters do not tend to live as long, due to a historically higher rate of running aground or being picked up. Examples include the western Indian Ocean and the northern Gulf of Guinea. (Other examples, such as the coast of Brazil, cannot be avoided due to ocean advection patterns.) By strictly avoiding any deployments in these regions, we will be less successful at reducing the potential satellite bias error in SST and surface current measurements (fewer 5°x5° bins sampled), but will be more successful at maintaining 1250 drifters with the present deployment rate.

Figure 5 shows the recent growth of the array as a function of the four major drifter manufacturers from which NOAA purchases drifters: Clearwater, Metocean, Pacific Gyre and Technocean. Technocean and Clearwater drifters dominate the global array. Death rates (second subplot) have remained relatively low and steady for Technocean drifters. Clearwater drifter deaths spiked to larger values in early to mid 2007, an issue which the Surface Drifter Program identified in mid-2007 and communicated to the manufacturer. Since mid-2008, the death rates of three of the four manufacturers (all but Technocean) have risen, perhaps reflecting the increasing age of the drifters. For the period September 2007 to the present, the mean death rate, per 1250 drifters, per month have been 108 (Clearwater), 89 (Metocean), 84 (Pacific Gyre) and 52 (Technocean). Some of these variations reflect various deployment regions, which are not uniform for drifters from the manufacturers, deployment techniques from individual platforms, storage times for some batches of drifters, etc.; these variations motivated the ADB study described below. Regardless, these results suggest that the longer operational lifetime of the Technocean drifters helps compensate for their higher price (~$450 more per drifter than the other three manufacturers).

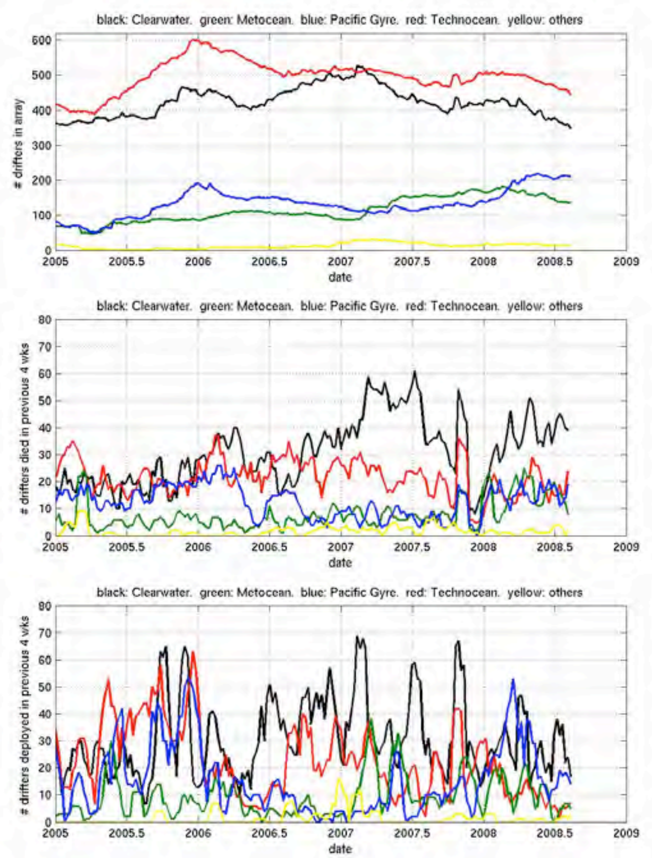

Figure 5. Size of the array divided into the four major manufacturers (top), the number of drifters that died each month (middle) and the number of drifters deployed each month (bottom).

2.4. AOML Data Buoy (ADB) Comparison Study

In FY08—09, as in FY05—06, the Surface Drifter Program is conducting an AOML Data Buoy (ADB) comparison study to evaluate the performance of the manufacturers. During this study, drifters from Clearwater, Metocean, Pacific Gyre and Technocean are deployed in clusters in various regions throughout the world. The clusters are initially only a few meters apart, allowing us to cross-compare for SST quality and wind-driven slip. It is the goal of the Surface Drifter Program to evaluate the performance of each product independently, and use these findings to determine the strengths and weaknesses (if any) that exist. Preliminary results show that after 5 months of data collected, a total of 4 drifters out of 20 have already ceased transmitting, one from Technocean after 50 days, two from Metocean after 34 and 64 days and one from Pacific Gyre after 91 days. We are concerned about the rapid death of the Metocean drifters, with 2 out of 5 dead already dead, and will continue to monitor the lifetimes of the remaining drifters. Five ADB drifters have already lost their drogues: one Clearwater drifter lost its drogue after 99 days, three Technocean drifters lost their drogues after 101, 99 and 75 days, and one Pacific Gyre showed drogue lost after only 12 days in the water. We are concerned with the rapid loss of Technocean drifters, and will monitor this issue more closely in the Bay of Biscay study (see below). With respect to SST, we found two problems with Pacific Gyre drifters: one had an offset of 0.45^0C with respect to its neighbors (confirmed not to be an error with the SST coefficients) … this offset was added to the GTS distribution to correct and avoid wrongful data dissemination; another drifter from Pacific Gyre had SST sensor failure after 30 days in the water. Also one Metocean drifter's SST failed five days after deployment.

As a subset of the 2008 ADB Comparison Study, fifteen SVPB drifters, five each from three manufacturers (Clearwater, Pacific Gyre, and Technocean), were developed to evaluate the addition of strain gauge for drogue detection. DBCP colleagues at Méteo-France recently deployed these drifters in tight clusters in the Bay of Biscay. As well as testing the tether strain sensors, we are taking this opportunity to examine other aspects of these drifters such as barometer port sensors, SST values, battery life, signal strength, etc. Preliminary results indicate that three of the five Technocean drifters lost their drogues within an extremely short time in the water, a result confirmed by the recovery of one drifter by Méteo-France, and that this drogue loss was successfully evaluated from tether strain.

2.5. Collaborations

The Global Drifter Program would not be able to maintain the drifter array without contributions from national and international partners who deploy the drifters worldwide. Drifters are deployed from many research cruises, several (such as PIRATA Northeast Extension, Western Boundary Time Series and NTAS) funded by NOAA/OCO. Many drifters are deployed from vessels cooperating in NOAA's Ship Of Opportunity Program (SOOP); SOOP personnel (J. Trinanes) also supports AOML's efforts to collect the hurricane drifter data for subsequent quality control and redistribution.

2.6. Research efforts

Since the introduction of multisatellite processing in January 2005, the mean temporal resolution of drifter data has decreased dramatically from its earlier values, now averaging slightly over one fix per hour. This increase in temporal resolution allowed AOML-funded postdoctoral fellow S. Elipot, with his advisor R. Lumpkin, to conduct a global census of high-frequency (inertial and superinertial) motion (Elipot and Lumpkin, 2008). The rotary (clockwise and counterclockwise) energy spectrum of hourly drifter velocity (Figure 6) reveals the energy content in the anticyclonic inertial band and in semidiurnal and diurnal motion. The energy content in the inertial band is much higher here than in analyses of kriged data at high latitudes, where kriging to ¼ day values removes much of the inertial variance. Resolving these high-frequency motions has significant climate implications as wind energy input as near-inertial waves is one of the primary energy inputs to drive the observed stratification of the ocean via interior ocean mixing.

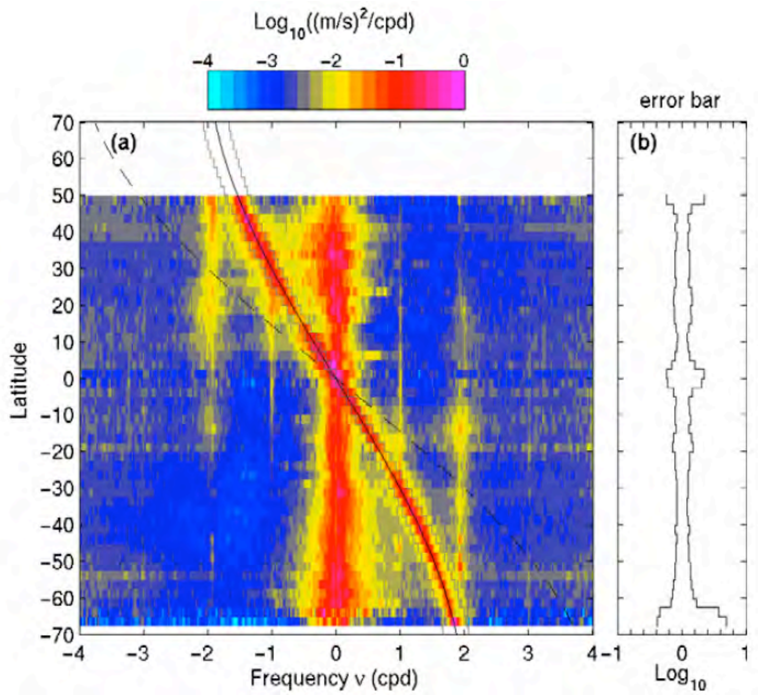

Figure 6. Clockwise (negative frequency) and counterclockwise (positive frequency) energy content in drifter velocities as a function of latitude, in the Pacific Ocean (from Elipot and Lumpkin, 2008). The local inertial frequency is indicated by the solid curve, twice the inertial frequency by a dashed curve. Diurnal and semidiurnal ridges of enhanced energy are seen at frequencies of ±1 and ±2 cycles per day.

With collaborators A. Griffa and M. Veneziani, R. Lumpkin has mapped the global distribution of "spin" from the drifter trajectories. Spin is calculated from the lagged correlation between zonal and meridional velocity, and indicates where looping trajectories dominate oceanic surface motion. In addition to the known dominance of anticyclonic spin at high latitudes, the investigators found a band of dominant cyclonic spin at 15-20°N and S in all ocean basins (Figure 7). This new feature may be related to submesoscale vortices generated at the equatorward edges of the subtropical gyres (Griffa, Lumpkin and Veneziani, 2008).

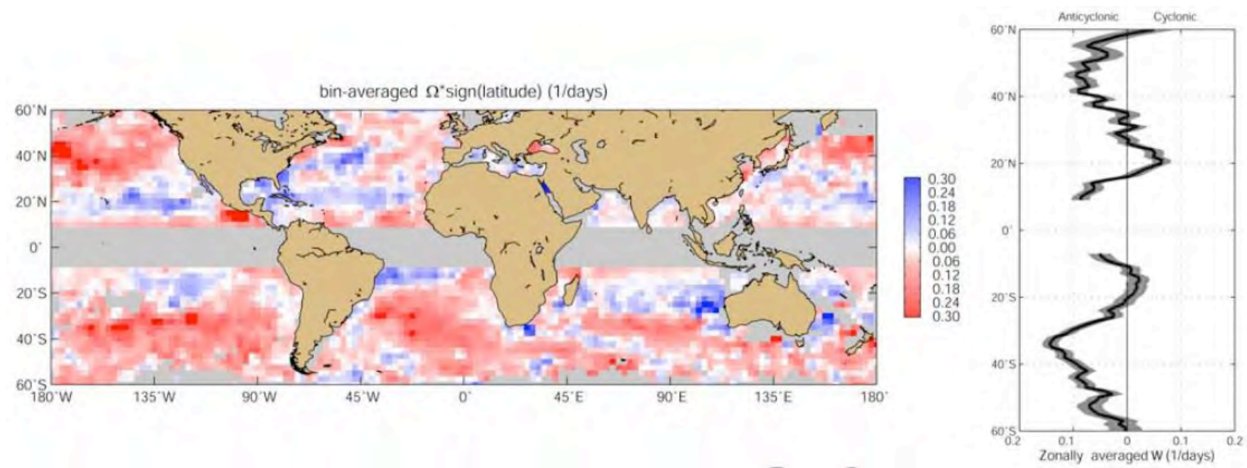

Figure 7. Mean distribution of spin (left) showing where anticyclonic (red) and cyclonic (blue) loopers are common. Zonal average (right) indicates the presence of cyclonic bands at the equatorial side of the subtropical gyres, a feature seen for the first time in these data. From Griffa et al. (2008).

A subcomponent of the Global Drifter Program, the Atlantic Drifters, was funded with the objectives to fill gaps in the observational network, in order to accurately describe the basin-scale Atlantic current and SST seasonal-to-interannual variations. This program was started to address the data coverage deficiency in the tropical and subtropical south Atlantic (20°N to 40°S). Lumpkin and Garzoli (2005) analyzed the time mean and seasonal variability of the equatorial currents using the resulting drifter data, and shed new light on different branches of the equatorial system and its variability. The PIs are currently completing an analysis of the data collected in the South Atlantic to characterize the near-surface circulation of the sub-tropical Atlantic. Two different data sets were derived for this study: a climatology for sea surface velocities derived from the period October 1992 to March 2007 and a product derived from sea surface currents observed with the drifters and altimeter covering the same time period. The study encompasses the whole basin as well as individual studies of the time-mean pathways of the boundary currents (Confluence of Brazil and Malvinas in the west; the Agulhas/Benguela system in the east) and the variations of the upper ocean exchanges associated with the bifurcation of the South Equatorial Current at the coast of Brazil. R. Lumpkin presented a highlight of the results of this study at the 2008 Office of Climate Observations annual review. In summary, the 1993—2008 southward migration of the Brazil/Malvinas current confluence (see Figure 8) was mostly likely driven by a southward migration of the wind stress pattern, as is known to happen at the seasonal time scale. Looking back for longer times, using the wind patterns as a proxy for the ocean at pre-altimetry and drifter times, we suggest that this decadal migration may be part of a multidecadal oscillation related to basin-scale SST anomalies in the subtropical South Atlantic Ocean.

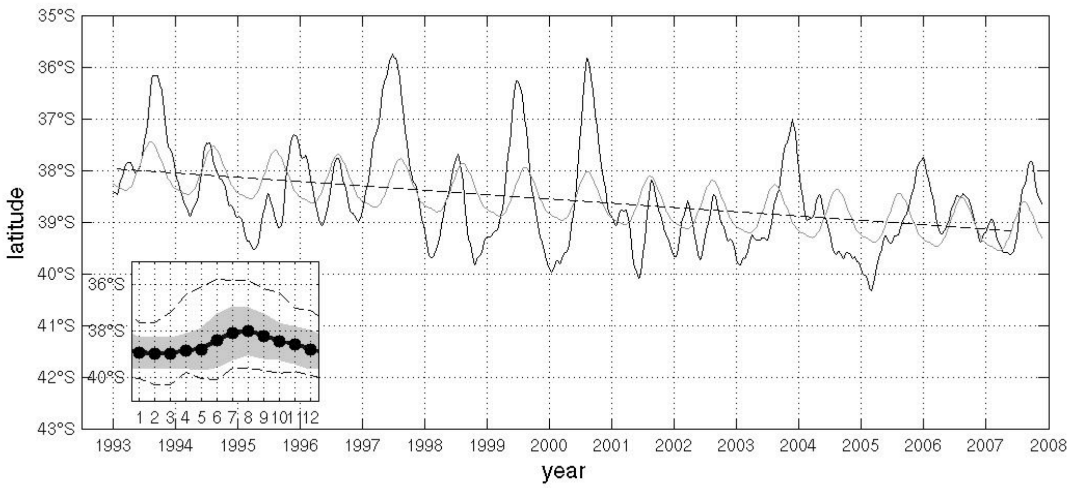

Figure 8. Location of the Confluence of the southward Brazil Current and northward Malvinas Current as a function of time (from Lumpkin and Garzoli, manuscript in revision). Subpanel shows the seasonal cycle, standard deviation (shading) and monthly extrema (dashed line).

3. MEETINGS

S. Dolk and M. Pazos (AOML) attended the 23nd Data Buoy Cooperation Panel (DBCP) meeting (15-19 October 2007, Jeju, South Korea). There, they presented the results of the 2007 drifter comparison study, attended numerous subpanel meetings such as regional planning panels, and attended the "First Panel Meeting of Coastal and Ocean Observations", a joint observation project between MOMAF/NORI (Korea) and NOAA. M. Pazos attended the Argos Users Meeting (30 Sept—2 Oct 2008, Annapolis, MD) and the ISABP-12 meeting (29-30 May 2008, Rio de Janeiro, Brazil), and was appointed technical coordinator of the ISABP. J. Redman attended a tether strain implementation meeting between three manufacturers and JIMO (13-14 December 2007, La Jolla, CA). S. Dolk attended the African Partnership Station meeting in Ghana, Africa (March 2008; see earlier in this report for more). R. Lumpkin presented drifter-based analysis at the Office of Climate Observations Annual Review (3—5 September 2008, Silver Spring, MD), the Ocean Sciences meeting (3—7 March 2008, Orlando, FL) and the CLIMODE PI meeting (6—7 August 2008, Woods Hole MD). R. Lumpkin and B. King organized the CLIVAR/GSOP Special Workshop on Velocity Observations (5—7 December 2007, La Jolla, CA).

4. OUTREACH

R. Lumpkin worked with Anand Gnanadesikan for the "Ocean Currents" display in the newly opened Ocean Hall of the National Museum of Natural History. He also authored a chapter of the National Geographic and Smithsonian Institution's "Hidden Depths: Atlas of the Ocean by NOAA" in concert with the Ocean Hall opening.

Our cooperation with the African Partnership Station program, noted earlier in this report, represents NOAA's contribution to this effort.

5. PUBLICATIONS AND REPORTS

Elipot, S. and R. Lumpkin, 2008: Spectral description of oceanic near-surface variability. *Geophys. Res. Letters*, **35**, L05605, doi:10.1029/2007GL032874.

Griffa, A., R. Lumpkin and M. Veneziani, 2007: Cyclonic and anticyclonic motion in the upper ocean. *Geophys. Res. Letters*, **35**, L01608, doi:10.1029/2007GL032100.

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Sallée, J-B., K. Speer, R. Morrow and R. Lumpkin, 2008: An estimate of Lagrangian eddy statistics and diffusion in the mixed layer of the Southern Ocean. *J. Marine Res.*, accepted July 2008.

Zhang, H.-M., R.W. Reynolds, R. Lumpkin, R. Molinari, K. Arzayus, M. Johnson, and T.M. Smith, 2008: An Integrated Global Ocean Observing System for Sea Surface Temperature Using Satellites and In situ Data: Research-to-Operations. *Bulletin of the American Meteorological Society*, accepted June 2008.

3. Tropical Moored Buoys

a. Tropical Moored Buoy Arrays: PIRATA, RAMA, Flux Reference Sites, and Tropical Sea Surface Salinity

b. Development of a Next Generation Platform and Instrumentation for Continuous Ocean Observations (PICO)

c. Tropical Atmosphere Ocean (TAO) Array

Tropical Moored Buoy Arrays: PIRATA, RAMA, Flux Reference Sites, and Tropical Sea Surface Salinity

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1. PROJECT SUMMARY

This report describes FY 2008 progress in the implementation of the Tropical Moored Buoy Array program as a NOAA contribution to development of the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS), and the Global Earth Observing System of Systems (GEOSS). The goal of the moored buoy program is to provide high quality moored time series and related data throughout the global tropics for improved description, understanding and prediction of seasonal to decadal time scale climate variability. Focus on the tropics is dictated by its role as a heat engine for the Earth's climate system, engendering phenomena such as the El Niño/Southern Oscillation (ENSO), the monsoons, the Indian Ocean Dipole, and tropical Atlantic climate variability. This program supports NOAA's strategic plan goal to "Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond." It also provides key observational underpinning for the international Climate Variability and Predictability (CLIVAR) program's research efforts on climate variability and change. Management of the tropical moored buoy array program is consistent with the "Ten Climate Monitoring Principles". Program oversight at the international level is through the CLIVAR/JCOMM Tropical Moored Buoy Implementation Panel (TIP). A new web site containing comprehensive information on the program can be found at http://www.pmel.noaa.gov/tao/global/global.html.

Four major elements to the Tropical Moored Buoy Array program are described below. These are the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA), the Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA), Flux Reference Stations, and Tropical Pacific Salinity. Discussion of these elements is followed by comments about fishing vandalism, point current meter measurements, a summary of community service, and a list of FY 2008 publications supported by this research. Chris Meinig of PMEL will submit a separate progress report on Engineering Development, a fifth element of the Tropical Moored Buoy Array program. The TAO array, also part of the Tropical Moored Buoy Array program, is managed by NOAA/NDBC.

2. ACCOMPLISHMENTS

2.1. PIRATA

As of September 30, 2008 the PIRATA Array consists of 17 ATLAS moorings and one subsurface ADCP. This includes the 10 ATLAS mooring PIRATA core array configuration (as agreed upon for the 2001-2006 consolidation phase of the program), three 'Southwest (SW) Extension" moorings, and 4 "Northeast (NE) Extension" moorings. The SW Extension moorings were first deployed in August 2005 and initial capitalization costs were supported by INPE in Brazil. NOAA has since assumed responsibility for ongoing equipment replacement and refurbishment. Two NE Extension moorings were deployed in June 2006 and two additional sites deployed in May 2007. A "Southeast (SE) Extension" mooring sponsored by the University of Capetown, South Africa, was deployed in June 2006 and recovered in June 2007, but not redeployed. This site may be reoccupied if sustained funding becomes available.

PMEL is charged with providing equipment and technical support for ATLAS moorings and instrumentation, and support for data processing, dissemination, and display. France provides equipment and processing for the subsurface ADCP site. France and Brazil provide ship time and support for equipment shipments and also provide technician support at sea. NOAA provided ship time in FY 2006 and FY 2007 to support the Northeast Extension and the core mooring at 0º, 23º W. NOAA ship time was planned for FY 2008, but mechanical problems and other issues with the NOAA Ship Ron Brown resulted in a cancellation of a Northeast Extension cruise scheduled for April 2008. NOAA contracted the French RV Antea for this work in October 2008. PMEL and AOML are jointly staffing this cruise.

Eight (8) ATLAS moorings were recovered and 8 moorings (5 core array and 3 SW Extension) were deployed from the Brazilian R/V Antares in March-May 2008 (36 sea days, 25 PMEL person-days: PMEL staffed only 2 of 3 cruise legs). Four core array moorings were recovered and 5 deployed from the RV Antea in September 2008. One of the moorings was vandalized before the end of the cruise. A second mooring was deployed from spare equipment, but the damaged mooring was not recovered due to lack of time.

All PIRATA moorings measure wind speed and direction, air temperature, relative humidity, short wave radiation, precipitation, sea surface temperature and salinity, ocean temperatures at 10 depths down to 500 m and salinity at 3 depths down to 120 m. Three PIRATA sites have been enhanced as flux reference sites (see 2.3 below). The four NE Extension moorings have been enhanced with a near surface current measurement and one additional subsurface salinity measurement. One of the NE Extension moorings has been enhanced to the level of a flux site.

PIRATA data are available from the PIRATA web site (www.pmel.noaa.gov/pirata/) and the TAO web site (www.pmel.noaa.gov/tao/disdel/disdel.html). There is also a mirror sites in France. A mirror site in Brazil is no longer active. Collection, processing, and dissemination of shipboard CTD and ADCP data are the responsibility of France and Brazil, with AOML taking responsibility for these data collected during the Northeast Extension cruises. Northeast Extension cruise data, including quality controlled CTD, Thermosalinograph and XBT data, and accompanying cruise reports are available at the PIRATA Northeast

Extension web site (http://www.aoml.noaa.gov/phod/pne).

Real-time data return was 76% overall for FY 2008, 11% lower than for FY 2007, but within 1% of FY 2006. The lower value in FY 2008 was due to the loss of a mooring in the Gulf of Guinea and the delay in the Northeast Extension cruise. The sites with the lowest data return were 0º, 23º W (42% data return due to vandalism and cruise delay), 0º, 0 º (58%, mooring lost) and the Northeast Extension moorings (57% to 70%, due to battery failure, vandalism and cruise delay).

Real-time PIRATA data return by variable for FY 2008 (and for comparison, FY 2007) is shown below. Three Flux Reference and one NE Extension sites are enhanced for current, longwave radiation (LWR) and barometric pressure (BP). The other NE Extension moorings also measure currents as well. Real time current velocity data return has been disappointingly low. In addition to vandalism and cruise delays affecting all data return, velocity data losses were higher due to problems with battery life and telemetry issues. Efforts to improve these measurements are in progress (Section 4).

	AIRT	SST	T(Z)	WIND	RH	Rain	SWR	LWR	SAL	BP	CUR	ALL
FY 2008	87	64	75	74	85	48	84	88	61	91	26	76
FY 2007	94	91	89	90	92	73	86	100	84	100	45	87

The TAO Project continues to update the content and functionality of its web site (http://www.pmel.noaa.gov/tao/). This site provides easy access to TAO/TRITON, PIRATA and Indian Ocean data sets, as well as updated technical information on buoy systems, sensor accuracies, sampling characteristics, and graphical displays. For FY 2008, a total of 8706 separate user requests delivered 90,554 PIRATA data files, which represent 16% and 47% increases, respectively, from the year before.

PIRATA data are distributed via the GTS to centers such as NCEP, ECMWF, and Météo-France where they are used for operational weather, climate, and ocean forecasting and analyses. PIRATA data placed on the GTS include spot hourly values of wind speed and direction, air temperature, relative humidity, and sea surface temperature. Daily averaged subsurface temperature and salinity data are also transmitted on the GTS. Daily ftp transfers are made from PMEL to the CORIOLIS operational oceanography program in France. The MERCATOR program in France makes use of the CORIOLIS data base to generate operational ocean model based data assimilation products. PIRATA data are also available on the GODAE server in Monterey, California.

The PIRATA project was highlighted this year in a cover article in the *Bulletin of the American Meteorological Society* (Bourlès, Lumpkin, McPhaden *et al.*, Vol **89** (8), August 2008). This article provided an overview of PIRATA's history, scientific and logistical accomplishments, and future for the general scientific community. In this article, the acronym PIRATA was redefined as the Predication and Research Moored Array in the Tropical Atlantic.

2.2. Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA)

The CLIVAR/GOOS Indian Ocean Panel (IOP) developed an implementation plan for a multi-component ocean observing system, IndOOS. A key element of the system is a 46 element moored buoy array, the Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA). The first elements of the array were deployed by Japan in 2000-2001 by India in 2002. PMEL and India's National Institute of Oceanography (NIO) deployed the first ATLAS moorings in 2004.

In FY 2008 the number of PMEL sites in RAMA increased from 9 to 15, bringing the total number of sites deployed to 20, or 43% complete. Two of the new ATLAS sites was deployed on a PMEL/NIO cruise in November 2007 (15 sea days, 30 PMEL person days) from the Indian R/V Sagar Kanya. The other two new ATLAS sites were deployed in August 2007 from India's newest research vessel the Sagar Nidhi (28 sea days, 84 PMEL person days). Other operations from the Sagar Nihdi included the recovery of 2 ATLAS and 1 ADCP mooring and the deployment of 3 ATLAS and 10 ADCP moorings. In August 2008 PMEL deployed one ATLAS mooring in collaboration with France's *Laboratoire d'Océanographie - Expérimentation et Approches Numériques* (LOCEAN) from the RV Marion Dufresne (8 sea days, 8 PMEL person days). An ATLAS mooring scheduled for recovery at the site was left in place due to weather conditions. However, negotiatons are underway to recover this mooring from the Sagar Kanya in November 2008. Four ATLAS moorings were recovered and new moorings deployed in September-October 2007 from the Baruna Jaya 3 (27 sea days, 54 PMEL person days).

PMEL has been actively engaged in developing partnerships to secure ship time necessary for implementing and maintaining RAMA. PMEL spearheaded efforts within NOAA to develop an MOU with the Ministry of Earth Science (MoES) in India for cooperative programs across a wide range of topics. The MOU was signed in April 2008. An Implementing Arrangement (IA) under this MOU for development of RAMA was signed in September 2008 in Delhi, India. As part of the IA, India has pledged a minimum of 60 days of ship time per year for 5 years. For the Baruna Jaya cruises, ship time was obtained via cooperative agreements between NOAA and Indonesia's Agency for the Assessment and Application of Technology (BPPT) and the Ministry for Marine Affairs and Fisheries (DKP). IAs between NOAA and each of the Indonesian agencies are under development and should be completed in 2009. Under these IAs, Indonesia will provide 30 sea days annually for dedicated RAMA implementation and maintenance. Additional sea days will be provided for joint RAMA/Indonesian GOOS (InaGOOS) mooring deployments a two designated RAMA sites. The most recent collaboration has been between PMEL and the Agulhas Somalia Current Large Marine Ecosystem (ASCLME) project. PMEL became aware of deployment opportunities on an ASCLME cruise through the IOP in mid 2008. As a result, two ATLAS moorings will be deployed in the southwest Indian Ocean (8°S and 12°S, 55°E) in November 2008.

All ATLAS moorings deployed in the Indian Ocean have the PIRATA suite of instrumentation, plus one additional water temperature measurement, 2 additional salinity measurements and one near surface velocity measurement. One of the ATLAS moorings is enhanced for flux reference measurements (see 2.3 below).

RAMA real-time data return was 52% overall for FY 2008, substantially lower than in TAO or PIRATA. This was mainly due to higher rates of vandalism in the Indian Ocean basin (see 2.6 below) and mooring service intervals longer than the 1-year design lifetime of the moorings. Most service intervals for recent moorings have been 18 months (Table 1.)

Table 1. RAMA mooring service schedules.

Sites	Ship Nationality	Deployment	Recovery
1.5º N, 80.5º E 0º N, 80.5º E 1.5º S, 80.5º E	India	September 2006	August 2008
8º S, 67º E	France	January 2007	Not recovered yet. New mooring deployed August 2008
0º N, 90º E 1.5º N, 90º E 4º N, 90º E 8º N, 90º E	Indonesia	September –October 2007	Planned for April 2009
12º N, 90º E 15º N, 90º E	India	November 2007	October 2008

Of the 3 surface moorings deployed in September 2006, one was not found in August 2008 and the other 2 had no surface instrumentation attached. Both of the latter returned nearly complete subsurface data, thus percent data return for RAMA will increase when delay mode data are considered. Data return from the PMEL ADCP deployed at 0, 81°E was 100% for the second deployment in a row, resulting in a continuous record of nearly 4 years.

We note that RAMA (and PIRATA) winds are currently being used to verify Advanced SCATterometer (ASCAT) data (see map at: http://www.knmi.nl/scatterometer/ascat_osi_25_prod/ascat_app.cgi?cmd=buoy_validations&period=week&day=0&flag=no). The analysis is described in Bentamy, A., 2008: Characterization of ASCAT measurements based on buoy and QuikSCAT wind vector observations. Ocean Sci. Discuss., 5, 77–101. (available at http://www.ocean-sci-discuss.net/5/77/2008/osd-5-77-2008.pdf)

2.3. Flux Reference Stations

The OCEAN Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES) is built around a worldwide network of long-term, deepwater reference stations measuring many oceanographic and meteorological variables of relevance to climate and biogeochemical cycles and is a contribution to the Global Ocean

Observing System and international research programs. PMEL is a major contributor to OceanSITES in the context of the Tropical Ocean Atmosphere (TAO) mooring array in the tropical Pacific, PIRATA and RAMA. Five equatorial Pacific moorings within the TAO/TRITON Array (4 ATLAS and 1 TRITON), three PIRATA moorings, and two (1 ATLAS and 1 TRITON) RAMA moorings presently have air-sea heat, moisture and momentum flux measurement capability. The RAMA plan calls for 8 flux sites when completed. Enhancements to the primary ATLAS measurements in each array provide the functionality for all flux reference moorings to measure shortwave and longwave radiation, precipitation, sea level pressure, water temperature with higher vertical resolution, surface and subsurface salinity at 8 depths, and velocity at one or more depths. PMEL's contributions to OceanSITES are highlighted in a web site created in 2008, http://www.pmel.noaa.gov/tao/oceansites/. As part of this website, a heat, moisture, buoyancy and momentum flux data display and delivery page has been created (http://www.pmel.noaa.gov/tao/disdel/flux/main.html).

2.4 Tropical Sea Surface Salinity

FY 2008 funding provided support to complete the instrumentation of tropical moorings to measure sea surface salinity (SSS) measurements at all surface mooring sites. The 55th and final site of the TAO array was instrumented in March 2008. Future funding will be required only to maintain TAOsites as a contribution to the combinedTAO/TRITON array. Data from this array are supporting efforts to better describe and understand variability and trends in surface salinity. One paper on trends in the western Pacific over the past 30 yrs is under review (Cravatte et al, 2008) and a second on the mean seasonal cycle in the Pacific is in preparation (Bingham, Foltz, McPhaden, and Suga).

3. VANDALISM

New hardware which inhibits the removal of sensors and the buoy towers was introduced on moorings deployed in September 2007. The effectiveness of these efforts has not yet been determined since few moorings with modifications have been recovered. Initial indications are not conclusive. Of two such moorings deployed in the Bay of Bengal, one was recovered in tact, while the other was missing its tower. The latter stopped transmitting in May 2008, coincident with the passage of cyclone Nargis. While the cessation of data telemetry was undoubtedly due to the cyclone, the cause of the loss of the tower has not yet been determined. Buoys on two surface moorings deployed in 2008 were modified to inhibit vandals from climbing aboard and attaching lines to the buoy. Transmissions from both moorings have continued since deployment in August 2008. These moorings do not have any meteorological sensors. If the modifications prove successful in reducing mooring loss, surface sensors protected from removal and damage will be reintroduced to the moorings.

4. CURRENT METER PERFORMANCE

Based on the relatively low data return rates for the Argonaut-MD, PMEL is looking at alternative instruments to replace these instruments. One possibility is a new short-range Doppler current meter recently developed by YSI RDI, Inc. PMEL has worked with the manufacturer on design criteria and testing of prototypes of this instrument. Field testing is underway on PMEL moorings and the DVS performance will be evaluated in 2009. Other point Doppler current meters were deployed in October 2008 on two PIRATA moorings for comparison with ADCPs and the instrument presently used on tropical surface moorings.

5. COMMUNITY SERVICE

McPhaden, the TAO Project Director, is chairman of the Tropical Moored Buoy Implementation Panel and serves on the PIRATA Scientific Steering Committee (SSC), the OceanSITES Science Team, the CLIVAR/GOOS Indian Ocean Panel, the CLIVAR Pacific Panel, the CLIVAR Global Synthesis and Observations (GSOP) Panel, and the JCOMM Observations Coordination Group. He is a member of the UK RAPID-WATCH Program Advisory Group and an editor for the *Bulletin of the American Meteorological Society.* McPhaden also is President-elect of the AGU. In FY 2008, he attended several CLIVAR panel meetings and a PIRATA SSC meeting in Natal, Brazil.

The PMEL TAO Project Manager represents the Tropical Moored Buoy Implementation Panel at the JCOMM Data Buoy Cooperation Panel (DBCP), the International Buoy Programme for the Indian Ocean (IBPIO) and serves on the OceanSITES Data Team. He attended the DBCP meeting in October 2007 (Jeju, Republic of Korea) and OceanSITES meeting in April 2008 (Vienna, Austria). He worked with the Climate Program Office and the International Activities staff in developing IAs for collaboration with India and Indonesia towards the implementation of RAMA. He also helped to lay the groundwork for a long-term collaboration with ASCLME for provision of ship time to implementation of RAMA.

Lumpkin, project collaborator at AOML, is scientific advisor for the Global Drifter Program and serves on the PIRATA SSC alongside McPhaden. He is also a member of the CLIVAR Tropical Atlantic Climate Experiment (TACE) working group on observations. He attended the TACE/AMMA meeting in Karlsruhe, Germany in November 2007 and the PIRATA-13 meeting in Natal, Brazil in February 2008. In December 2007, he co-convened (with Brian King) the CLIVAR/GSOP workshop on velocity observations in La Jolla, CA. He served as OAR representative for the safety inspection of the R/V Ronald H. Brown in Montevideo, Uruguay in April 2008, where he provided input regarding how problems with the vessel were impacting the scientific objectives of various cruises. He helped organize the charter of the R/V Antea for the October 2008 PIRATA Northeast Extension cruise, and developed the cruise plan with PMEL colleagues.

6. PUBLICATIONS (Refereed Literature)

Bourlès, B., R. Lumpkin, M.J. McPhaden, F. Hernandez, P. Nobre, E. Campos, L. Yu, S. Planton, A. Busalacchi, A.D. Moura, J. Servain, and J. Trotte, 2008: The PIRATA Program: History, Accomplishments, and Future Directions. *Bull. Amer. Meteor. Soc.*, 89, 1111-1125.

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Development of a Next Generation Platform and Instrumentation for Continuous Ocean Observations (PICO)

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1. PROJECT SUMMARY

This continuation proposal requests funds to advance the state of NOAA's open ocean observation systems with the development of an easy to deploy and low cost mooring system which make use of new and commercially available sensors and instrumentation and which addresses issues of improved data return rates in areas prone to vandal induced data losses and reducing costs of high quality ocean observations. This effort is motivated by the need to develop a mooring & instrumentation system to replace and significantly improve upon the performance of existing ATLAS moorings used in NOAA's contribution to tropical moored buoy arrays in support of climate research and forecasting. A candidate system presently under development at PMEL is the Platform and Instrumentation for Continuous ocean Observations (PICO) mooring. A web site containing comprehensive information on the system under development can be found at http://www.pmel.noaa.gov/pico/.

2. ACCOMPLISHMENTS

From FY '08 Work Statement:

a. Build, test and deploy a complete PICO mooring with Prawler in local waters and off-shore.

Results:

Two PICO deployments were completed during this fiscal year, both of them successful and encouraging that our concept of a low-cost self deployed mooring with integrated ocean profiler (Prawler) is viable. The first test remarkably showed that even in protected water of Puget Sound in 200m the Prawler was still able to crawl in wind chop condition, completing 484 profiles and 16,250 meter during the 8 days test.
During a test deployment of two system in ~3000m south of Oahu, two PICO mooring system were deployed with surface MET measurements and Prawlers. During this ~40day test one Prawler (Figure 2) climbed 370km and telemetered temperature, pressure and engineering data in realtime via an inductive modem to the PICO surface buoy (Figure 1). Remarkably, the system average 30

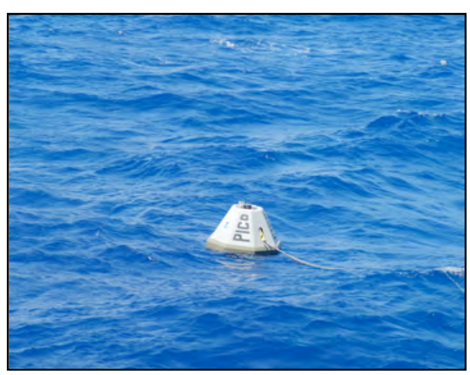


Figure 1. Hawaii Deployment 2008.

profiles per day to a depth of 350m using the heave energy from the surface buoy. Sensors and communication systems were powered by lithium batteries which determine the endurance of this first ocean deployment. We are encouraged by these results and plan on building the next generation Prawlers with increased endurance and climate quality CTD sensors.

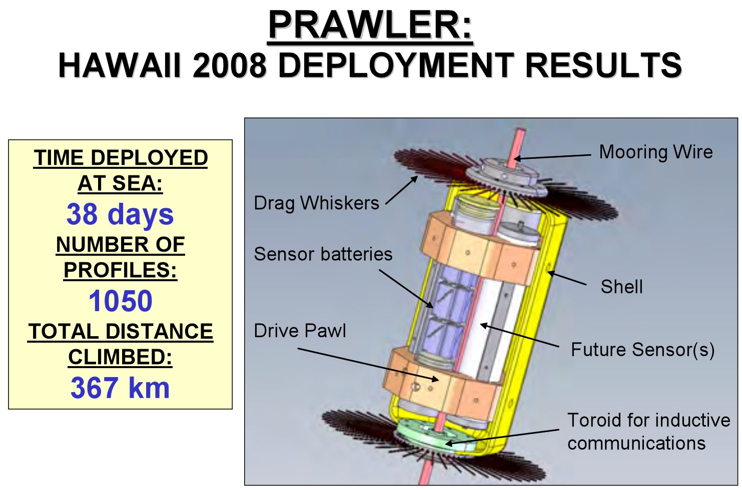


Figure 2. Prawler Configuration.

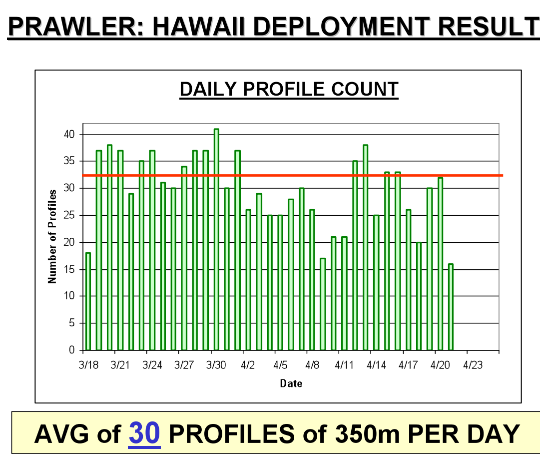


Figure 3. Profile Histogram.

b. Validate field data and correlate with WHOI cable software model results, with goal of 4 year, low-cost surface mooring endurance in tropical waters.

Results:

A detailed study was completed on various PICO mooring using WHOI cable software. The effects, on the PICO mooring's dynamic responses, from the addition of a profiler, appear to be largely dependant upon the vertical location (depth) of the profiler. Fixing the profiler at a depth of 325m consistently yields the most severe results, and this location should be used for future mooring modeling. The profiler's effects on static tension and mooring catenary can be considered to be negligible. The influences of profiler depth on the vertical movement of the mooring remain inconclusive.
Surprisingly, the addition of a weighted line section only has a moderate effect on the PICO mooring's catenary and line slope between 325m and 650m (at most 8%, assume the model has a "built-in" +-5% error). The addition of the weighted section has no beneficiary effect on the tension spread, but it does have a pronounced effect on the static tension at the buoy. Under calm current conditions and choppy seas the additional weight reduces the PICO buoy's tendency towards shock loading by greatly increasing the mean tension, while only slightly increasing the tension spread. Based on these results, it is recommended that the weighted line section be retained within the PICO mooring design.

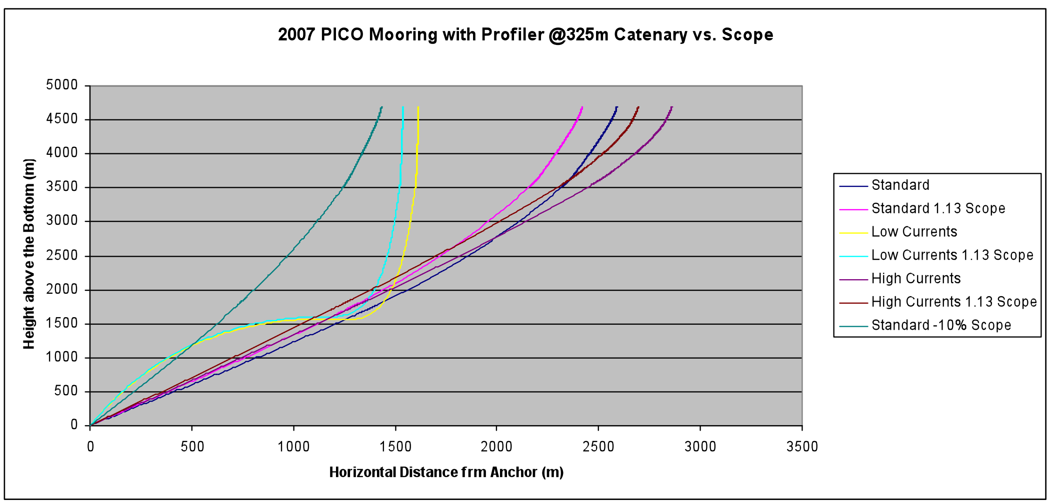


Figure 4. WHOI Software Mooring simulations.

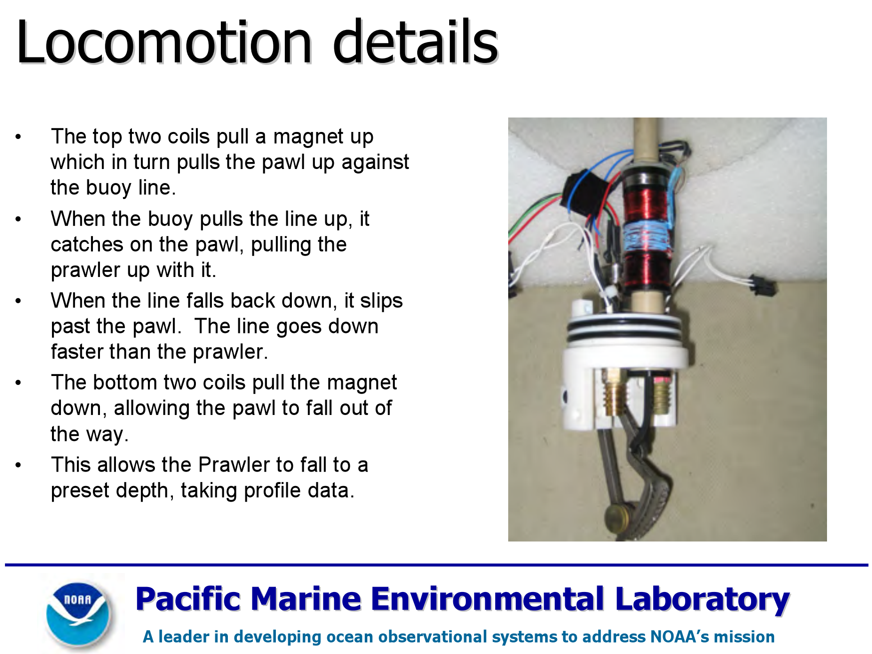
c. Design and evaluate upper terminations for ease of assembly, while meeting endurance goals.

Results:

The upper termination on the PICO mooring is the most complex design challenge of the mooring. A novel termination was designed, manufactured and tested in PMEL's Dynamic Line Testing machine then ultimately deployed on the two full ocean test moorings. One termination failed after 90 days while the other performed very well with minor signs of wear. Lessons learned will be incorporated in future designs and deployments.

d. Evaluate the design of the Prawler wave driven crawler mechanism. Determine endurance limits and evaluate alternative.

Two Prawlers were built, tested and deployed in Puget Sound and in 3200m south of Honolulu, Hawaii. We are encouraged by the results of our 38 day test deployment, in which on Prawler crawled over 367km. Upon recovery, the mechanism was 100% functional and was completely free of any bio-fouling or corrosion. The 2nd Prawler's communication system failed after a few days of testing, but the failure was unrelated to the Prawler wave driven mechanism (Figure). We are extremely encouraged by these results and plan on incorporating this mechanism in the next generation Prawler that we are proposing to build in FY'09.



e. Evaluate energy harvesting techniques and equipment for the PICO surface buoy and Prawler. Measure accelerations on Prawler to determine available energy for electrical conversion, build prototypes.

A PRAWLER as configured in Figure 1 was outfitted with a bi-axial accelerometer and place on a mooring line that was attached to a rotating armature on the R/V SP HAYES. The speed of the armature was set to match the data collected during the PICO Hawaiian deployment. The preliminary data analysis for available energy to convert to electrical power is not encouraging and in FY'09 we hope to explore alternative energy harvesting techniques on the PRAWLER.

f. Develop and test electronic circuit boards and systems for energy harvesting in the Prawler.

Test electronics A/D boards and computer were developed and outfitted as part of the SP HAYES testing in section e. All system performed very well, although the results of those tests will lead us in a different direction.

g. In addition to the PICO mooring hardware development described above we will continue to evaluate the Vaisala WTX510 for tropical moored buoys. Tests include:

a. Wind tunnel evaluation and calibration of the Vaisala WTX510 wind sensor.

b. Rain gage evaluation compared to standard ATLAS sensor at Seattle facility.

c. Atmospheric Temperature and relative humidity sensor calibration in PMEL lab.

Results:

The Vaisala WTX 510 sensor was evaluated by PMEL staff using standardized sensors for wind, rain and ATRH. Wind tunnel test were encouraging and compared well with our standard Gill Windsonic sensors. The RH sensors were calibrated in the chamber at 55-95% humidity in 10% increased steps and the Vaisala appears to be reading ~2% lower than standard ATLAS RH Rotronic Sensors. The Vaisala rain gauge is currently being evaluated relative to standard ATLAS rain gauges and testing is not yet complete. Currently a repackaging design is underway to include compass and Iridium telemetry options for the Vaisala WTX512, so that at sea testing can be conducted.

Tropical Atmosphere Ocean (TAO) Array

Landry Bernard[1] and Michael J. McPhaden[2]
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[2] NOAA Pacific Marine Environmental Laboratory (PMEL), Seattle WA

1. PROGRAM SUMMARY

FY 2008 funding was expended to maintain the Tropical Atmosphere (TAO) array as part of NOAA's effort to "Build a Sustained Ocean Observing System for Climate". TAO is the U.S. contribution to the TAO/TRITON array, a network of moored buoys spanning the tropical Pacific Ocean maintained in partnership with the Japan Marine Science and Technology Center (JAMSTEC). TAO/TRITON supports NOAA's strategic plan goal to "Understand Climate Variability and Change to Enhance Society's Ability to Plan and Respond". It also underpins Climate Variability and Predictability (CLIVAR) research efforts on El Niño/Southern Oscillation (ENSO). Management of the array is consistent with the "Ten Climate Monitoring Principles". Program oversight at the national level is through the Climate Observing System Council (COSC). Program oversight at the international level is through the CLIVAR/JCOMM Tropical Moored Buoy Implementation Panel (TIP). Web site containing comprehensive information on the TAO Program can be found at (http://www.tao.noaa.gov/). This report summarizes the progress and accomplishments of the TAO Program in FY2008, including the progress and achievements for the TAO transition from PMEL to NDBC.

2. FY 2008 PROGRESS

2.1. TAO/Triton Array

2.1.1. Background

FY 2008 was the eighth full year of the combined TAO/TRITON array and the partnership with JAMSTEC is working well. NOAA maintains the portion of the array between 95°W and 165°E, while JAMSTEC maintains sites between 156°E and 138°E. JAMSTEC added three moorings along 130°E for its own purposes in FY 2002, though these moorings complement those of the TAO/TRITON array proper. Basic measurements from ATLAS and TRITON buoys are transmitted on the GTS and are merged into a unified data set available on the World Wide Web (http://www.tao.noaa.gov/).

2.1.2. TAO Program Highlights

The weak La Niña which was prevalent during much of FY 2008 was replaced by ENSO-neutral conditions in June 2008. Although the atmospheric circulation over the western and central Pacific continues to show aspects of La Niña, the overall, ocean-atmosphere system remains consistent with ENSO-neutral conditions. Based on these conditions, recent trends, and model forecasts, the ENSO-neutral conditions are expected to continue into early 2009.

2.1.3. Field Work

NDBC is responsible for maintaining 55 ATLAS sites at and east of 165°E. At four of these sites (165°E, 170°W, 140°W, 110°W along the equator) current meters are attached to the ATLAS mooring lines, and a nearby subsurface Acoustic Doppler Current Profiler (ADCP) mooring is deployed. During the past year, NDBC deployed 54 ATLAS moorings and 4 subsurface ADCP current meter moorings in the tropical Pacific. All ATLAS electronics and mooring hardware specific to ATLAS electronics were provided by PMEL. Two experimental TAO Refreshed buoy were deployed in the Pacific for a side-by-side test with TAO Legacy buoys. One (1) DART buoy was recovered and deployed in the Pacific. Three (2) Refreshed TAO buoys were deployed in the Gulf of Mexico and one recovered as part of continuing development tests.

2.1.4. Ship Time and Sea Time

In FY 2008, 276 days at sea were allocated to the program by NOAA's Marine and Aviation Operations (NMAO) (223 days on *Ka'imimoana** and 53 days on *Ronald H. Brown***) to support the TAO portion of the TAO/TRITON array. This total includes transit days for repositioning the ships and traveling to and from the shipyard. NDBC participated in 852 person-days at sea (number of people times days at sea) and deployed 54 TAO moorings, 4 ADCP moorings, and 1 DART mooring. For comparison, during FY 2007, 232 days at sea (191 days on *Ka'imimoana* and 41 on *Ronald H. Brown*) were required to maintain the array, and 56 moorings were deployed.

* Due to a budget shortfall at NMAO, 51 of the 223 sea days on *Ka'imimoana* were funded by the National Weather Service.

** 36 of the 53 sea days on *Ronald H. Brown* were accomplished as an ancillary project during the CLIVAR cruise along 110W.

2.1.5. Data Return

Percentage real-time data return for primary TAO variables integrated over the 55 sites for FY 2008 follows:

	AirT	SST	T(z)	WIND	RH	ALL
FY 2008	86	86	83	78	81	83
FY 2007	90	86	84	77	87	85
FY 2006	91	86	83	82	87	84

A decrease in the percentage of air temperature and relative humidity measurements led to a decrease in the percentage of total measurements from the TAO array. Almost one-third of the buoys reported less than 80% return of air temperatures and relative humidity values, with the 155°W line showing the lowest return for these parameters. Vandalism in FY 2008 and pre-existing vandalism in FY 2007 account for most of the data deficiencies. Vandalism appears to be spreading across the array. Only the 180 line did not show any evidence of vandalism in late

FY 2007 or FY 2008. The vandalism events also had an impact on the temperature profile data decrease.

Eighteen point-source current meters continue to be deployed on the TAO moorings along the equator, adjacent to the ADCP moorings. The real-time data return during FY 2008 was 62.9%, a decrease of 2.9% from FY 2007.

2.1.6. Shipboard Measurements

CTD casts, and underway ADCP and thermosalinograph measurements, are conducted from mooring servicing cruises on the *Ka'imimoana* and *Ronald H. Brown*. These data are an integral part of the TAO Program, providing in situ calibration checks on mooring sensor performance. They also provide hydrographic and current field information that helps to put the moored time series measurements into a broad scale hydrodynamic context. The data are a valuable resource for climate model development and climate analyses, and are frequently used together with moored times series data in scientific publications.

Two hundred ten (210) CTD casts were made on TAO cruises in FY 2008, which was an increase over FY 2007 (67). In spite of lost of ship time and equipment problems, the number of CTD casts increased. The shipboard ADCP data are forwarded to, processed, archived, and distributed by Eric Firing and colleagues at the University of Hawaii.

In support of TAO Refresh Test and Evaluation in the Gulf of Mexico, NDBC requested that NOAA Vessel Nancy Foster make CTD casts. The casts were made serendipitously before the passages of Tropical Storm Faye, Hurricane Gustav, and Hurricane Ike. The data will be forwarded to NOAA's National Ocean Data Center for use by hurricane researchers.

2.1.7. Guest Investigator Research Projects Using TAO Moorings and TAO Cruises

The primary mission of the TAO/TRITON array is to provide real-time data for improved detection, understanding, and prediction of El Niño and La Niña. The primary function of NOAA Ship *Ka'imimoana* is to service buoys of the TAO/TRITON array. However, the TAO Program Office actively promotes the use of *Ka'imimoana* and, when it is used for TAO cruises, *Ronald H. Brown* for other meritorious scientific investigations that are of relevance to NOAA's mission. These projects are developed, funded, and lead by investigators from NOAA laboratories, other national research laboratories, and academia. Two categories of ancillary projects are described which are (a) ongoing and (b) one-time or for a limited number of cruises. An ongoing project is either planned or has been onboard already for several years. A list of PIs, their institutions and project titles are itemized below. The name of the ship from which the work is done (KA or BROWN) is indicated in parentheses.

a. Ongoing ancillary projects on TAO cruises for FY 2008 (Project, Principal Investigator, Institution (Ship):

- Underway CO2, Richard Feely, NOAA/PMEL (KA and BROWN)

- Turbulent flux measurements and wind profiler, Chris Fairall and Jeff Hare, NOAA/ESRL (BROWN)
- Carbon cycle, Michael Bender, Princeton University (BROWN)
- Discreet Gas Sampler, Michael Bender, Princeton University (KA)
- Argo float deployments, Greg Johnson, NOAA/PMEL (KA)
- Global Drifter Program, Rick Lumpkin, NOAA/AOML (KA and BROWN)
- Iron limitation, Mike Behrenfeld, NASA/Goddard (BROWN)
- CO2 moorings, Chris Sabine, NOAA/PMEL/Francisco Chavez, MABARI (KA)
- Bio-optical measurement and nutrient analysis, Francisco Chavez, MBARI (KA)
- Underway ADCP, Eric Firing, University of Hawaii (KA and BROWN)
- Underway pO2/pN2- Gas Tension device and O2 probe, Craig McNeil, University of Rhode Island (BROWN)
- Microstructure Chipod development, James Moum, Oregon State University (KA)
- Nutrient Samples, Cathy Cosca, NOAA/PMEL (KA)
- Tsunami/DART, NDBC, Craig Kohler
- Turbidity/fluorescence CTD measurements, Pete Strutton, Oregon State University (KA)

b. *One-time or limited-term ancillary projects on TAO cruises for FY 2008* (Project, Principal Investigator, Institution (Ship):

- Nutrient-poor seawater collection, Calvin Mordy, NOAA/PMEL (KA)
- Oxygen Concentration and Isotopic Composition in Upper Ocean, Michael Bender, Oregon State University.
- Carbon cycle seawater collection, Rachael Stanley, WHOI (KA)
- Modified ARGO float deployments, Steve Riser, University of Washington (KA)

2.2. TAO Program Web Pages

During FY 2008, the official TAO web site maintained by NDBC at http://tao.noaa.gov/ provided easy access to TAO/TRITON data sets, as well as updated technical information on buoy systems, sensor accuracies, sampling characteristics, and graphical displays. The NDBC TAO web site received 10,126,386 hits and delivered 7,662,121 TAO files to the end users. These web statistics represent a significant increase from FY 2007. NDBC mirror web site at NWS Headquarters in Silver Spring, MD functioned as planned during this hurricane season. This mirror site is globally load balanced and automatically redirects any traffic destined for the NDBC web farm to the Headquarters web farm when the NDBC network is inaccessible.

2.3. Operational Use of TAO/TRITON Data

TAO/TRITON data are distributed via the Global Telecommunications System (GTS) to national and international operational forecast centers, such as NOAA's National Centers for Environmental Prediction and the Department of Defense's Fleet Numerical Meteorology and Oceanography Center. Within NOAA, these data are used for operational weather, climate, and and Pacific tropical cyclone modeling and forecasting. The National Core Processing Center for Multi-Channel Sea Surface Temperature (MCSST) uses TAO/TRITON and PIRATA sea surface temperatures distributed via the GTS to perform validation and improvement to the MCSST processing algorithms. TAO/TRITON and PIRATA are the only moored data used in the MCSST analysis. The Global Temperature-Salinity Profile Program (GT/SPP) collects the TAO/TRITON subsurface temperature and salinity distributed over the GTS and makes them available in real-time via NOAA's National Oceanographic Data Center web site.

Plots of TAO/TRITON Monthly Mean SST and Winds, Five-Day Zonal Wind, SST, and 20^{o}C Isotherm Depth 2^{o}S to 2^{o}N Average, and Five-Day Zonal Wind, SST, and 20^{o}C Isotherm Depth Anomalies 2^{o}S to 2^{o}N Average are transmitted to NCEP monthly for inclusion in the Climate Diagnostics Bulletin. Additionally, plots and data are transmitted to the Integrated Global Ocean Services System (IGOSS) for the IGOSS Products Bulletin. The plots include zonal and meridional average and anomaly winds and average SST and SST anomalies and data made available include SST and SST anomaly and mean zonal and meridional wind and anomalies in netCDF format.

In support of forecasts and warnings for Hurricane Ike, NDBC temporarily released real-time data from the two TAO (flux-configurations) Refresh Test and Evaluation moorings in the northwest Gulf of Mexico. The TAO Refresh buoys provided hourly data. Ike passed about 70 to 80 nm from the moorings, which sustained no damage or data outages from the hurricane. Highest sustained winds measured by the buoys were about 41 knots and seas reported by nearby NDBC buoys were about 20 feet. More information can be found at: http://www.ndbc.noaa.gov/hurricanes/2008/ike/.

NDBC releases data to the GTS from the drifting buoy formerly moored at 5S110W under a drifting buoy WMO identifier, 32746, so that the buoy and instrumentation continue to provide operational data outside of the TAO area (data are also posted to http://www.ndbc.noaa.gov/station page.php?station=32746).

TAO current data area used to validate ocean currents from satellite altimetry and scatterometer data for the OSCAR Project (Ocean Surface Current Analyses – Real-time, http://www.oscar.noaa.gov).

2.4 Vandalism

Vandalism continues to plague portions of the TAO/TRITON arrays. Data and equipment return are generally lower in regions of high tuna catch in the eastern and western equatorial Pacific. In addition to partial mooring hardware and instrumentation losses, 11 complete moorings systems were confirmed lost in the Pacific due to the effects of vandalism and 4 other mooring were missing towers. Two mooring remain adrift in the array and may be lost, but not yet confirmed.

Efforts to combat vandalism continue, though it is not clear they are making much impact. Additional vandalism is expected as Ecuadorian fishing fleet expands its range into the Central Pacific.

2.5. Public Service

NDBC attended the 6th meeting of the North Pacific Data Buoy Advisory Panel (NPDBAP) in Jeju, Korea, 14 - 19 October 2007, where Bill Burnett chaired the Drifter Evaluation Panel, Co-Chaired the Science and Technology Workshop, and served as the U.S. Representative for the 23rd Session of the Data Buoy Cooperation Panel (DBCP).

NDBC attended the World Meteorological Organization (WMO) – Intergovernmental Oceanographic Commission (IOC) Workshop on the Global Telecommunications System (GTS) for the Effective Exchange of Tsunami Warnings, Related Information and other Warnings in the Indian Ocean in Bangkok, Thailand, 18-20 December 2007.

NDBC attended the OceanSITES Data Management and Science Committee Meeting in Vienna, Austria, 10 – 12 April 2008 and presented "Introduction, Overview, and OceanSITES Global Data Assembly Center".

NDBC hosted Aryo Hanggono (Head of Research Centre for Marine Technology), Aulia Farhan, Taufiq Ferindra, Denny Kusuma, and Marza Marjuki (Indonesia Agency for Marine and Fisheries Research) 9 – 11 July 2008.

NDBC chaired the Metadata-Temperature (META-T) Working Group and attended the WMO Integrated Global Observing Systems (WIGOS) Working Group meeting in Geneva, Switzerland, 16-19 September 2008.

Landry Bernard of NDBC presented "Refreshed Data System for Tropical Atmosphere Ocean (TAO) Array" and Dr. Chung-Chu Teng presented "Test and Evaluation of Refreshed Tropical Atmosphere Ocean (TAO) Buoy System" at Oceans 2008 Kobe, Japan. Richard Crout presented "Preliminary Results of Comparisons between Tropical Atmosphere Ocean (TAO) Oceanographic Refresh and Legacy Sensors" at Oceans 2008 in Quebec City, Canada. TAO Program Manager Shannon McArthur, Richard Crout, and Landry Bernard prepared a poster presentation, Tropical Atmosphere Ocean (TAO) Array, for the NOAA Climate Observation Division Annual System Review, 3-5 September 2008. They were unable to attend the review in Silver Spring, MD due to Hurricane Gustav, but the poster was displayed.

TAO winds are currently being used to verify the ASCAT data, see map at:
http://www.knmi.nl/scatterometer/ascat_osi_25_prod/ascat_app.cgi?cmd=buoy_validations&period=week&day=0&flag=no

Application that used TAO wind data (amongst NDBC and Euro buoys) were used to characterize the Advanced SCATterometer. Though the data were from Mar-Oct 2007, the results weren't published until March 2008:

Characterization of ASCAT measurements based on buoy and QuikSCAT wind vector observations, A. Bentamy, Ocean Sci. Discuss., 5, 77–101, 2008
www.ocean-sci-discuss.net/5/77/2008/
http://www.ocean-sci-discuss.net/5/77/2008/osd-5-77-2008.pdf

NDBC has a standing group of Regional Association Coordinators for the Coastal Ocean Observing System, who provides updates of NDBC efforts to the eleven Regional Associations and acquire suggestions for future operations. Landry Bernard serves on the IOOS Steering Team.

NDBC will serve as Co-Chair of the Technical Program Committee for MTS/IEEE Oceans 2009 Conference in Biloxi, MS in October 2009.

2.6. TAO Transition FY 2008 Accomplishments

In a memo dated 13 August 2002, the Deputy Directors for OAR and the National Weather Service instructed the directors of PMEL and NDBC to develop a plan for transferring PMEL operations to NDBC. The memo was in response to the Administrator of NOAA's endorsement of a recommendation by the NOAA Program Review Team that TAO mooring operations be consolidated with those at NDBC. After several iterations, the Deputy Administrator of NOAA formally approved a TAO transition plan. The TAO Transition is being executed in accordance with the approved TAO Transition Plan of August 31, 2004, and yearly Work Plans.

FY 2008 TAO Transition efforts continued to focused on five areas: (1) NDBC continued the daily/monthly/quarterly QA/QC of TAO real-time and delayed data, (2) NDBC continued as the "Official" TAO web site for QA/QC data, (3) NDBC continued responsibility for all TAO cruises, (4) development and testing of the TAO refreshed buoy system which is to replace obsolescent components and sensors, and (5) NDBC continued enhancements to the TAO IT/data system for the refreshed TAO buoy systems (more real-time data via Iridium satellite system).

For the TAO data and IT transition, NDBC accomplished the following goals in FY 2008:

- NDBC manages the release and non-release of TAO data via GTS.
- Maintained the TAO mirror web site at NWS Headquarters in Silver Spring, MD.
- Continued to make DAC Management Console enhancements.
- Updated the TAO Data Management Plan
- Updated the TAO IT Detailed Architecture Plan.
- Updated with cruise data the KA ship web page and CTD Cast Data Delivery page.
- Updated the DMAC Operating Procedures Manual for Delayed Mode Data.
- Maintained the OPeNDAP services for TAO data distribution.

For the TAO refresh buoy system, NDBC accomplished the following tasks:

- Sensor calibration procedures were enhanced.
- A flux site configuration of the TAO refresh was deployed in the Gulf of Mexico for test and evaluation.
- A standard TAO Refresh configuration was deployed at 2S140W and 9N140W.

During FY 2008, NDBC accomplished the following goals for data/IT part of the TAO refresh:

- Continued to enhance the NDBC refreshed TAO database.
- Continued to enhance the TAO real-time processing systems for NDBC AMPS payloads.
- Continued to enhance the NDBC DAC Management Console.
- Continued to enhance the TAO data display and data delivery web pages.

- Supported the use of the DAC management console and Engineering web pages in support of test buoys deployed in the Gulf of Mexico and the Pacific.

4. Ocean Reference Stations

Ocean Reference Stations

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1. PROJECT SUMMARY

The goal of this project is to maintain long-term surface moorings, known as Ocean Reference Stations, as part of the integrated ocean observing system. The scientific rational for these Ocean Reference Stations is to collect long time series of accurate observations of surface meteorology, air-sea fluxes, and upper ocean variability in regions of key interest to climate studies and to use those data to quantify air-sea exchanges of heat, freshwater, and momentum, to describe upper ocean variability and describe the local response to atmospheric forcing, to motivate and guide improvement to atmospheric, oceanic, and coupled models, to calibrate and guide improvement to remote sensing products and capabilities, and to provide anchor point for the development of new, basin scale fields of the air-sea fluxes. Model, satellite, and climatological fields of surface meteorology and air-sea fluxes have large errors; high quality, in-situ time series are the essential data needed to improve our understanding of atmosphere-ocean coupling and to build more accurate global fields of air-sea fluxes. Prediction and analysis of climate variability based on model or other products that have large errors in their atmosphere-ocean exchanges of heat, freshwater, and momentum is flawed; this effort to collect the critical in-situ flux time series and related efforts to develop air-sea flux products that use these Ocean Reference Stations as anchor points aim to remedy these flaws and greatly improve our understanding of how the atmosphere and ocean are coupled and together influence climate.

This project is now maintaining three Ocean Reference Stations at key locations: a site at 20°S, 85°W under the stratus cloud deck off northern Chile (Stratus), the Northwest Tropical Atlantic Station (NTAS) at 15°N, 51°W, and a site north of Hawaii near the Hawaii Ocean Timeseries (HOT) site. The surface buoys are equipped with Air-Sea Interaction Meteorology (ASIMET) systems developed at WHOI and capable of climate-quality measurements once per minute for one year. Telemetered near-real time data are provided to numerical weather prediction centers (but not included in their model runs, thus providing an independent means to examine model performance); these data are used to investigate model errors and biases and test improvements to the models. Data are also provided to validate remote sensing products and to guide development of new flux products. In addition, these data support research done by NOAA and other climate studies and these Ocean Reference Stations are coordinated with other flux reference sites. The Stratus Ocean Reference Station has proved to be a provider of key benchmark time series for examining atmospheric, coupled, and oceanic model performance in the important but challenging marine stratus region of the eastern tropical Pacific. The NTAS site is being upgraded as the prototype of implementation of real time telemetry of upper ocean data and coincident reporting of both surface flux and upper ocean heat content variability and anomalies.

2. ACCOMPLISHMENTS

The project is managed as four Tasks, with accomplishments reported by task.

Task I: Engineering, oversight and data

All three sites are now occupied by the modular-hull buoy (Figure 1). Hourly meteorological data are transmitted in near-real time via Argos telemetry and made available on an FTP server and a website with download capability. Data processing continues on schedule. The "best" quality meteorological and flux data is being made accessible through the web, typically within a year of recovery. New engineering and capability upgrades are being implemented and evaluated now at Stratus and at NTAS. In October 2007 and again in October 2008 an NDBC surface wave sensing and telemetry (Iridium) system was deployed on the Stratus buoy. In early 2007, the NTAS mooring was deployed with new hardware to permit telemetry of upper ocean data from instruments on the mooring line; this mooring was recovered and redeployed in the summer of 2008 with additional effort spent on the delivery of subsurface data in real time.

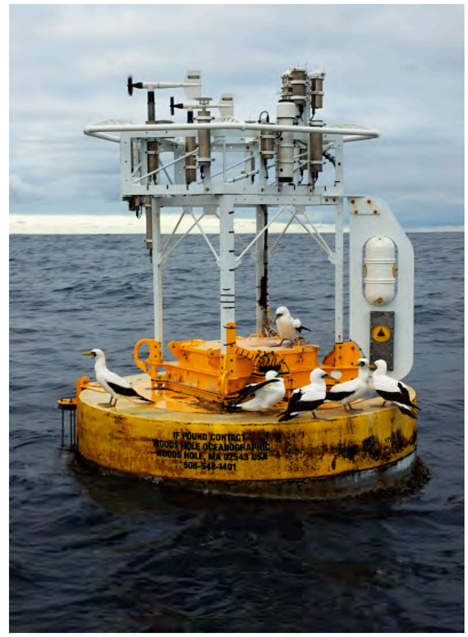

Figure 1. The new modular buoy in use at all Ocean Reference Stations. Photo taken during the 2006 Stratus deployment and recovery cruise.

Task II: Stratus Site

The stratus surface mooring was originally deployed in October 2000. It has been annually redeployed and recovered since that time, including the most recent done during the October 6 - November 3, 2008 cruise of the NOAA Ship *Ronald H. Brown*. This cruise was Leg 1 of two legs on the *Brown* as part of VOCALS (VAMOS Ocean Cloud Atmosphere Land Study); and the Stratus ORS provided one of the observational foci of this project. Accurate prediction of cloud amount and cover in marine stratus regions has long been a challenge; this is true off Peru and northern Chile. Further, model studies point to the dependence of the coupled climate variability of the Pacific Basin and surrounding continents to the atmosphere-ocean coupling in the stratus region. Thus, establishment and maintenance of an Ocean Reference Station in this critical but data sparse area has been a high priority. The Stratus ORS data has contributed significantly to the development and conduct of VOCALS.

Data recovery this year was good (though the RDI ADCP flooded), post-calibrations are being done, and equipment is still on the *Brown*. Post-calibrations and final data quality control will be done once the instruments return to WHOI in January 2009. On the buoy we measure air temperature, sea surface temperature, relative humidity, incoming shortwave and longwave radiation, wind speed and direction, rain rate, and barometric pressure. On the mooring line the instrumentation is concentrated in the upper 300m and measures temperature, salinity, and velocity. Hourly surface meteorological data are archived at WHOI (http://uop.whoi.edu/projects/Stratus/stratus.htm), arriving within hours of when it was observed. These data are exchanged in near real time with ECMWF and NCEP; they in turn provide operational data at the model grid point nearest the buoy. It is also shared with the Chilean Navy (SHOA). The same data are shared with CLIVAR investigators, especially modelers interested in the Stratus region and VAMOS/VOCALS investigators in the U.S. and in South America. This meteorological data are used to assess the realism of operational atmospheric models in the stratus region. Once per minute as well as hourly surface meteorological time series are provided to the VOCALS and other investigator communities (including Sandra Yuter, Chris Bretherton, Meghan Cronin) after recovery. The surface meteorological data have been made available to the satellite community (including radiation – Langley, winds – Remote Sensing Systems and JPL, SST – Dick Reynolds, all variables – the SEAFLUX project).

The oceanographic data are being used by Weller at WHOI to investigate air-sea coupling and upper ocean variability under the stratus deck. The initial archive is maintained by the Upper Ocean Processes Group at WHOI, which runs a public access server for their mooring data. The data are also available from OceanSITES (http://www.oceansites.org). We are collaborating with the Baseline Surface Radiation Network (BSRN) and the GEWEX (Global Energy and Water Cycle Experiment) Radiation Panel. Long time series of incoming radiation along with the other coincident surface meteorological observations are very rare in the open ocean. The accuracy of the ORS radiation data has made them of high value for development of improved estimates of surface radiation fields over the oceans.

The Stratus ORS has been occupied since October 2000. We are now able (see Table 1, for example) to show how far climatological means of the air-sea fluxes, such as those computed from the 40-year ECMWF reanalysis (ERA-40), are incorrect in their representation of the atmosphere-ocean coupling under the very important stratus deck region off northern Chile. The ocean there receives more heat than ERA-40 suggests but the sky is cloudier (lower mean shortwave) than ERA-40 suggests. The additional gain comes from the observed latent, sensible, and longwave heat fluxes being smaller than indicated by the ERA-40 climatology. As an example of our collaboration with modeling centers, ECMWF retrieves our buoy data and does offline runs of modifications of the their atmospheric model to explore how to improve the realism of their model under the stratus clouds.

Table 1. Year-long means of the latent, sensible, longwave, shortwave, and net heat fluxes (net is the sum of the first four, where a positive sign indicates the ocean is being heated) from the first 5 deployments of the Stratus ORS compared to the 40-year mean ECMWF reanalysis values of these heat fluxes.

Variable	Stratus 1	Stratus 2	Stratus 3	Stratus 4	Stratus 5	ECMWF
Latent	-103.1	-118.0	-107.3	-99.0	-99.5	-124.6
Sensible	-7.0	-10.3	-7.1	-7.1	-5.0	-15.2
Longwave	-40.6	-49.2	-36.6	-21.7	-44.6	-55.0
Shortwave	202.0	199.5	190.4	191.3	183.5	220.2
Net	51.4	22.1	39.4	63.4	34.3	25.5

That models need to be improved is evident in Figure 2, a comparison of the daily-averaged incoming shortwave radiation climatology (average of six years of data) with the incoming shortwave radiation climatology from ERA-40 (ECMWF 40-year reanalysis) and NCEP-2 (National Center for Environmental Prediction reanalysis). During October to December, the models produce too few clouds, and as a consequence supply too much insolation to the sea surface, with the error close to 50 W m^{-2}.

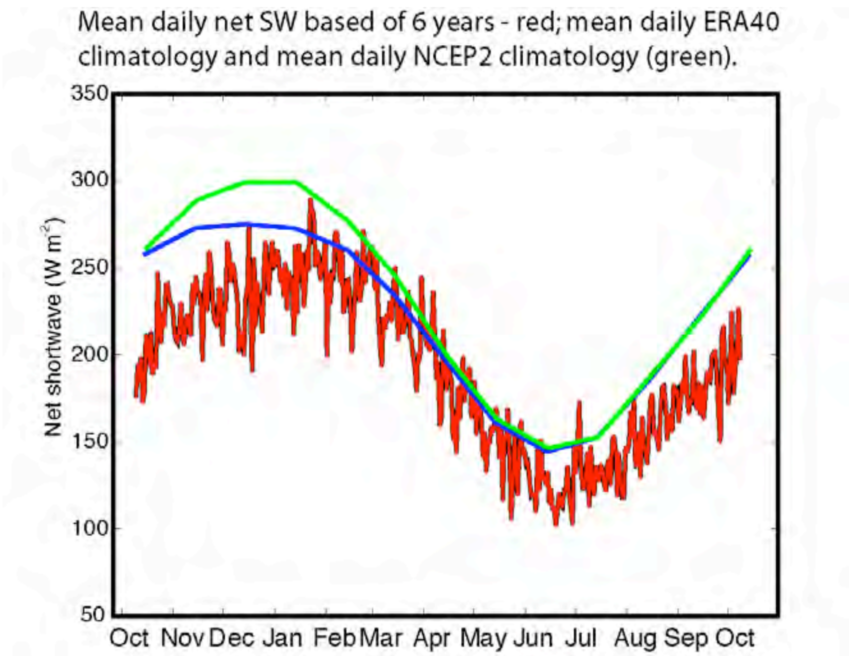

Figure 2. Comparison of observed incoming shortwave radiation at the Stratus Ocean Reference Station (mean daily, averaged over 6 years, in red) with the monthly climatological incoming shortwave radiation from ERA40 (blue) and NCEP2 (green).

The Stratus cruises serve the wider scientific community by providing a platform on which to study the regional ocean. Additional researchers who participated in collaborative research or benefited from shared ship time in FY2008 have come from many institutions: NOAA Earth System Research Laboratory, Servicio Hydrografico y Oceanografico de la Armada (SHOA, Chile), the NOAA National Data Buoy Center, Bigelow Laboratory, the Argo float program, the NOAA surface drifter program, and IMARPE (Institute of Marine Research, Peru). Ten Argo floats and 20 surface drifters were deployed during this year.

The work this year included recovering and redeploying the Chilean Navy tsunami warning buoy at 20°S, 75°W; this tsunami warning buoy was installed in 2006 with WHOI meteorological sensors on the surface buoy and ocean sensors on the mooring line. The deployment marked the beginning of a growing partnership between the ORS project and SHOA. We mount self-recording ASIMET modules on the tsunami buoy and temperature and temperature/salinity recorders on the buoy's mooring line (Figure 3.).

Figure 3. Chilean Navy (SHOA) DART buoy equipped with WHOI meteorological sensors. Shown here the internally recording sensor modules being recovered and replaced with fresh modules in October 2007.

Task III: NTAS Site

The Northwest Tropical Atlantic Station (NTAS) project for air-sea flux measurement was conceived in order to investigate surface forcing and oceanographic response in a region of the tropical Atlantic with strong SST anomalies and the likelihood of significant local air-sea interaction on seasonal to decadal time scales. The strategy is to maintain a meteorological measurement station at approximately 15^{o} N, 51^{o} W through successive (annual) turn-arounds of a surface mooring. Redundant meteorological systems measure the variables necessary to compute air-sea fluxes of heat, moisture and momentum using bulk aerodynamic formulas.

NTAS has two primary science objectives: 1) Determine the air-sea fluxes of heat, moisture and momentum in the northwest tropical Atlantic using high-quality, in-situ meteorological measurements from a moored buoy. 2) Compare the in-situ fluxes to those available from operational models and satellites, identify the flux components with the largest discrepancies, and investigate the reasons for the discrepancies. An ancillary objective is to compute the local (one-dimensional) oceanic budgets of heat and momentum and determine the degree to which these budgets are locally balanced.

A mooring turn-around cruise was planned on the NOAA ship *Ronald H. Brown* in during May 2008 order to retrieve the existing mooring (NTAS-7) and replace it with a new mooring (NTAS-8). Unforeseen circumstances resulted in the *Brown* being the shipyard for maintenance during the planned cruise period. As a result, the turn-around cruise was re-scheduled on the *RV Oceanus* for the period 14 July to 1 August 2008, about 8 weeks later than planned. In preparation for this cruise, three ASIMET systems were calibrated and tested, and two systems, comprised of the best performing sensors, were prepared for deployment. The NTAS-8 mooring was deployed on 28 July 2008 and the NTAS-7 mooring was recovered on 29 July. The period between deployment and recovery was dedicated to a comparison of the two buoy systems, with the shipboard system as an independent benchmark. Data return from NTAS-7 was very good during the first 14 months, with all meteorological sensors showing complete records except for SST, for which one system had 72% return. Since the second system had a complete record, no data will be missing in the first 14 months of the final (combined) data set. However, because the service cruise was delayed, the ASIMET logging system, designed for a maximum of 14 months of operation, terminated data acquisition prior to servicing. This will result in a data gap of about 20 days between NTAS-7 and NTAS-8

NTAS surface meteorological data are archived on the UOP web site (http://uop.whoi.edu/projects/NTAS/ntas.htm) and also available in near real time from the NDBC web server (http://www.ndbc.noaa.gov). Data are exchanged with ECMWF and NCEP, and they in turn provide operational model output at the grid point nearest the buoy. NTAS data are also available through OceanSITES (http://www.oceansites.org) and are shared with the Baseline Surface Radiation Network (BSRN) and the GEWEX (Global Energy and Water Cycle Experiment) Radiation Panel.

The 2008 NTAS cruise represented the second year of collaboration with the Meridional Overturning Variability Experiment (MOVE). The MOVE effort involved mooring turnarounds and data offload from several Pressure/Inverted Echo Sounders (PIES; Figure 4). Subsurface moorings were recovered and re-deployed at the MOVE site (about 40 nmi northwest of the NTAS site) as well as the M3 and M4 sites (along the continental slope near Guadeloupe). Acoustic telemetry was used to offload data from PIES located at MOVE sites M1-M4 and M7.

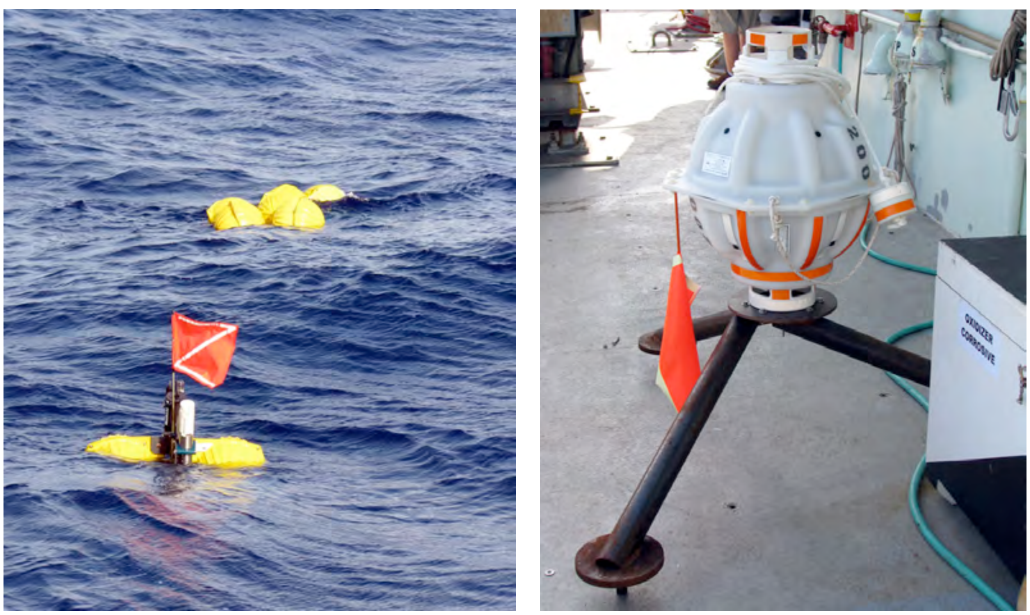

Figure 4. Flotation from MOVE subsurface mooring at the surface prior to recovery (left). Pressure/Inverted Echo Sounder (PIES) sensor ready for deployment (right).

The NTAS-8 mooring represented the second year of development for real-time telemetry of subsurface data. Engineering work undertaken as part of the WHOI VOS project resulted in an acoustic telemetry subsystem utilizing two Benthos underwater acoustic modems (Figure 5) interfaced to an Iridium communication controller through the same electromechanical interface developed for NTAS-7 (Figure 6). Using these new electronics, the mooring was outfitted with a prototype system for both inductive and acoustic telemetry of underwater instruments. Unfortunately, despite successful testing of all system components prior to assembly, the fully assembled system did not function as expected at sea prior to deployment. Several rounds of debugging were executed at sea, but ultimately the NTAS-8 mooring was deployed without a functional subsurface telemetry system. A similar system has since been assembled and successfully tested for another project, and we expect the NTAS-9 system to be fully functional.

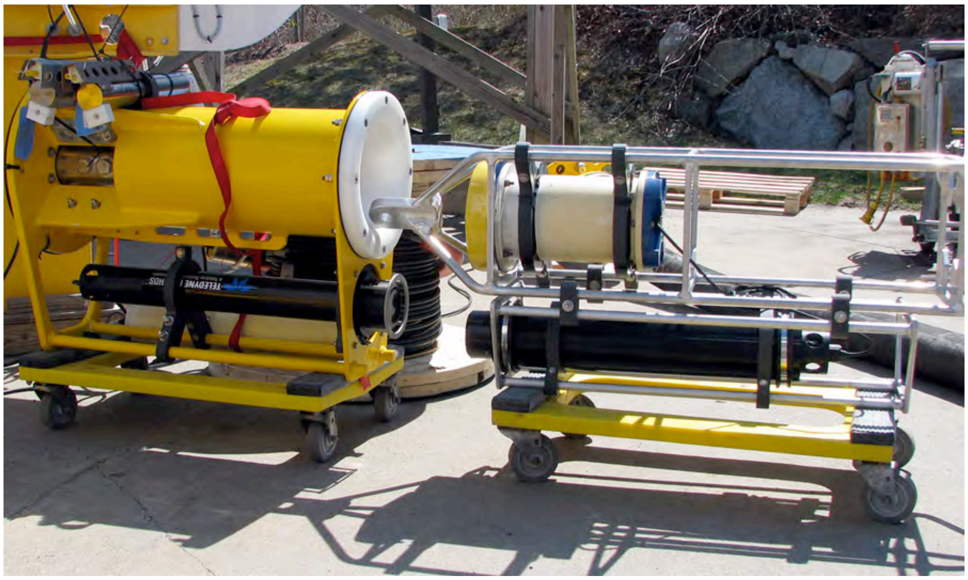

Figure 5. Pre-deployment testing of NTAS-8 acoustic telemetry subsystem, with upper acoustic modem mounted at bell mouth flange (left) and lower acoustic modem attached to ADCP cage (right).

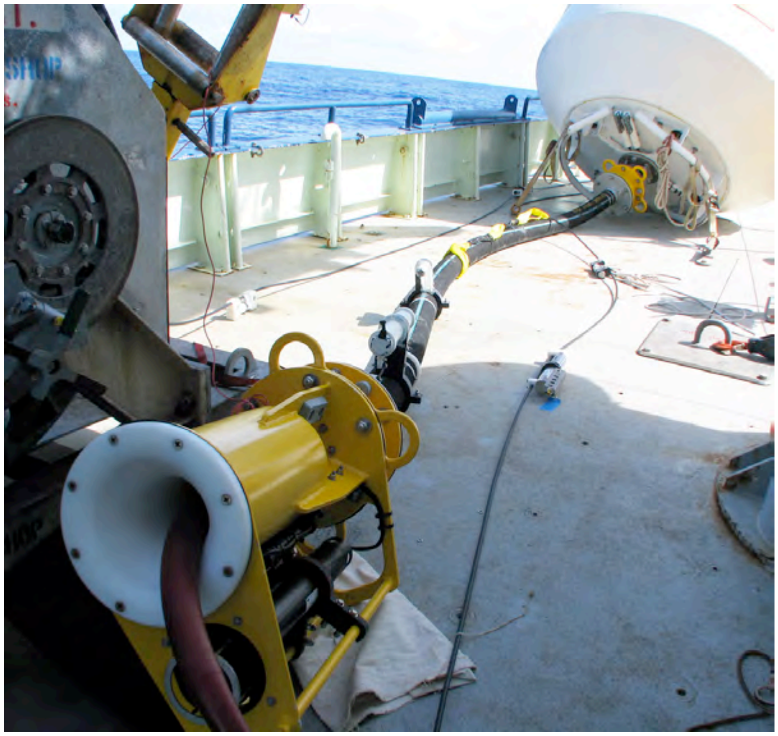

Figure 6. NTAS-7 telemetry hardware prior to deployment. Fully assembled telemetry interface section laid out on deck and connected to the buoy, showing bell-mouth flange and wire-coupling assembly (foreground), compliant electro-mechanical section, and universal joint and upper flanged spacer at the buoy hull.

For the telemetry trial on NTAS-8, the mooring line was outfitted with four instruments from the UOP inventory which contained inductive modems: Three Seabird SBE-37s at 25, 45 and 65 m and a Sontek Argonaut current meter 14 m.

Task IV: Hawaii Site

The Hawaii Ocean Time-series (HOT) site, 100 km north of Oahu, Hawaii, has been occupied since 1988 as a part of the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS). Among the HOT science goals are to document and understand seasonal and interannual variability of water masses, relate water mass variations to gyre fluctuations, and develop a climatology of high-frequency physical variability in the context of interdisciplinary time series studies. The primary intent of the WHOI Hawaii Ocean Timeseries Station (WHOTS) mooring is to provide long-term, high-quality air-sea fluxes as a coordinated part of the HOT program and contribute to the goals of observing heat, fresh water and chemical fluxes at a site representative of the oligotrophic North Pacific Ocean. It is expected that establishment of the WHOTS mooring will accelerate progress toward understanding multidisciplinary science at the site, provide an anchor site for developing air-sea flux fields in the Pacific, and provide a new regime in which to examine atmospheric, oceanic, and coupled model performance as well as the performance of remote sensing methods.

The observational strategy is to maintain a surface mooring at approximately

22.75° N, 158° W, instrumented to obtain meteorological and upper ocean measurements, through successive (annual) turnarounds done in cooperation with HOT investigators. Redundant meteorological systems on the surface buoy measure the variables necessary to compute air-sea fluxes of heat, moisture and momentum using bulk aerodynamic formulas. Subsurface oceanographic sensors on the mooring are being provided through cooperation with Roger Lukas (U. Hawaii; funded by the National Science Foundation).

A mooring turn-around cruise was conducted on June 3-11, 2008 on the U. Hawaii ship *Kilo Moana*. The field work was done in cooperation with Roger Lukas and other HOT investigators from U. Hawaii. In preparation for this cruise, three ASIMET systems were assembled and tested. The WHOTS-5 mooring was deployed and the WHOTS-4 mooring was recovered. The period between deployment and recovery was dedicated to a comparison of the two buoy systems, with the shipboard system as an independent benchmark. The standard *Kilo Moana* meteorological sensors were complemented by installation of a UOP AutoIMET system similar to that used on Volunteer Observing Ships. Data return from the two WHOTS-4 ASIMET systems was very good. The remaining sensors operated for the full 368 days deployment.

We invited Dr. Frank Bradley of CSIRO, Canberra, Australia to participate on the cruise. He assisted in intercomparison of the shipboard and moored meteorological systems. We also continued ongoing analyses of the performance of shortwave and longwave radiometers at sea.

Commercial bird barrier strips were installed on the WHOTS-3 buoy to reduce data contamination and sensor shadowing due to birds and their accompanying guano deposition. Evaluation of the buoy prior to and after recovery indicated that the prevention efforts were largely successful, little evidence of birds having perched on the on the tower and sensors. The same barrier strips were installed on the WHOTS-4 buoy. Installation on the WHOTS-5 buoy found that the spot welds on these strips are slightly magnetic, so care is required in not placing these too close to the compass of the anemometer.

In cooperation with C. Sabine of PMEL, and with the assistance of D. Sadler (U. Hawaii), a pCO2 system was incorporated in the WHOTS-5 buoy (Figure 7) as it had been in the WHOTS-4 buoy. Incorporation of CO2 measurements on the WHOTS buoy provided continuation of the time series begun in 2004 from the MOSEAN buoy. CO2 measurements are made every three hours in ambient air and in air equilibrated with surface seawater using an infra-red detector. A summary file of the measurements is transmitted once per day and plots of the data are posted in near real-time to the web. To view the daily data visit the NOAA PMEL Moored CO2 Website: http://www.pmel.noaa.gov/co2/moorings/hot /hot_main.htm. Within a year of system recovery, the final processed data are submitted to the Carbon Dioxide Information Analysis Center (CDIAC).

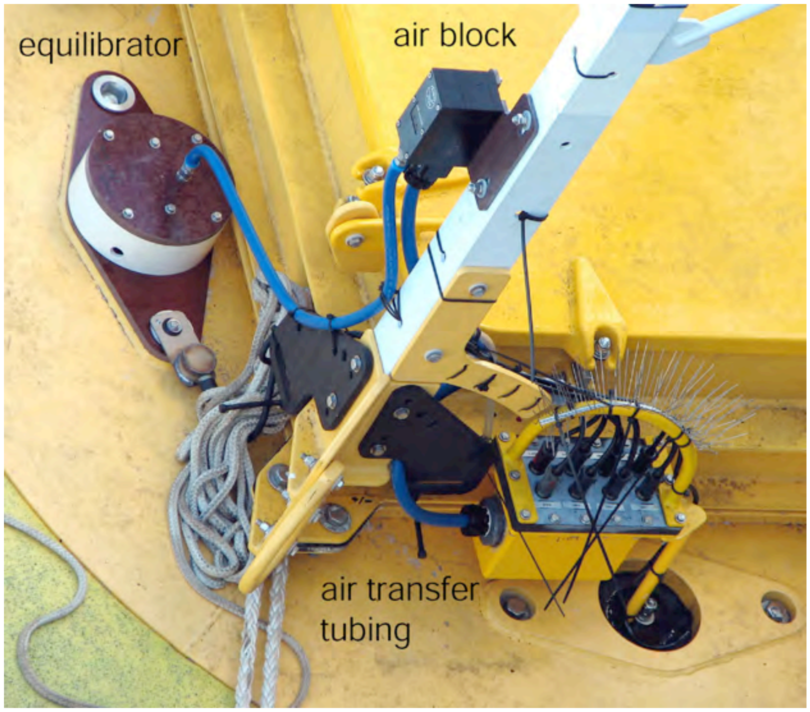

Figure 7. Principal external components of pCO2 system on the WHOTS-4 buoy. The equilibrator tube extends through a hole in the foam hull into the water below. Air transfer tubing within a protective conduit (blue) connects the equilibrator to the air block and the air block to instrumentation inside the buoy well.

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Western Boundary Time Series in the Atlantic Ocean

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1. PROJECT SUMMARY

The Western Boundary Time Series project represents NOAA's longest term observing system for the Atlantic Meridional Overturning Circulation (MOC). Over the past 20+ years the program has worked to measure both the warm upper and cold lower limbs of the MOC near the western boundary of the Atlantic Ocean at 27°N. The Western Boundary Time Series project consists of two main elements, each of which is broken into several sub-elements:

Element 1 – Observe and quantify the Florida Current transport and water property variability

- Florida Current transport time-series variability is monitored using an out-of-service phone cable instrumented with a voltage recording system. Recording system failures (either computer or wiring) occur approximately once per year. Additional funding is required to provide spares and to repair failed equipment. Tests of possible future replacement systems for the cable have commenced (using AOML Base funds and old instruments) to prepare for the day in which the cable fails in a terminal manner. Additional funds to support these instruments (e.g. batteries, anchors) has been added to the budget in addition to funds for repairing the cable voltage systems.
- Florida Current transport snapshot variability and the calibration and continuity of the cable system are monitored using dropsonde/XBT cruises up to 10 times per year (this data is also used by the SOOP program for analysis of the data from the AX7 line). Dropsonde floats have been lost or damaged about once per year. Additional funds are needed to repair/modernize/improve the dropsonde floats. This expense has been included in an Equipment Support add-task.
- Florida Current transport and water mass snapshot variability are also monitored by CTD/LADCP sections each year (this data is also used for SOOP – AX7 analysis). Charter funding for these cruises has been inadequate in recent years.

Element 2 – Observe and quantify the Antilles and Deep Western Boundary Current transport and property variability

- Antilles and Deep Western Boundary Current transport and water mass snapshot variability are monitored by annual CTD/LADCP cruises. The capability and reliability of the NOAA fleet to support these cruises in recent years has been insufficient.
- Antilles and Deep Western Boundary Current transport time-series variability is monitored using a line of five PIES/CPIES moorings. These moorings were bought using a mix of OCO (four instruments) and AOML Base funds. The latter covered one instrument in the original array and also covered the purchase of one replacement PIES after an instrument was lost. If this program component is to continue, more

robust funding from OCO is required. Additional equipment funds for replacement instrument, sensors, and deck units have been included in the Equipment Support add-task.

2. PROJECT BACKGROUND

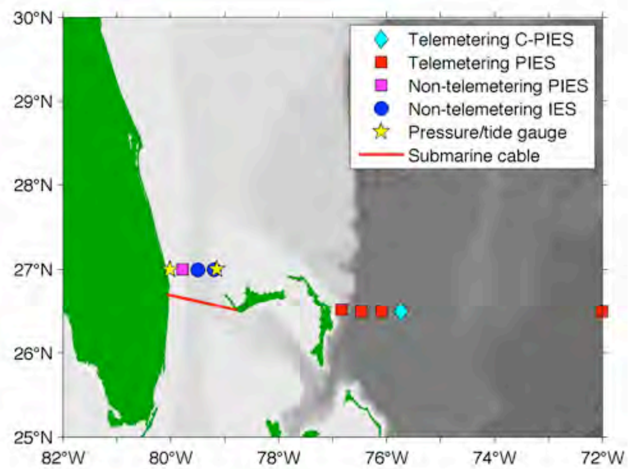

Figure 1. Moored components of the Western Boundary Time Series program**.**

In the subtropical North Atlantic, the meridional overturning circulation consists primarily of two western boundary components: the northward flowing Gulf Stream and the southward flowing Deep Western Boundary Current. The Gulf Stream is the strong surface intensified flow along the east coast of the United States that brings warms waters of tropical origin northward along the eastern seaboard of the United States. The Gulf Stream also brings with it carbon, nutrients and tropical fish. It supplies warm waters along the coast that impact a multitude of important climate phenomena including hurricane intensification, winter storm formation and moderate European weather. The Gulf Stream includes the bulk of what we call the 'upper limb' of the meridional overturning circulation in the subtropical Atlantic, in addition to a strong wind-driven flow. As the Gulf Stream flows northward it loses heat to the atmosphere until eventually, in the subpolar North Atlantic, some of the waters carried in the current become cold enough to sink to the bottom of the ocean. This cold deep water then flows southward along the continental slope of the eastern United States as the Deep Western Boundary Current, which represents the 'lower limb' of the meridional overturning circulation.

Along the east coast of Florida, the Gulf Stream is often referred to as the Florida Current and it is fortuitously confined within the limited bathymetric channel between Florida and the Bahamas Islands, thus making a long-term observing system both practical and cost effective. Similarly, the Deep Western Boundary Current is located within several hundred miles to the east of Abaco Island, Grand Bahamas. The convenient geometry of the Bahamas Island chain thus allows an effective choke point for establishing a long term monitoring program of both the upper and lower limbs of the overturning circulation.

This project consists of two components to monitor the western boundary currents in the subtropical Atlantic: *Element 1:* Real-time Florida Current transport measurements using a submarine telephone cable and calibration cruises, *Element 2:* Deep Western Boundary

Current water property measurements using dedicated research ship time and quasi-real-time transport monitoring using moored instruments.

Element 1: Continuous Transport measurements of the Florida Current

The project maintains NOAA's well-established and climatically significant Florida Current volume transport time series. Over 25 years of daily mean voltage-derived transports have been obtained for the Florida Current using out-of-service and in-use cables spanning the Straits of Florida. The cable voltages can be converted to physically meaningful transport estimates i.e., intensity of the flow, using electromagnetic induction theory. These transport measurements contain interannual and decadal changes on the order of 10% of the long-term mean transport, and during some periods the decadal changes track the North Atlantic Oscillation Index. The strong correlation of Florida Current transport variability with the North Atlantic Oscillation during some time periods, and by extension with the large-scale sea-surface temperature patterns associated with the North Atlantic Oscillation, suggests connections to tropical Atlantic variability on climatically significant time scales. These strong correlations also link the Florida Current transport with the numerous significant weather and climate phenomena that are related through large-scale ocean-atmosphere patterns in the Atlantic, including decadal and inter-decadal variations in fisheries, rainfall, and hurricane activity.

Funding provides for continuous collection of cable voltages (each minute) and automated removal of geomagnetic noise. In addition to the cable measurements, regular calibration cruises are required for this project's success. These measurements are funded through a complementary project that measures the upper ocean thermal structure in the Atlantic through high-density VOS XBT observations. Funding from the high-density XBT program provides for four two-day small charter boat calibration cruises on the R/V F. G. WALTON SMITH each year and eight-ten one-day charters onboard small fishing vessels, provided sufficient ship-time is available.

Future continuance of the Florida Current transport time series is dependent at present upon the continuing stability of the telephone cable itself (which is beyond NOAA control as the cable belongs to AT&T). As will be discussed shortly, investigations of new monitoring systems are being made to plan for any future cable failure.

Element 2: Deep Western Boundary Current Time Series

Over the past 20+ years a variety of snapshot sections and time series mooring arrays have been placed along the continental slope east of Abaco Island, Grand Bahamas, in order to monitor variability of the transport carried by the Deep Western Boundary Current. The Abaco time series began in August 1984 when the NOAA Subtropical Atlantic Climate Studies Program extended its Straits of Florida program to include measurements of western boundary current transports and water mass properties east of Abaco Island, Grand Bahamas. Since 1984, more than 20 hydrographic sections have been completed east of Abaco, most including direct velocity observations, and salinity and oxygen bottle samples. Many sections have also included measurements of carbon, chlorofluorocarbon, and other water mass tracers.

The repeated hydrographic and tracer sampling at Abaco has established a high-resolution, high quality record of water mass properties in the Deep Western Boundary Current at 26.5ºN. Events such as the intense convection period in the Labrador Sea and the renewal of classical Labrador Sea Water in the 1980's are clearly reflected in the cooling and freshening of the Deep Western Boundary Current waters off Abaco with the arrival of a strong chlorofluorocarbon pulse approximately 10 years later. This data set is unique in that it is not a single time series site but in instead a time series of transport sections, including high quality water property measurements, of which very few are available in the ocean that approach even one decade in length. This element includes annual cruises across the DWBC to measure the water mass properties and transports. With the cooperation of University of Miami researchers (Drs. Johns and Beal) and funding from the National Science Foundation for the Meridional Overturning Circulation and Heat transport Array (MOCHA), and sharing of personnel and ship-time resources, these cruises have been conducted twice each year since 2004. This level of sampling will continue through 2014.

Also starting in 2004, a new component was added to the project consisting of a low-cost monitoring system that provides a daily time-series of the magnitude of the Deep Western Boundary Current mass transport in quasi-real-time (downloaded to research ships twice each year). This new monitoring system includes a moored array of Inverted Echo Sounders (IESs), and each instrument is additionally equipped with a bottom pressure gauge (PIES) and in one case a bottom current meter (CPIES). The line of PIES/CPIES moorings stretches across the shallow northward flowing Antilles Current as well as the southward flowing Deep Western Boundary Current. The IES monitoring system will also be compared to a series of measurement systems that have been deployed as part of an interagency and international partnership that is testing a variety of low cost methods for observing the complete meridional overturning circulation cell at 26.5ºN in the Atlantic (e.g. MOCHA and the United Kingdom's Rapid Climate Change Program).

Continued time series observations at Abaco are seen as serving three main purposes for climate variability studies:

- Monitoring of the DWBC for water mass and transport signatures related to changes in the strengths and formation regions of high latitude water masses in the North Atlantic for the ultimate purpose of assessing rapid climate change.
- Serving as a western boundary endpoint of a subtropical meridional overturning circulation (MOC)/heat flux monitoring system designed to measure the interior dynamic height difference across the entire Atlantic basin and its associated baroclinic heat transport.
- Monitoring the intensity of the Antilles Current as an index (together with the Florida Current) of interannual variability in the strength of the subtropical gyre.

The Western Boundary Time Series project is one component of the NOAA "Ocean Reference Station" system in the Atlantic Ocean, and it specifically addresses the NOAA climate goals by providing long term integrated measures of the global thermohaline (overturning) circulation. This project is designed to deliver yearly estimates of the state of the thermohaline circulation, i.e. its intensity, properties, and heat transport. Heat and carbon generally are released to the atmosphere in regions of the ocean far distant from where they enter. Monitoring the transport within the ocean is a central element of documenting the overturning circulation of fresh water, heat and carbon uptake and release. Long-term monitoring of key choke points, such as the boundary currents along the continents including the Gulf Stream and the Deep Western Boundary Current, will provide a measurement of the primary routes of ocean heat, carbon, and fresh water transport and hence include the bulk of the Meridional Overturning Circulation.

Project web sites:

http://www.aoml.noaa.gov/phod/floridacurrent/
http://www.aoml.noaa.gov/phod/wbts/

3. FY 2008 PROGRESS

Element 1: Continuous transport of the Florida Current

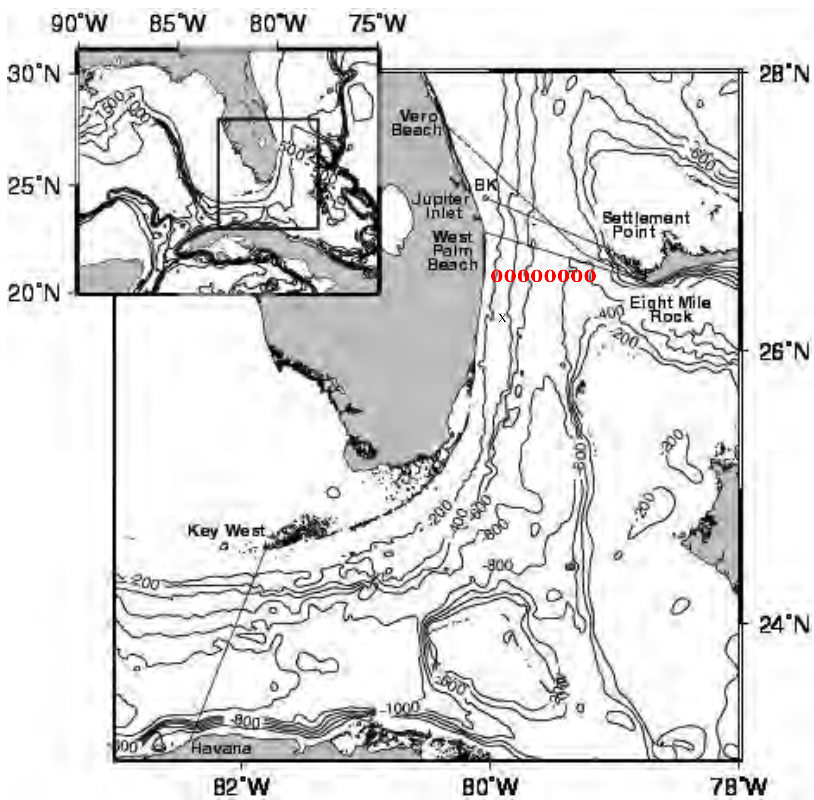

Figure 2. Location of submarine telephone cables (solid black) and nine stations (red) occupied during calibration cruises.

Recording instruments are located at Eight Mile Rock, Grand Bahamas Island. At Eight Mile Rock and in West Palm Beach, Florida, electrode equipment is in place, securing a stable reference voltage (i.e. grounds) at either end of the submerged telephone cable owned by AT&T. The monitored cable can be seen in Figure 2, stretching across the Florida Straits. Data acquisition has continued using the cable during FY08 however there were several short periods of up to three-weeks that data collection was not possible due to electronics failures with the recording system. The largest loss was of 20 days in December 2007 when there was a failure in a conductor in the wire to the anode. A failure in the voltage recording computer in March 2008 resulted in a loss of 8 days of data, and a recording system upgrade made in June 2008 resulted in the loss of a few hours of data. Last year during the period from January 2007 through October 2007 there was a slight low-bias in the cable transports relative to the dropsonde cruise data. This offset was traced to a failure in one of the anodes (Earth ground), which was replaced in October 2008. The data during the low offset period was completely recovered and a new version was available via the web site in October 2008. This FY has seen the continued success of the stable system of processing and quality control for both the calibration section data and the cable transport data implemented in FY05. Cable voltages are recorded every minute, and are post processed to form daily transport estimate. The Table 1 below shows the number of hourly averaged voltage measurements. Note that OCO funding in recent years has been insufficient to maintain the necessary recording system repairs and replacements, and at times AOML Base funds have been used for the purchase of replacement systems and parts. A small amount of additional funds has been added to the budget for this year to address this shortfall.

Table 1. Data return from continuous cable voltages (% Return based on the maximum number of days possible in one year: e.g. 365 for non-leap years and 366 for leap years like 2004).

FY 2008	FY 2007	FY 2006	FY 2005	FY 2004
93% Return	100% Return	98% Return	88% Return	87% Return[2]

Utilizing both AOML Base funds and OCO funds, in July 2008 a set of moored instruments was deployed to test combinations of different of equipment that could be used to monitor the transport of the Florida Current continuously in case of a future failure of the real-time cable system. Some funds for this were provided by OCO in 2006 as a one-time add-task to add voltage recorders to a second cable across the Florida Straits. Subsequent to the delivery of those OCO funds the Bahamian telephone cable company Batelco declined to allow the instrumentation of their active fiber optic cable, so alternative methods are being tested. Three inverted echo sounders (one including a bottom pressure sensor, a PIES) from old experiments in the 1980s and 1990s and two new pressure gauges were deployed at five sites spanning the straits (Figure 3). Together these instruments will be tested to find which combination of instruments will give us the best delayed-mode estimate of the transport. These instruments will necessitate one additional day of ship time each year to service the instruments. Data will be available annually, approximately

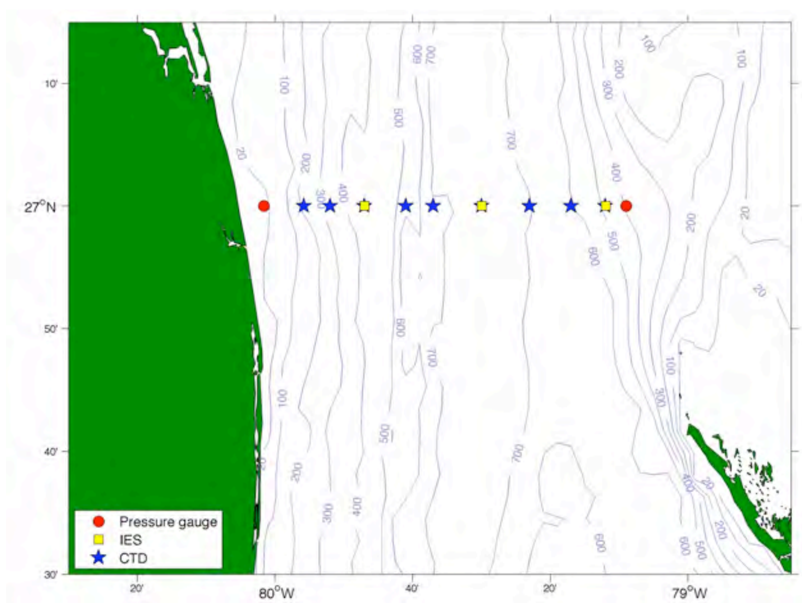

Figure 3. Locations of new moored instruments being tested as possible replacement systems for measuring Florida Current transport. Also shown are the locations of the standard CTD/LADCP and dropsonde/XBT sites used in the Florida Straits.

3 months after servicing the array. Additional funds will be required to maintain these moored equipment, and a small increase has been included in the budget to account for fixed equipment costs. If the moored equipment proves to reproduce the measurements of the cable, at a future date OCO funds will be required for the purchase of modern, more reliable inverted echo sounders as well as of spare pressure gauges.

Table 2. Cruise dates for 1-day small boat calibration cruises using dropsonde instrument.

Planned Cruise	FY 2008	FY 2007	FY 2006	FY 2005	FY 2004
1	4-Oct-2007[1]	13-Dec-2006	11-Nov-2005	19-Nov-2004 dropsonde lost	9-Dec-2003
2	6-Nov-2007	15-Dec-2006	17-Nov-2005	29-Nov-2004	16-Dec-2003
3	28-Nov-2007	29-Mar-2007	2-Feb-2006	17-Feb-2005	9-Jan-2004
4	7-Dec-2007	19-Jun-2007	14-Mar-2006	24-Feb-2005 section incomplete due to weather	13-Jan-2004 – GPS failure on two stations
5	23-Jan-2008	10-Jul-2007	27-Mar-2006	18-May-2005	7-May-2004
6	29-Jan-2008	5-Sep-2007, dropsonde electronics problems	22-Jun-2006	21-Jun-2005 dropsonde lost	24-May-2004
7	22-Apr-2008	27-Sep-2007	30-Jun-2006	31-Aug-2005	Jun 7, 2004
8	7-May-2008	Postponed to early FY08 due to weather	20-Jul-2006		Jun 11, 2004
9	10-Jul-2008[2]		15-Sep-2006		Aug 24, 2004
10	14-Jul-2008				1-Sep-2004 - GPS antenna failure
	90% successful	87.5% successful	100% successful	50% successful[3]	100% successful[4]

Small charter boat calibration trips:

A total of ten 1-day surveys were conducted using a dropsonde profiler (the first cruise had been postponed from the last FY due to weather; on one cruise the dropsonde was lost). Measurements are taken at nine stations along 27ºN (same locations as the CTD sites shown in Figure 3) and include vertically averaged horizontal velocity, surface

[1] Carry-over cruise from FY07 that had been postponed due to weather/scheduling isues.

[2] Dropsonde was lost.

[3] Final cruise postponed to next fiscal year due to weather/scheduling issues. Two dropsonde instruments were lost due to equipment malfunctions. One cruise was only partially completed due to weather.

[4] Two additional cruises were planned for FY04 due to dropsonde failures in FY03.

velocity and expendable temperature probes (XBTs). The cruise dates are shown in Table 2. Over the course of the year our engineering staff has been designing a new generation of dropsonde and we are testing the final components during the most recent cruises. This new generation of dropsonde will include a portable CTD capable of measuring pressure, salinity and temperature. Development of this new generation of dropsonde, and replacements that have been made for losses of older style dropsondes, have been covered using largely AOML Base funds.

Full Water Column calibration cruises:
Two-day cruises on RV Walton Smith are generally scheduled four times per year. Sufficient ship-time funds for only one of the cruises were provided by the charter ship fund in FY08, however days for an additional three-day cruise were provided by a related U. Miami program that could not use all of their days. All cruises include nine stations with full water column CTD, lowered ADCP, and continuous shipboard ADCP. The station locations are shown in Figures 2 and 3. Table 3 below includes the cruise dates and number of water samples taken for oxygen concentration (O2) and salinity (S).

Table 3. Cruise dates for 2-day calibration cruises on the R/V Walton Smith. Note FY2005: The last cruise planned for in FY 2005 was postponed for early FY 2006. Note FY 2007: Only three cruises were completed due to lack of ship-time charter funds. Note: FY2008 Only one two-day cruise was planned in FY2008 due to lack of ship-time charter funds; a second three-day cruise was done using sea-days donated by a related program at U. Miami.

FY2008		FY2007		FY2006		FY 2005		FY 2004	
Date	Samples	Date	Samples	Date	Samples	Date	Samples	Date	Samples
Dec 2007	19-20, 60 O2, 48 S	Dec 2006	13-14, 60 O2, 48 S	Dec 2005	14-16, 60 O2, 48 S	Dec 3-4, 2004	58 O2, 44 S	Jan 2003	8-9, 55 O2, 46 S
Jul 2007	7-9, 60 O2, 48 S	Jun 2007	28-29, 60 O2, 48 S	Jan 2006	29-31, 60 O2, 48 S	Jun 2005	3-4, 58 O2, 45 S	May 2004	6-7, 47 O2,
		Oct 2007	4-5, 60 O2, 48 S	Jun 2006	25-27, 60 O2, 48 S	Jul 2005	11-12, 58 O2, 45 S	Jul 4-5, 2004	56 O2,
				Sep 2006	18-19, 68 O2, 48 S	Nov 2005	20-23, 60 O2, 48 S	Aug 2004	27-28, 55 O2, 42 S
50% of planned cruises		75% of planned cruises		100% of planned cruises		100% of planned cruises		100% of planned cruises	

Element 2: Deep Western Boundary Current time series
Two cruises involving full-water-column CTD, lowered ADCP, and shipboard ADCP were planned during FY08 within the Florida Straits and east of Abaco Island, Bahamas. At each station, a package consisting of a Seabird Electronics Model 9/11+ CTD O_2 system, an RDI 150 kHz Workhorse Lowered Acoustic Doppler Current Profiler, a RDI 300 kHz Workhorse Lowered Acoustic Doppler Current Profiler, and 23 10-liter Niskin bottles, was to be lowered to the bottom. This provides profiles of velocity, pressure, salinity (conductivity), temperature, and dissolved oxygen concentration. Water samples were collected at various depths and analyzed for salinity and oxygen concentration to aid with CTD calibration.

The first hydrographic cruise this year took place on the R/V Seward Johnson during Apr. 4-30. The second cruise was originally planned to go on the NOAA Ship Ronald H.

Brown, however maintenance issues with that vessel required both rescheduling and downsizing (due to a funding shortfall) the cruise which then took place on the R/V Cape Hatteras during Sept 26-Oct. 3. (This downsizing of the cruise due to insufficient funds from the NOAA fleet resulted in the loss of about 70% of the planned CTD stations including nearly all of the deep stations, which was the primary scientific goal of the hydrographic survey). The stations were occupied at the locations shown in Figure 4. Table 4 lists the cruise dates and bottle samples taken compared to previous years.

Also listed in Table 4 are the operations completed at the inverted echo sounder mooring sites during the cruises. The easternmost inverted echo sounder with a pressure gauge (PIES) shown in Figure 4 was recovered in April 2008 due to an electronics failure in the instrument; data from the other four instruments was successfully downloaded via acoustic telemetry during the April 2008 cruise. The westernmost PIES washed ashore in the Bahamas in June 2008 due to an anchor failure; the instrument was recovered and redeployed 16 days after it surfaced. Two of the five inverted echo sounders (IES) sites shown in Figure 4 were recovered and redeployed during the September 2008 cruise due to concerns about their anchors and a replacement PIES was deployed at the easternmost site. Four additional temporary IES/PIES sites had been deployed during the September 2006 cruise (supplied by between the permanent sites for a planned two-year evaluation of the array resolution; two of the four were successfully recovered during the September 2008 cruise, the other two were lost, probably due to anchor failures. Note that OCO support to date for the PIES/CPIES moorings has been sufficient to repair and replace these mooring failures. To date CPO has provided funds for five instruments for the five permanent sites. One of these instruments was lost and replaced with AOML base funds. All other IES/PIES/CPIES described above are provided from AOML's aging stable of instruments (dating as far back as 1986, which partly explains the instrument failure). Additional OCO funds will be required in the future if the array of PIES/CPIES is to be maintained long-term especially with telemetry capable instruments. Funds for a spare CPIES (required for the turn-around cruise in spring 2010), for a replacement pressure sensor (to replace a failing sensor) and for a replacement deck unit (which has been damaged) have been included in an Equipment Support add-task.

Table 4. Cruise dates and water samples taken for Large Vessel full water column surveys of the Deep Western Boundary Current. September 2008 cruise was on the R/V Cape Hatteras. September 2006 and April 2008 cruises aboard the R/V Seward Johnson and the May 2005 cruise aboard the R/V Knorr were with ship time funded by NSF. April 2001 cruise on the R/V Oceanus. All other cruises were conducted on the NOAA Ship Ronald H. Brown. Additional nutrient and carbon measurements that were taken during the March 2006 cruise were collected using base funds. Funding for collection in future years is being requested as an Add Task.

FY	Date	Stations	Bottle Samples	Comments
2008	Sep, 2008	17	105 O2, 174 S	Telemetry data collected from one PIES and one CPIES, three PIES were deployed, three PIES and one IES were recovered, one PIES and one IES were lost
2008	Apr, 2008	45	400 O2, 634 S	Telemetry data collected from four PIES/CPIES, and one PIES was recovered
2007	Sep, 2007	48	737 O2, 706 S	Telemetry data collected from five PIES/CPIES
2007	Mar, 2007	74	1092 O2, 1135 S	Telemetry data collected from five PIES/CPIES
2006	Sep, 2006	42	465 O2, 568 S	2 IES recovered, 1 IES lost (but data retrieved via telemetry), 7 IES deployed, and data retrieved via telemetry from 2 IES
2006	Mar, 2006	72	921 O2, 943 S, 391 nut., 506 DOC/TOC, 80 DIC, 40 TALK	2 IES recovered, 2 IES deployed, data from 3 IES recovered via acoustic telemetry
2005	Sep, 2005	53	728 O2, 728 S	1 IES deployed, 2 IESs recovered, data from 3 IESs recovered via acoustic telemetry
2005	May, 2005	70	1084 O2, 1180 S	1 IES deployed, data recovered from 3 IESs via acoustic telemetry
2004	Sep, 2004	42	634 O2, 629 S	5 IES mooring deployments
2003	Feb, 2003	54	844 O2, 843 S	3 IES Mooring recoveries, Short Seabeam in Florida Straits
2002	June 2002	57	924 O2, 924 S	Extended Seabeam survey east of Abaco Island, SF6 samples.
2001	April 2001	33	607 O2, 659 S	4 IES mooring deployments

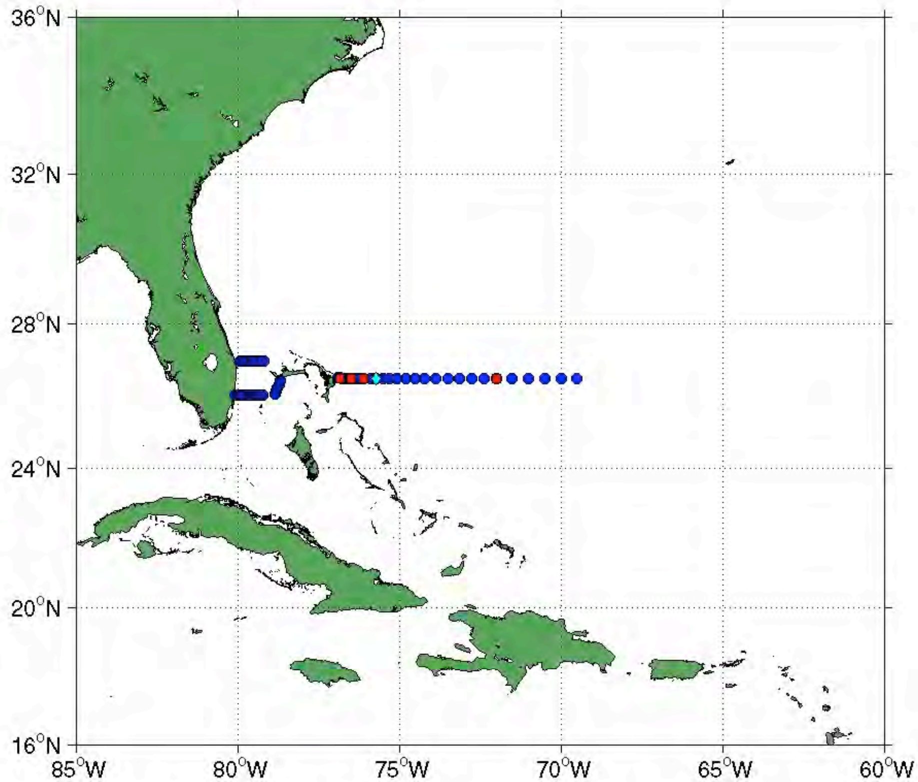

Figure 4. Approximate locations of full water column hydrographic stations sampled on the two cruises in FY 2005. Blue circles denote CTD sites. Red squares denote PIES moorings and the cyan diamond denotes a CPIES mooring. Note nearly all of the CTD stations east of Abaco Island were not occupied during the September 2008 cruise due to time constraints as discussed in the text.

4. RESEARCH HIGHLIGHTS

1. A recent publication illustrated how well the joint NOAA-NSF-NERC collaborative program is doing at capturing the total basin-wide-integrated transport through the combination of different types of measurement systems (Kanzow et al., 2008).

2. In a pair of papers (DiNezio et al., 2008, Meinen et al., 2008) the long-term variability of the Florida Current transport is documented back to the 1960s using modern and reanalyzed historical data and this variability is studied in the context of wind stress variability over the basin interior. The high percentage of variance in sub-annual periods is shown to conclusively necessitate continuous time-series observations in order to extract and study annual and interannual variations in the Florida Current transport.

3. Baringer and Meinen (2008) summarized in the State of the Climate Report (BAMS, 2008, 89(7), s49-s51) results from the first year of this new MOC monitoring array that appeared in Science in August (Kanzow *et al.,* 2007, Cunningham *et al.,* 2007). The results from the first year of this array indicate a

surprising amount of variability in the MOC strength. In fact within one year, all the MOC values estimated from Bryden *et al.,* (2005) can be found within the first year of the time series. These results cannot disprove the presence of a long-term trend in the strength of the MOC, but they do suggest that a careful error analysis be performed that includes the underlying variability of the MOC (the standard deviation of this first year was estimated as 3.1 Sv[5]). Fluctuations in the Florida Current show a clear negative correlation with NAO during the 1982-1998 time period (Baringer and Larsen, 2001); however while the NAO has been tending to decrease over the past twenty years, the Florida Current transport shows no corresponding long-term trend through 2007. The annual mean Florida Current transport observed in 2007 (31.8 Sv) falls only slightly below the long term mean of 32.1 Sv, and given the statistical standard error of the mean of 1 Sv for a year, 2007 cannot be termed as an unusual year in terms of the Florida Current transport. Compared to 2006 (annual mean of 31.3 Sv) the Florida Current appears to have increased only slightly. Note that 2007 shows similar variability to previous years and no anomalous events occurred during the year.

4. A paper analyzing the data from an array of 6 moorings deployed east of Abaco, Bahamas along 26.5ºN during March 2004 to May 2005 was published. These moorings formed the western boundary array of a trans-basin observing system designed to continuously monitor the meridional overturning circulation and meridional heat flux in the subtropical North Atlantic, under the framework of the joint U.K./U.S. RAPID-MOC (Rapid Climate Change – Meridional Overturning Circulation) program. Important features of the western boundary circulation include the southward-flowing Deep Western Boundary Current (DWBC) below 1000 m, and the northward-flowing "Antilles" Current in the upper 1000 m. Transports in the western boundary layer are estimated from direct current meter observations and from dynamic height moorings that measure the spatially-integrated geostrophic flow between moorings. The results of these methods are combined to estimate the time varying transports in the upper and deep ocean over the width of the western boundary layer to a distance of 500 km offshore of the Bahamas escarpment. The net southward transport of the DWBC across this region, inclusive of northward deep recirculation, is -26.5 Sv, which is divided nearly equally between Upper (-13.9 Sv) and Lower (-12.6 Sv) North Atlantic Deep Water (NADW). In the top 1000 m, 6.0 Sv flows northward in a thermocline-intensified jet near the western boundary. These transports are found to agree well with historical current meter data in the region collected between 1986 and 1997. Variability in both the shallow and deep components of the circulation is large, with transports above 1000 m varying between –15 to +25 Sv and deep transports varying between –60 to +3 Sv. Much of this transport variability occurs on relatively short time scales of several days to a few weeks associated with barotropic fluctuations. Upon removal of the barotropic fluctuations, slower baroclinic transport variations are revealed, including a temporary stoppage of the lower NADW transport in the DWBC during November 2004.

[5] Sv is a Sverdrup or 10^6 m^3/s, a unit commonly used for ocean volume transports.

4. PEER REWIEDED PUBLICATIONS

Baringer, M. O., and C. S. Meinen, 2008:"The Meridional Overturning Circulation", in "State of the Climate in 2007", D. H. Levinson and J. H. Lawrimore (eds.), *Bull. Am. Met. Soc.*, 89(7), s49-s51, doi:10.1175/BAMS-89-7-StateoftheClimate.

DiNezio, P. N., L. J. Gramer, W. E. Johns, C. S. Meinen, and M. O. Baringer, 2008: "Observed Interannual Variability of the Florida Current: Wind Forcing and the North Atlantic Oscillation", *J. Phys. Oceanogr.*, in press.

Johns, W.E., L.M. Beal, M.O. Baringer, J.R. Molina, S.A. Cunningham, T. Kanzow, and D. Rayner., 2008: “Variability of shallow and deep western boundary currents off the Bahamas during 2004-2005: Results from the 26°N RAPID-MOC array”, *J. Phys. Oceanogr.*, 38(3), 605-623.

Kanzow, T., J. J-M. Hirschi, C. S. Meinen, D. Rayner, S. A. Cunningham, J. Marotzke, W. E. Johns, H. L. Bryden, L. M. Beal, M. O. Baringer, 2008: "A prototype system of observing the Atlantic Meridional Overturning Circulation - scientific basis, measurement and risk mitigation strategies, and first results", *J. Operational Oceanogr.*, 1, 19 - 28.

Meinen, C. S., M. O. Baringer, and R. F. Garcia, 2008: "Florida Current Transport Variabilty: An Analysis of Annual and Longer-Period Signals", *J. Geophys. Res.*, submitted.

5. ABSTRACTS/MEETING PROCEEDINGS

Meinen, C. S., M. O. Baringer, and R. F. Garcia, 2008: “Florida Current Transport Variability: An Analysis of Annual and Longer-Period Signals”. (RAPID Annual Meeting, June 30-July 2, Cambridge, United Kingdom.)

Baringer, M., W. Johns, C. Meinen, D. Shoosmith, and H. Bryden, 2008: “On the Structure of Florida Current Variability”. (RAPID Annual Meeting, June 30-July 2, Cambridge, United Kingdom.)

Johns, W., H. Bryden, M. Baringer, L. Beal, S. Cunningham, T. Kanzow, J. Hirschi, J. Marotzke, Z. Garraffo, C. Meinen, and R. Curry, 2008: “Observations of Meridional Heat Transport Variability from the 26.5°N RAPID-MOC Array”. (RAPID Annual Meeting, June 30-July 2, Cambridge, United Kingdom).

Kanzow, T., S. A. Cunningham, D. Rayner, M. O. Baringer, W. E. Johns, J. J.-M. Hirschi, L. M. Beal, C. Meinen, H. L. Bryden, 2008: “Observations of the temporal variability of the Atlantic meridional overturning circulation from the Rapid-MOC transatlantic array at 26.5ºN”. (RAPID Annual Meeting, June 30-July 2, Cambridge, United Kingdom).

Meinen, C. S., M. O. Baringer, and R. F. Garcia, 2008: “Variations of the Florida Current transport from 1964 to 2007 and the relationship to forcing”. (2008 Ocean Sciences Meeting, March 2-7, Orlando, Florida).

Garcia, R. F., C. S. Meinen, M. O. Baringer, 2008: “Utilizing Voltage Measurements on a Submarine Cable to Estimate Florida Current Transport Operationally: A Real-Time Observing System. (2008 Ocean Sciences Meeting, March 2-7, Orlando, Florida).

Fonseca, C. A., M. O. Baringer, C. S. Meinen, 2008: “Water Mass Changes in the Deep Western Boundary Current Along 26.5ºN”. (2008 Ocean Sciences Meeting, March 2-7, Orlando, Florida).

Cunningham, S. A., T. Kanzow, D. Rayner, M. O. Baringer, W. E. Johns, J. Hirschi, L. M. Beal, C. S. Meinen, H. L. Bryden, J. Marotzke, 2008: “Observations of the Temporal Variability of the Atlantic Meridional Overturning Circulation”. (2008 Ocean Sciences Meeting, March 2-7, Orlando, Florida).

Johns, W. E., H. L. Bryden, M. O. Baringer, L. M. Beal, S. A. Cunningham, T. Kanzow, J. Hirschi, J. Marotzke, Z. Garraffo, C. S. Meinen, 2008: “Observations of Atlantic Meridional Heat Transport Variability at 26.5°N from the RAPID-MOC Array. (2008 Ocean Sciences Meeting, March 2-7, Orlando, Florida).

Peng, G, Z. Garraffo, G. Halliwell, O. Smedstad, C. S. Meinen, and V. Kourafalou, 2008: “Variability of the Florida Current Transport at 27ºN”. (2008 Ocean Sciences Meeting, March 2-7, Orlando, Florida).

Bryden, H. L., S. A. Cunningham, T. Kanzow, D. Rayner, M. O. Baringer, W. E. Johns, J. Marotzke, J. Hirschi, L. M. Beal, C. S. Meinen, 2008: “An Operational Array for Monitoring the Atlantic Meridional Overturning Circulation at 26°N”. (2008 Ocean Sciences Meeting, March 2-7, Orlando, Florida).

Flux Mooring for the North Pacific's Western Boundary Current: Kuroshio Extension Observatory (KEO)

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1. PROJECT SUMMARY

Overview:

As a NOAA contribution to the global network of Ocean Sustained Interdisciplinary Timeseries Environmental Observatory (OceanSITES) timeseries reference stations, in June 2004, an air-sea flux buoy site was launched near 144.6°E, 32.4°N in the Kuroshio Extension recirculation gyre. The mooring, referred to as the Kuroshio Extension Observatory (KEO), carries a suite of sensors to monitor carbon dioxide uptake; air-sea heat, moisture and momentum fluxes; temperature and salinity to 500 m, and near-surface currents. The Kuroshio Extension (KE) is the North Pacific's western boundary current after separating from the coast near 35°N. The KE jet carries approximately 140 milllion cubic meters per second (140 Sv) of warm water eastward into the North Pacific. About a third of this is forced by the basin-scale winds and associated with the wind driven Sverdrup transport and the other 90 Sv is due to a tight recirculation gyre whose size varies on seasonal-decadal time scales.

The KE atmosphere-ocean system represents a major branch of the global heat cycle, whereby excess heat input at the top of the atmosphere in the tropics is carried poleward by a combination of the oceanic and atmospheric circulations (e.g., Trenberth and Caron 2001). In the subtropical North Pacific, a significant fraction of this heat is transported poleward by the Kuroshio. As cold dry air of continental origin comes in contact with the warm KE water, heat and moisture are extracted from the surface (Figure 1), resulting in vigorous convection and rainfall. The KE is co-located with the Pacific storm track and heat released to the atmosphere is then carried further poleward through the action of storms.

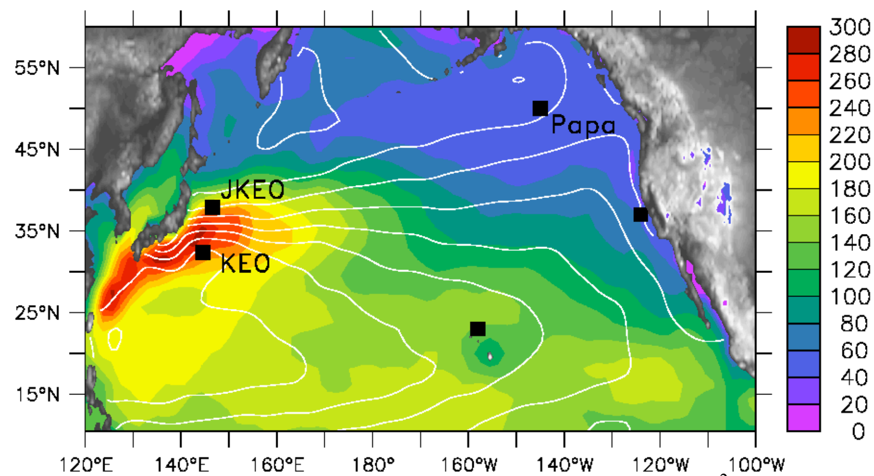

Figure 1. Climatolocial wintertime (January-March) latent heat flux (color shade in Wm^{-2}) and sea level height (white contours) for the North Pacific. Squares indicate OceanSITES time series reference sites.

The KEO project is working closely with international research communities. The KEO site was within the study domain of the 2-year (June 2004 - June 2006) National Science Foundation-funded Kuroshio Extension System Study (KESS). (Donohue et al. 2008, also see http://uskess.org). KEO data are being combined with KESS data for a series of analyses on mode water formation, seasonal thermocline erosion, recirculation gyre strength, and air-sea interaction associated with summer typhoons and winter storms in the region. KEO PIs (Cronin and Bond) are members of the U.S. CLIVAR Working Group on Air-Sea Interaction in Western Boundary Current Regions. KEO data also serve the operational community and are being used as reference time series to assess numerical weather prediction analyses and reanalyses (Kubota et al. 2008, Tomita et al. 2008).

Strong currents, typhoons, winter storms, shipping traffic and fishing vandalism make the KEO region challenging for surface moorings. A manufacture defect in the nylon caused the buoy to become adrift in November 2005, as did fishing vandalism in May 2007. The May 2007 break led to loss of all subsurface sensors. Despite these challenges, the preliminary data return is 100% for all variables in FY08 (Table 1). Recognizing the success of the KEO project, PMEL has been approached by a number of academic and international groups and several have subsequently become partners. In particular, the KEO project is working closely with scientists from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). In February 2007, JAMSTEC Institute of Observational Research for Global Change (IORGC) in partnership with NOAA PMEL successfully deployed a NOAA-designed KEO mooring (JAMSTEC-KEO or "JKEO") north of the Kuroshio Extension jet. In 2008 this was replaced by a JAMSTEC-designed mooring. Likewise, since September 2007, KEO mooring operations have been performed on JAMSTEC research vessels. In addition, as part of a NSF-funded Carbon and Water Cycle project led by biogeochemists from the University of Washington, in June 2007 PMEL deployed a KEO-type air-sea flux mooring at the Ocean Weather Station Papa (50°N, 145°W) site in the Northeast Pacific. An add task for FY09 requests funds to continue the Station Papa mooring as an OceanSITES time series reference site. If this add-task is not funded, the Station Papa mooring will be recovered in June 2009 and not redeployed. Within PMEL, the KEO, JKEO, and Station Papa projects are being unified under the new name of PMEL Ocean Climate Stations (OCS) Program: http://www.pmel.noaa.gov/OCS/. The OCS program website provides links to the individual project pages and data for KEO: http://www.pmel.noaa.gov/keo/, for JKEO: http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/, and for Station Papa: http://www.pmel.noaa.gov/stnP/.

2. FY2008 ACCOMPLISHMENTS

The KEO project has 3 broad deliverables, each described below. The Carbon component of KEO is described separately in the progress report for Sabine's "High-Resolution Ocean and Atmosphere pCO_2 Time Series Measurements" project.

Deliverable 1: Calibrated surface meteorological and subsurface temperature, salinity and currents at the KEO site in the Kuroshio Extension recirculation gyre at 32.4°N, 144.6°E.

Operation of the KEO mooring requires refreshing the system at least once a year, pre- and post-calibrating all sensors, processing realtime data and making it available in near-realtime through the KEO website, processing delay-mode high resolution data and making it available with 6 months through the KEO website.

The KEO mooring was redeployed using charter funds for two sea-days on the R/V Kaiyo in September 2008. As shown in Figure 2, the recovered KEO-2007 and re-deployed KEO-2008 moorings have 2.5 m discus hulls, larger than the original retrofit TAO buoy. The new hull makes the buoy more robust to the drag caused by the strong full-water column currents. In addition, the larger hull enables the buoy to carry a larger payload. The KEO-2008 was also redesigned to have more glass balls above the release so that in the event that that the line parted from the buoy and sank (as happened in May 2006), the mooring line and sensors could be recovered from the ocean floor. For KEO-2008, we replaced these lost sensors with new Seabird, Inc. sensors with titanium cases that would protect the sensor electronics even at depths of 7000 m. In addition, KEO-2008 included a barometric pressure sensor and duplicate meteorological sensors on the independent data logger and telemetry system referred to as FLEX (Figure 2). Given the high number of typhoons in this region, this redundancy is prudent.

As can be seen in Table 1, KEO had 100% data return for FY08. The full suite of KEO meteorological measurements from the ATLAS data logger are shown in Figure 3 and include: wind speed and direction from a sonic anemometer, air temperature, relative humidity, rainfall, and solar and longwave radiation. The ATLAS data logger telemeters daily-averages of all its met data and spot samples of some of its met measurements in near-realtime via Service Argos; while the FLEX data logger telemeters hourly averages of its met measurements and hourly spot values of subsurface measurements in near-realtime via Iridium. Upper ocean temperature has approximately 25 m depth resolution, subsurface salinity has ~50-75 m resolution, and subsurface pressure (to remap the slackline depths) has 75 m resolution. This resolution is necessary to monitor the mode water formation when the mixed layer can be more than 400 m deep. Three current meters were also attached at 5 m, 15m, and 35 m (all of which are telemetered) to monitor the near surface currents.

Table 1. KEO data return for FY08 based upon daily-averaged data.

	FY08 Data Returns
Meteorological variables	100%
Upper ocean temperature	100%
Upper ocean salinity	99.7%
Near surface currents	100%

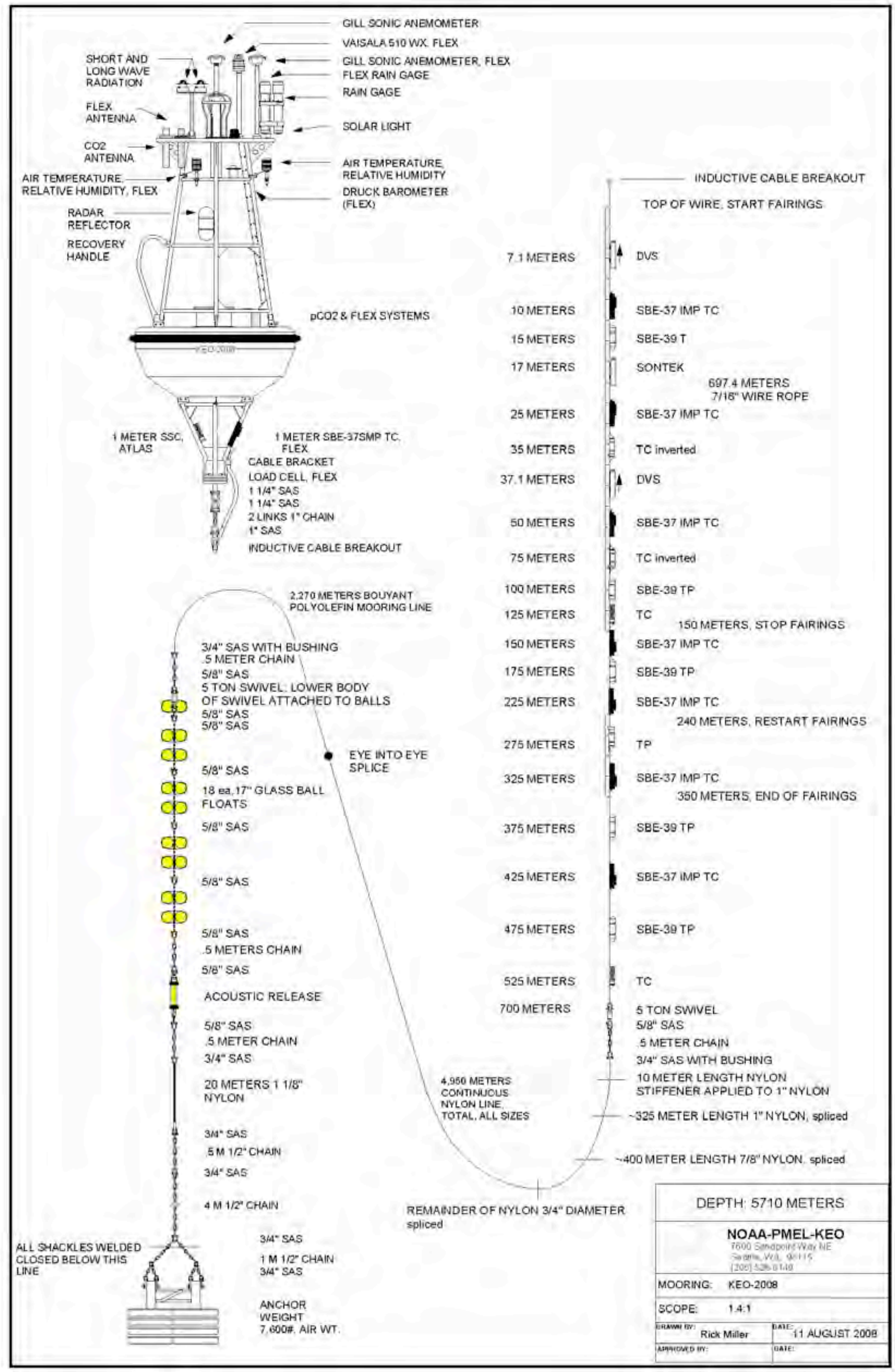

Figure 2. KEO-2008 diagram.

Deliverable 2: Access to KEO data and metadata in a format and through linked webpages to encourage broad use of data.

KEO, JKEO and station Papa data are all in compliance with the OceanSITES data standard. Daily-averages of nearly all data (surface and subsurface) are telemetered to PMEL and made available in near-realtime from:

For KEO: http://www.pmel.noaa.gov/keo/data.html
For JKEO: http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo
For Station Papa: http://www.pmel.noaa.gov/stnP/data.html

High-resolution surface and subsurface data continue to be made publicly available through these websites within 6-months of recovery. To date, there is no user registry and so we have no way of monitoring the number of data downloads.

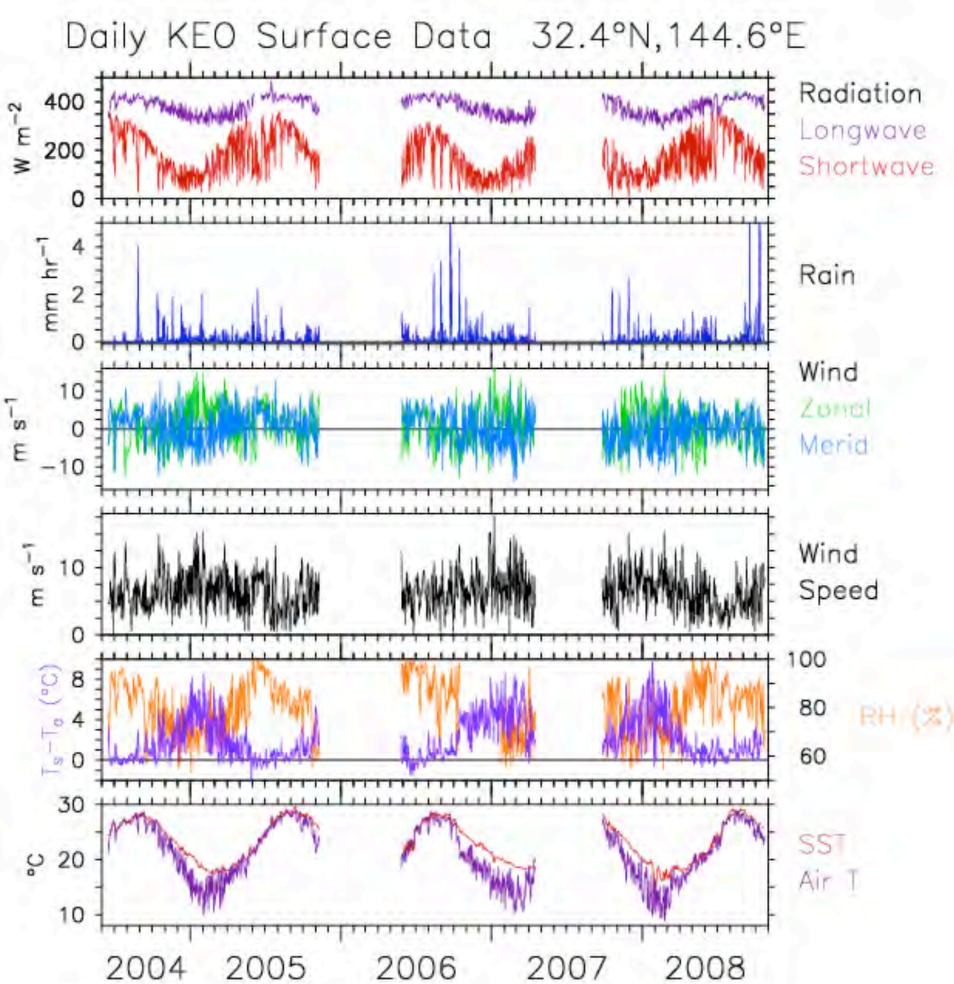

Figure 3. KEO meteorological daily-averaged data through October 23 2008.

Beginning in FY07, the PMEL Ocean Climate Station surface met data from the ATLAS data logger have been distributed to operational meteorological centers via the Global Telecommunications System (GTS) This way operational meteorological centers can use all available data in operational weather forecasts. The KEO project strongly believes however that the reference site data should be withheld from reanalysis products so that the products will remain independent of the time series reference site data used to assess them. Each time series reference station has a unique World Meteorological Organization (WMO) identifying number containing the digits "84" for this purpose.

All three sites (KEO, JKEO, and Station Papa) can be considered as contributions to the Global Earth Observation System of Systems (GEOSS) and a manuscript describing the strategy of these moorings has been published in the IEEE Systems journal special issue for GEOSS (Cronin et al. 2008).

Deliverable 3: Scientific analyses utilizing KEO data. (Scientific analyses are funded through research grants as described below.)

KEO was an element of the Kuroshio Extension System Study (KESS) (see: http://uskess.org, and Donohue et al. 2008) and its data are a critical component of several studies. In particular, FY08 represents the final year of a 3-year NOAA CLIVAR project titled "Role of Air-Sea Interaction in the Kuroshio Extension Recirculation Gyre", with PIs Cronin and Dr. N. Bond (UW JISAO). During FY08, both Cronin and Bond participated in the U.S. CLIVAR working group on Air-Sea Interactions in Western Boundary Currrents (http://usclivar.org/Organization/wbc-wg.html). In November 2007, Cronin, Bond, and NOAA Corp officer Kamphaus participated in a workshop at IPRC in Honolulu that brought together the Japanese and US partners working with surface mooring data in the Kuroshio Extension. This group subsequently named itself the "Kuroshio Extension Implementation Panel" (KIP). The next KIP meeting is planned in conjunction with the US CLIVAR working group conference in January 2009.

Two KEO analyses were published in 2008: Bond and Cronin (2008) and Kubota et al. (2008). Bond and Cronin (2008) analyzed the regional weather and climate patterns associated with anomalously high and low fluxes at KEO. The analysis shows that during the cool season, prevailing winds at KEO are northwesterly and anomalous heat loss by the ocean is associated with increased northerly winds (cold air outbreaks). During summer, on the other hand, prevailing winds switch to be southerly and anomalous cooling tends to occur during enhanced southeasterly winds out of the deep tropics. When the analysis was extended to identify weather patterns associated with anomalous fluxes on seasonal time scales, a surprising result was found. The warm seasons with anomalous heat fluxes tend to have composite patterns similar to the episodic composites, but the cool seasons with anomalous heat fluxes have composite circulation patterns that are weak and little resemble their episodic event counterparts. It's not just a matter of having more or less cold-air outbreaks. Instead, these results suggest that on interannual timescales, the ocean may be playing an important role in determining wintertime heat flux anomalies.

The KEO data have also been used as a time series reference to assess Numerical Weather Prediction (NWP) forecast analyses and reanalyses, and other numerical and satellite products. In particular, Kubota et al. (2008) used the KEO data to assess the radiative and turbulent heat flux fields of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) and NCEP/Department of Energy (DOE) reanalyses (referred to as NRA1 and NRA2) and found that:

- Overall, the NRA latent heat losses were too large relative to KEO. For NRA1, the latent heat bias was 41 W/m^2; for NRA2, the bias was 62 W/m^2 (there was a 21 W/m^2 bias between the two products).

- Although the magnitude of the fluxes had significant biases, the NRA were able to capture many of the synoptic disturbances. The cross-correlation between the KEO latent heat flux and the co-incident NRA latent heat fluxes were greater than 0.9 for both NRA1 and NRA2.
- The bias in the NRA latent heat flux could be reduced significantly by using a more sophisticated bulk algorithm for its heat flux calculations.
- Of all the state variables (SST, humidity, air temperature, wind speed), humidity contributed the largest source of error to the NRA flux. During summer when prevailing winds are from the south (of maritime origin), the NRA humidity is too low, while during the winter when prevailing winds are from the north (of continental origin), the humidity is too high. Although the prevailing wind systems are well reproduced, the air humidity does not seem to be properly modified by boundary layer effects.
- The NRA SST had significant errors in comparison to KEO measurements. The RMS error in latent heat flux was significantly reduced when the NRA SST was replaced with the Microwave Optimum Interpolation (MWOI) SST, indicating that both reanalyses could be improved by assimilating better SST data.

The KEO group is hoping to work more closely with scientists at NCEP to evaluate the operational products and to improve our understanding of air-sea fluxes leading to better predictions of weather and climate variations. Further analyses are described in the FY09 Workplan.

3. PUBLICATIONS

Bond, N. and M. F. Cronin, 2008: Regional weather patterns during anomalous air-sea fluxes at the Kuroshio, Extension Observatory (KEO). *J. Climate*, 21, 1680-1697.

Cronin, M. F., C. Meinig, C. L. Sabine, H. Ichikawa, and H. Tomita, 2008: Surface mooring network in the Kuroshio, Extension. *IEEE Systems Special Issue on GEOSS*, 2, 424-430.

Donohue, K. A., and colleagues, 2008: An integrated system study of the Kuroshio Extension. *EOS Trans. AGU,* 89,161-162.

Kubota, M., N. Iwabe, M. F. Cronin, and H. Tomita, 2008: Surface heat fluxes from the NCEP/NCAR and NCEP/DOE, reanalyses at the KEO buoy site. *J. Geophys. Rev*., 113, C02009, doi:10.1020/2007JC004338.

4. LIST OF ACRONYMS

CLIVAR	Climate Variability and Predictability
DOE	Department of Energy
FLEX	Flexible Low-powered Electronics for ocean experiments
GEOSS	Global Earth Observation System of Systems
GTS	Global Telecommunications System
IORGC	Institute of Observational Research for Global Change

JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
JKEO	JAMSTEC-Kuroshio Extension Observatory
KE	Kuroshio Extension
KEO	Kuroshio Extension Observatory
KESS	Kuroshio Extension System Study
KIP	Kuorhio Extension Implementation Panel
K-TRITON	Kuroshio-TRIangle Trans-Ocean buoy Network
MWOI	MicroWave Optimum Interpolation
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NRA	NCEP Reanalysis
NSF	National Science Foundation
NWP	Numerical Weather Prediction
OceanSITES	Ocean Sustained Interdisciplinary Time series Environmental Observatory
PI	Principal Investigator
PMEL	Pacific Marine Environmental Laboratory
RMS	Root-Mean-Square
SST	Sea Surface Temperature
TAO	Tropical Atmosphere and Ocean
UW	University of Washington
WMO	World Meteorological Organization

Weddell Sea Moorings

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1. PROJECT SUMMARY

The world's deep oceans are filled with water masses formed at the continental margins of Antarctica. The Weddell Sea is a major source of these so-called Antarctic Deep and Bottom Waters. Relatively warm, saline Circumpolar Deep Water (CDW) enters the Weddell Gyre to the east of the Greenwich Meridian. As it traverses the gyre, it feeds bottom water-forming processes on the continental shelves, and interacts with floating ice shelves to produce a variety of Weddell Deep and Bottom water types.

This project maintains three deep and bottom water focused moorings south of the South Orkney Islands in the Northwest Weddell Sea to provide a time series of the combined outflow (currents and temperature/salinity) of Antarctic Deep and Bottom Water drawn from various sites within the Weddell Sea. The moorings were initially installed and maintained as part of the NOAA-funded Consortium on Oceans Role in Climate: AbRupt climate CHangE Studies (CORC-ARCHES) Southern Ocean Modern Observations program.

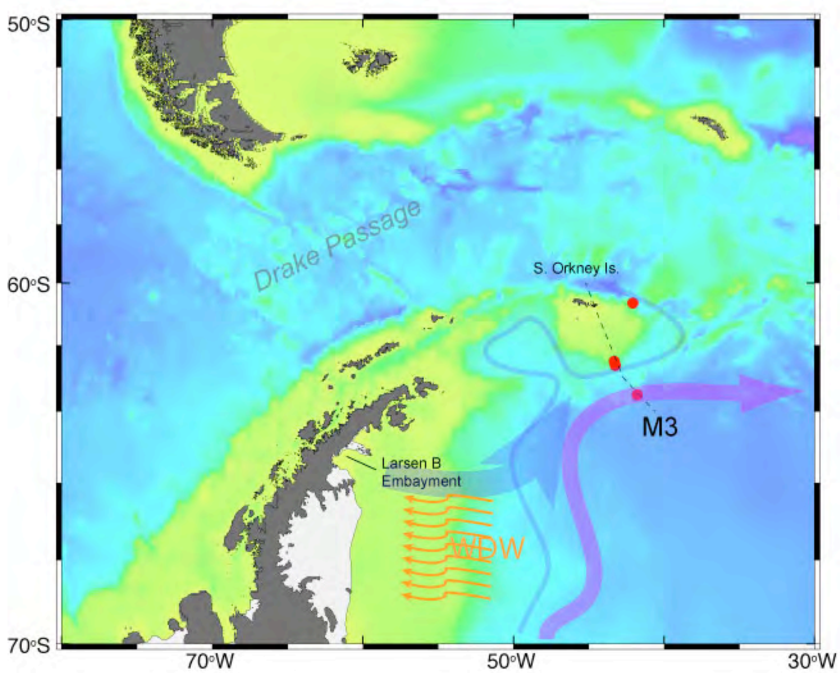

Figure 1. Location of the Weddell Sea moorings (red dots) and repeat CTD/Tracer line (dashed line). Shown schematically are the pathways of deep and bottom waters formed by interaction of WDW with continental and ice shelf waters.

First installed in April 1999, the moorings have been serviced using ship time made available by other programs, primarily through the National Science Foundation Office of Polar Programs (OPP), and principal investigators funded by OPP who graciously allow our team to sail on their cruises. As time and resources allow during the mooring maintenance cruises, oceanographic stations to collect profiles of conductivity, temperature and tracers (CTD/tracer) are occupied at the mooring sites and at stations distributed along a line between the mooring locations (Figure 1). The cost of ship time devoted to the mooring work and associated CTD/tracer stations, typically 3 to 5 days, has been supported by funding from OCO.

More recently, ship time arrangements have been made with colleagues at the British Antarctic Survey (BAS), governed by an Agreement of Cooperation between LDEO and BAS. The agreement with BAS provides for sharing of equipment, personnel and data between LDEO and BAS to allow the mooring sites to be serviced at nominally two-year intervals, with BAS providing the ship time to do so. Our collaboration with BAS will continue, so this work is part of an international effort.

The most recent rotation of the moorings was achieved from the BAS vessel RRS Ernest Shackleton in February-March 2007. The newest of the ARCHES moorings, M_4, within the trough feeding Weddell water into the Scotia Sea is now part of an enhanced array of moorings in the trough, using LDEO and BAS equipment to better resolve this branch of bottom water spreading.

We now have time series of currents, temperature and salinity of the outflow of dense water from the Weddell Sea spanning 8 years at M_3 (Figure 2), which is positioned within the primary pathway of outflow of dense Weddell water, and 6 years at M_2. The M_2 gap of 2005 and 2006 was due to lack of ship time to re-deploy M_2 after recovery in March 2005, but it has now been reinstalled in March 2007.

The time series reveals significant seasonal and interannual variability in the outflow of dense Weddell Sea water. An annual pulse of the coldest bottom water at the mooring site is evident in the May-July time frame, which suggests (from the mean bottom speed) export of shelf water into the deep ocean at the upstream bottom water formation sites in the Dec-Feb period, i.e. austral summer (a rather unexpected discovery). However, the exact timing of the outflow events and their temperature and salinity characteristics vary from year to year.

The extended time series will contribute to an understanding the processes that control the transport and characteristics of the bottom waters that emanate from the Weddell Sea, as required to better assess the reaction of the Southern Ocean meridional overturning circulation and associated deep ocean ventilation to a warming climate. Research questions that could be pursued with the extended Weddell Sea time series include: are there any ‘environmental’ conditions, e.g. wind, sea ice, Larsen Ice shelf break-up, or climate oscillations such as the Antarctic Dipole, Southern Annular Mode, that can account for the seasonal and interannual fluctuations observed in the bottom flow passing the Weddell Mooring sites? How does the observed behavior of the Weddell MOC compare to model output? How might the Weddell Sea MOC change with climate warming?

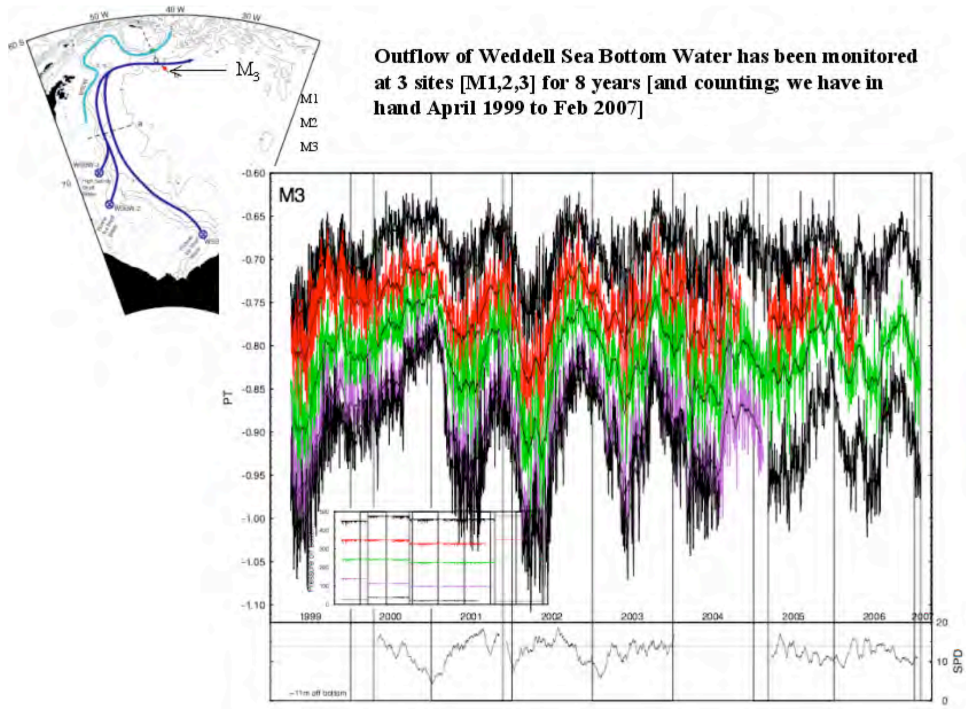

Figure 2. M3 temperature and bottom speed time series.

2. ACCOMPLISHMENTS

The performance period covered by this report is 1 July 2008 – 30 September 2008; no OCO funding was received in FY2007. To date, we have completed all preparations for a cruise on RRS Ernest Shackleton, to be carried out under a cooperative arrangement with colleagues at the British Antarctic Survey (BAS) to continue servicing the Weddell moorings, and to expand the array in conjunction with the BAS and other IPY programs in the region (Figure 3). The configuration of the joint LDEO-BAS array of moorings is shown in Figure 4.

Data are archived and made available as they are recovered from the moorings at the project web site: http://www.ldeo.columbia.edu/res/div/ocp/projects/corc.shtml
This web site will be upgraded during the next year.

A preliminary analysis of the time-series data collected to date will be presented at the 2008 Fall AGU meeting:

Eight Year time series of the outflow of Weddell Sea Bottom water
Arnold L. Gordon, Bruce A. Huber, Darren McKee, Xiaojun Yuan
Lamont-Doherty Earth Observatory of Columbia University

We present a nearly 8 year record (April 1999 to February 2007) of the currents and thermohaline stratification within the lower ~500 m of the water column at a mooring (M3) at 4565 m depth, south of the South Orkney Islands, positioned within the outflow of dense Weddell AABW. The time series reveals significant seasonal and interannual variability. A pulse of the coldest bottom water is evident in the May-July period, though the precise timing and duration varies with year. Intensification of the near bottom stratification is observed as the bottom water attains its coldest values. The coldest bottom events occurred in 1999 and 2002, while in 2000 it was absent. At bottom temperatures <-0.8°C the salinity fluctuations produce a 'fan-like' appearance in T/S space suggesting a varied source of dense shelf water. The coldest bottom water <-1.0°C is relatively salty indicating a source in the southwest Weddell Sea, about 1300 km along isobaths to the mooring site. The typical bottom speed at M3 of 10-15 cm/sec implies a shelf water export time during the austral summer. A record at a second mooring (M2) at 3059 m depth displays a much reduced annual cycle, but it too records a relatively warm period in 2000. Correlations of the M3 time series with NINO3.4 and SAM suggest that these indices lead M3 on the order of 14-20 months, implying a likely relationship between the water mass and surface forcing. Both M3 and M2 were reinstalled in March 2007.

Figure 3. Planned mooring recovery/redeployment activities during RRS Ernest Shackleton cruise scheduled for Jan-Mar 2009.

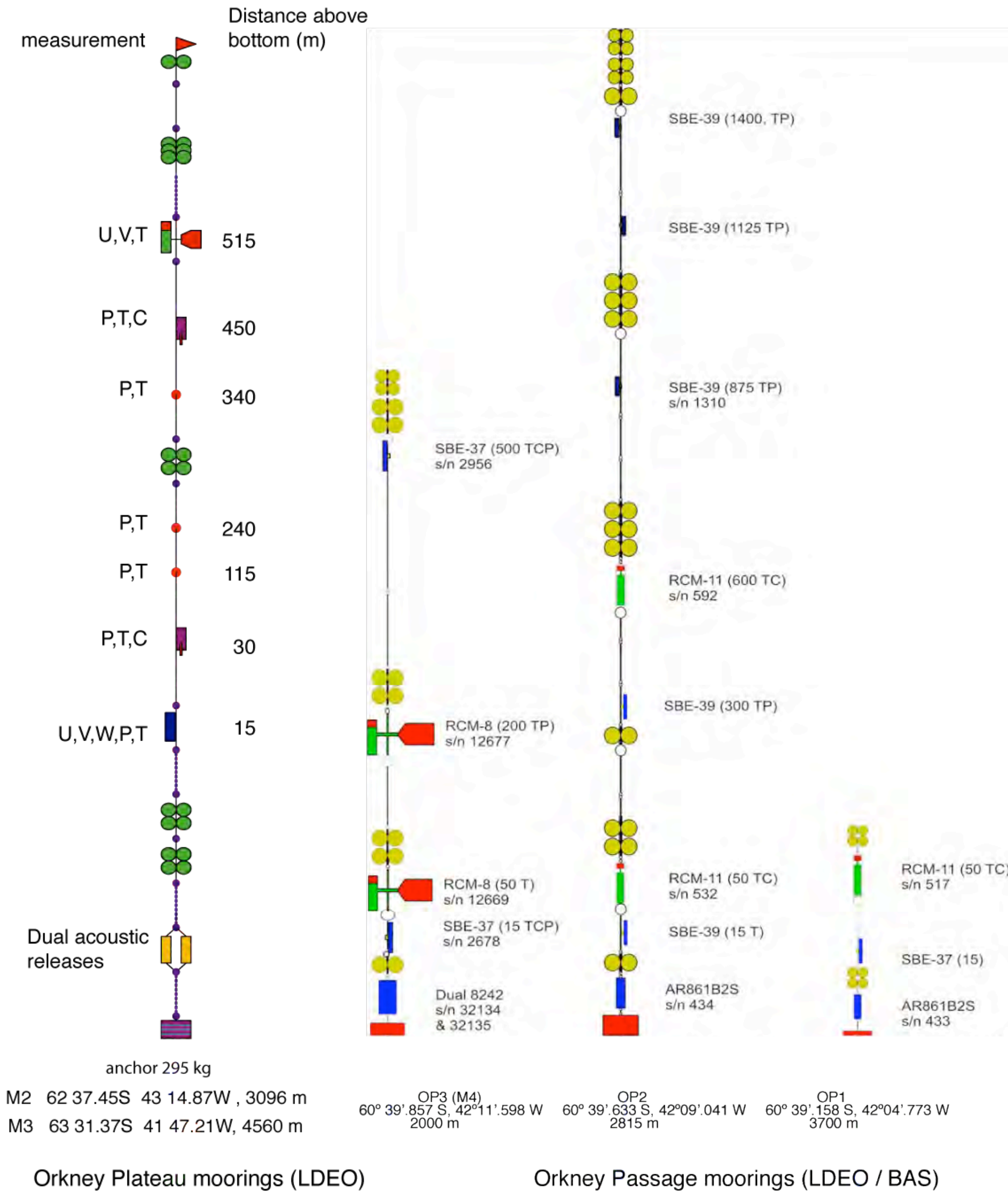

Figure 4. Weddell mooring configurations and positions. RCM current meters will gradually be replaced with acoustic current meters. Additionally, new temperature and temperature/salinity recorders are purchased in off-field years and phased into the mooring array to allow for return and recalibration of older units.

Monitoring the Indonesian Throughflow in Makassar Strait

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1. PROGRESS REPORT

The transfer of tropical Pacific water into the Indian Ocean through the Indonesian seas, the so-called The Indonesian Throughflow (ITF), is a significant part of the ocean system of interocean fluxes, ocean-scale heat and freshwater budgets and sea-air fluxes. The ITF is believed to provide an interactive link with the ENSO and Asian monsoon climate features. Additionally, the ITF to a large extent governs the overall oceanographic stratification, circulation and ecosystems within the Indonesian Seas.

The ITF amounts to ~12 Sv, >80% of which is channeled through Makassar Strait. The 45 km wide Labani constriction of Makassar Strait near 3°S is an ideal place to measure the bulk of the ITF. There the throughflow was measured during the NSF funded INSTANT program from January 2004 to November 2006. The Figures 1, 2 3 provide a view of the 3 year INSTANT time series within Makassar Strait.

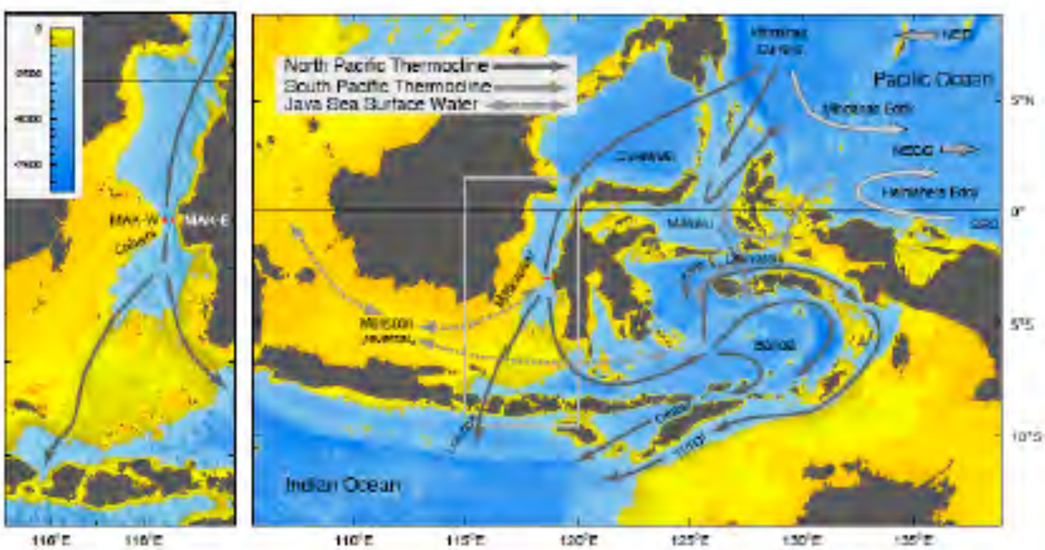

Figure 1. Schematic of the Indonesian Throughflow pattern is shown in the right panel. In the left panel, the Makassar Strait region (as delineated by the grey box in the right panel) is expanded, and the solid grey lines mark the approximate pathway of the Makassar throughflow.

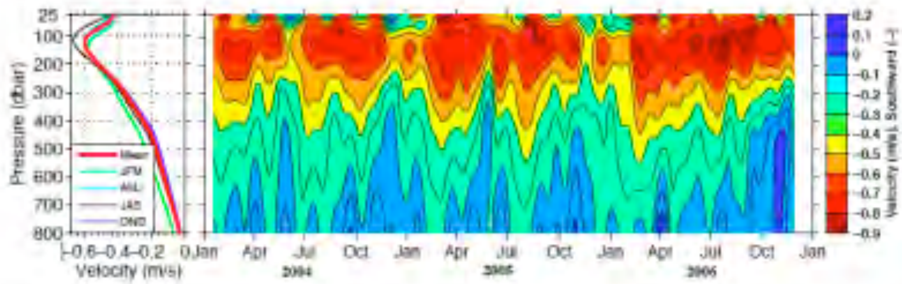

Figure 2. The along-channel velocity section (right panel) and seasonal profiles (left panel). The velocities represent an average of MAK-west and the MAK-east values. The vertical coordinates are given in decibar (dbar), which is approximately a meter (m).

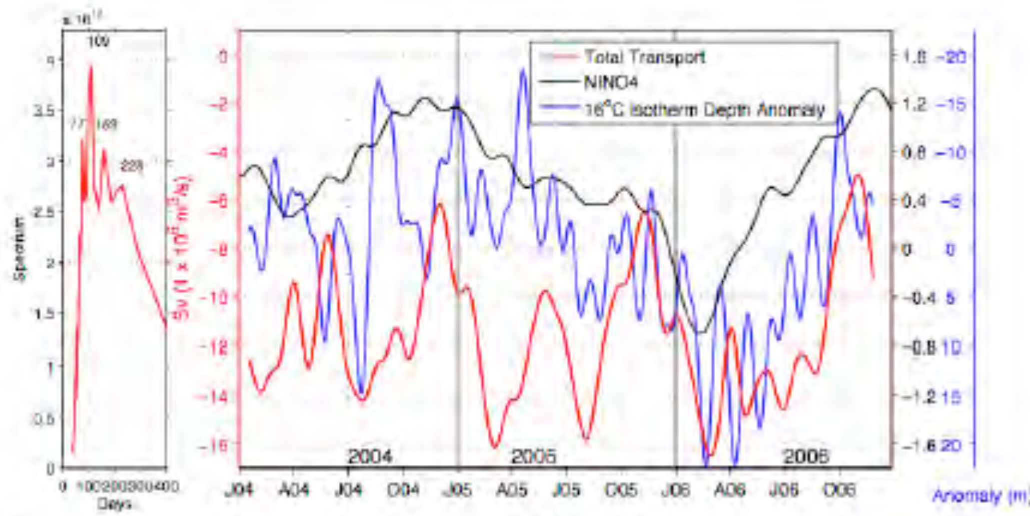

Figure 3. The right panel shows the total Makassar Strait volume transport (Sv, red line, red left axis) and depth anomaly of the 16°C isotherm (m, blue line, blue right-most axis) after a 30-day low pass filter has been applied, as well as the Niño4 time series (area-average SST anomaly within 5°N to 5°S, 160°E to 150°W; black line, inner right black axis). The spectrum (power spectral energy, Sv^2/day) of the total Makassar Strait volume transport is shown in the left panel with the peaks (in days) of the periods labeled.

The objective of the NOAA/OCO program is to extend the INSTANT time series so as to establish a long-term measurement program of the ITF within Makassar Strait. Such an extended time series (decadal scale) is needed to better relate the ITF to such climate fluctuations as those associated with El Niño, the Indian Ocean Dipole and of the Asian monsoon. “Monitoring the Indonesian Throughflow” contributes to the global ocean observational system overseen by the Joint GCOS-GOOS-WCRP Ocean Observations Panel for Climate (OOPC), http://ioc3.unesco.org/oopc/.

2. ACCOMPLISHMENTS

Immediately after the INSTANT moorings were recovered on 22 November 2006, with NOAA OCO support, a single mooring at the site of the INSTANT MAK-

WEST 2°51.11'S; 118°27.33'E was deployed (Figure 4). The NOAA Makassar mooring will be recovered and redeployed in April 2009. A two-year rotation schedule is the plan, with specific dates dependent on ship availability (which explains the slightly longer than 2 year deployment of this 1st rotation).[1]

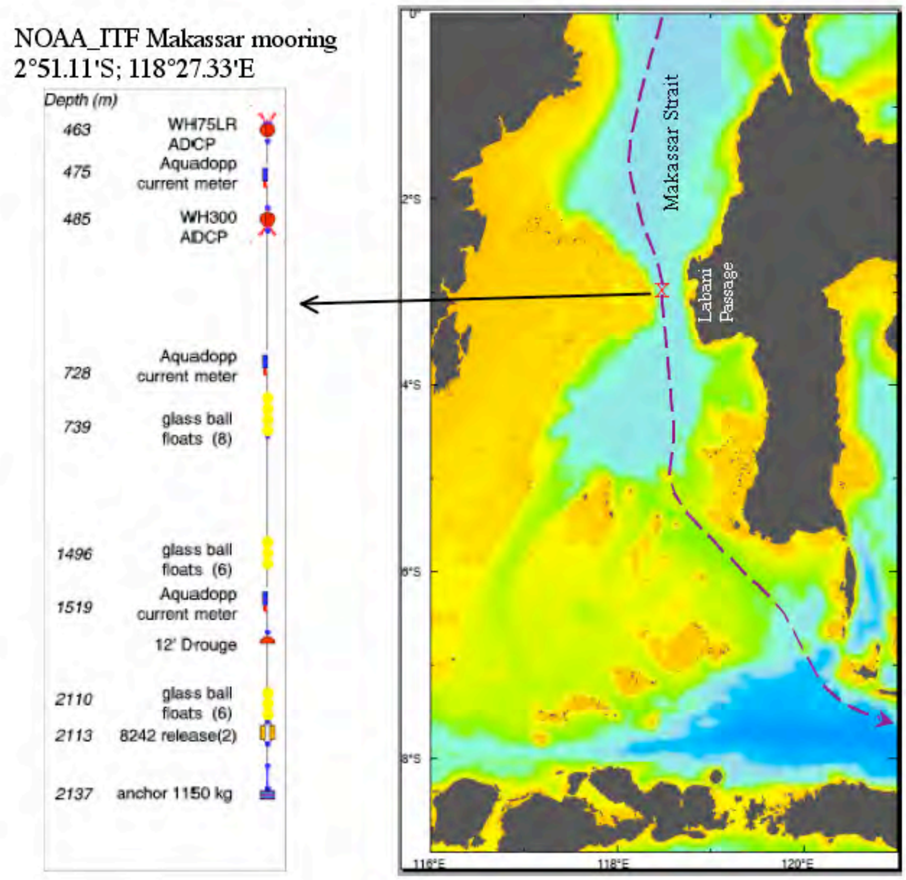

Figure 4. Configuration of the NOAA-ITF Makassar mooring deployed in November 2006 at the Red X in the bathymetry map of Makassar Strait.

During the FY08 period we engaged in discussion concerning the timing of the mooring rotation, which is now scheduled for the April/May period of 2009, at the end of the present FY08 funded increment.

In June 2008 we signed the Implementation Agreement defining the parameters of the cooperative effort between Lamont-Doherty Earth Observatory and Agency for Marine and Fisheries Research (BRKP).

[1] Note added, June 2009: The NOAA funded mooring, deployed on 22 November 2006 at 2°51' S; 118°28' E, was recovered on 31 May 2009, and re-deployed for another 2 years to continue to build the time series. With the 2004-2006 INSTANT program mooring at the same site, we now have a 5.5 year continuous time series of Makassar throughflow.

When we obtain the first products of the NOAA/OCO Makassar ITF mooring the data will be processed and placed on a web site at Lamont, where it will be available for the community. This will be updated within 12 months of every mooring rotation.

Meridional Overturning Variability Experiment

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1. PROJECT SUMMARY

A present gap in the sustained ocean climate observing system are techniques and programs for monitoring the circulation and mass/heat/freshwater transports of major current systems. Depending on the intensity, width, and depth extension of the current to be observed, different approaches and technologies exist now which allow implementation and maintenance of such "transport reference sites". For broad-scale and deep-reaching circulations, a recently demonstrated method consists of fixed-point installations with moored and bottom-mounted instruments to obtain horizontally and vertically integrated measurements throughout the watercolumn. The MOVE project intends to maintain the developed elements of the first such system by taking over partial operation of a moored transport array in the Atlantic.

In the year 2000 the German CLIVAR programme initiated the circulation monitoring array (MOVE) in the subtropical west Atlantic along 16N, in order to observe the transport fluctuations in the North Atlantic Deep Water layer. Since then, three "geostrophic end-point moorings" plus one traditional current meter mooring on the slope have been used to cover the section between the Lesser Antilles (Guadeloupe) and the Midatlantic Ridge. The goal is to determine the transport fluctuations through this section, using dynamic height and bottom pressure differences between the mooring for estimates of the geostrophic transport.

To date, the array has delivered over 90% data return, and due to the built-in redundancy, transports are available for the full 8-year deployment period including the German funded period. The goal of the NOAA project is the continuation of the MOVE transport array in a reduced form (2 endpoint moorings plus current meter mooring on the slope), while complementing it on the eastern side of the Atlantic with a German-funded and operated mooring (near the Cape Verde islands). Numerical simulations by T.Kanzow (Ph.D. dissertation) have shown high skill of such an ocean-wide system for capturing the total meridional NADW transport across the latitude line, and IFM-GEOMAR/Kiel has committed to cooperate by providing the eastern end-point mooring.

With the new MOVE project, SIO will operate the two geostrophic endpoint moorings between the western boundary and the Midatlantic Ridge, plus the small current meter mooring on the slope. In the first years, the acquisitions for complete configuration of the moorings will take place, and the array will gradually be built up to its full implementation. In later years, routine operation will be achieved, and routine delivery of indicators about the state of the thermohaline overturning circulation at this latitude will be enabled.

2. PROGRESS

In the reporting period, the MOVE mooring array was serviced on a research cruise which was originally supposed to take place on the RV "Ron Brown" in May 2008. Due to technical problems with the ship the cruise was cancelled at short notice and alternate ships had to be sought. Fortunately, it was possible to arrange usage of the "Oceanus" departing from Woods Hole on 14 July. All shipments already had been on the way to or arrived in Barbados and needed to be re-routed to Woods Hole. The ship was smaller than needed and could barely take all the equipment and provide the lab space needed for the combined MOVE and NTAS cruises. However, with appreciable effort and compromises everything could be accommodated. Figure 1 shows the cruise track in the work area, with final port in Barbados. Moorings MOVE4, MOVE3, and MOVE1 were recovered successfully and data from the PIES at locations MOVE3, MOVE2, and MOVE1 were retrieved acoustically. The data from the moored instruments are complete (except for one current meter record) and of good quality. The PIES at location MOVE3 was behaving abnormally (probably a transducer arcing problem) and a spare/duplicate one was deployed next to it for safety. Raw data processing has been performed, and scientific data analysis is now possible with the data, some preliminary results are shown below.

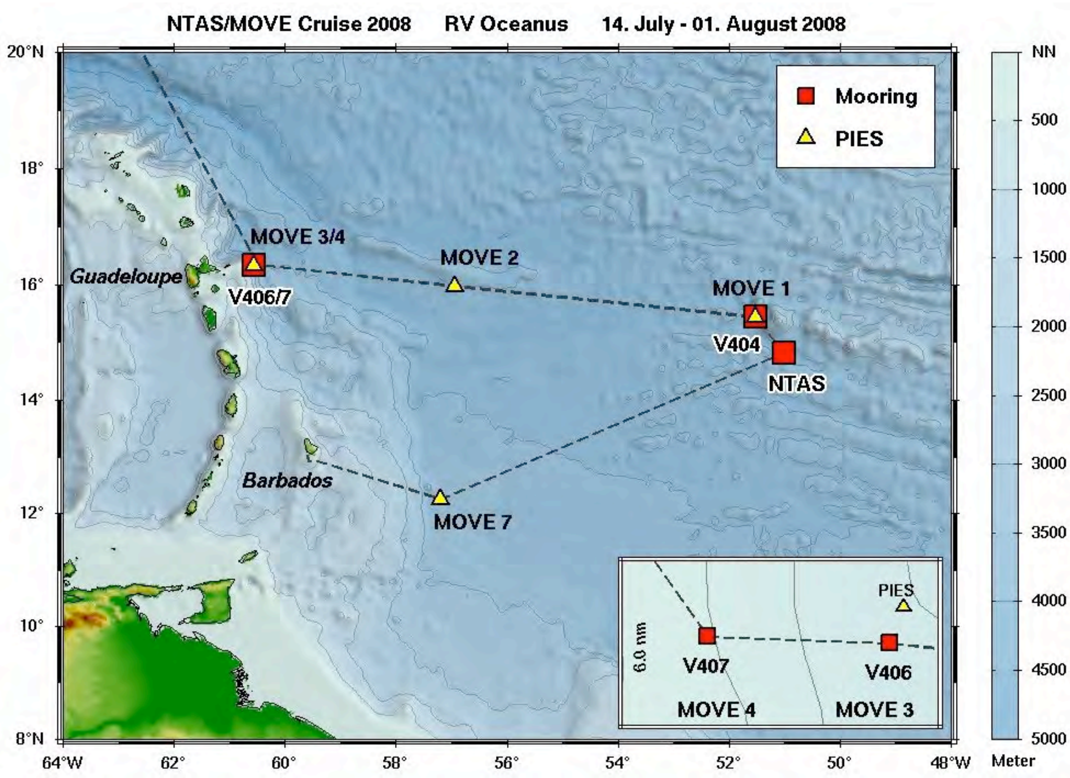

Figure 1. Map of cruise track, moorings MOVE1, MOVE3, MOVE4, and pressure sensors/inverted echosounders (PIES) at locations MOVE1, MOVE2, MOVE3, MOVE7. Shown also is the location of the NTAS mooring which was deployed by Woods Hole Oceanographic Institution.

Much of the raw data processing and calibration was carried out during the cruise. Figure 2 shows an example of processing the time-coded acoustic telemetry data from the PIES, cleaning them up and converting them to bottom pressure anomalies. The RCM current meters which still belonged to IFM-GEOMAR in Kiel/Germany were also processed, one example is shown in Figure 3.

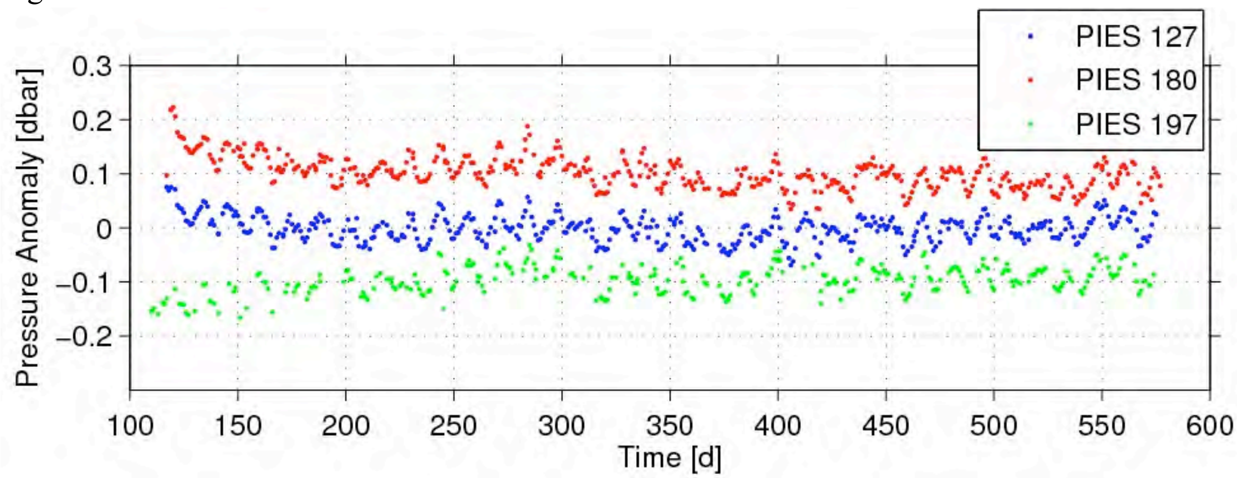

Figure 2. Daily average pressure anomalies from the 3 PIES along the MOVE section, retrieved acoustically and converted to pressure units.

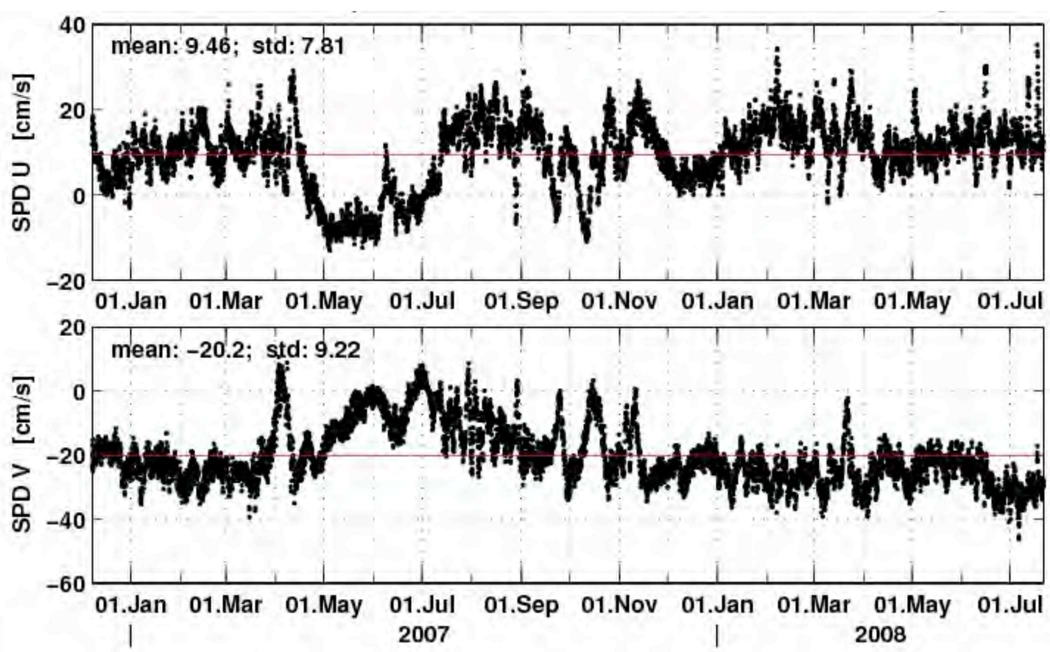

Figure 3. Example of the currents recorded by RCM rotor current meters on moorings M3 and M4. Shown here is the southward flow component in the core of the western boundary current, on mooring M3 at a depth of 2250m. Vertical mooring excursions by up to 400m were observed due to knock-down by strong current.

Extreme care is required for the calibration of the 36 microcat temperature/conductivity sensors, since the accuracy of the density, dynamic height, and geostrophic transport estimates is very sensitive to any offsets in those sensors. All microcats that were recovered (and also those which were going to be deployed) were attached to the CTD rosette and simultaneous vertical profiles were recorded with the CTD system and the attached microcats. In addition, the CTD conductivity probe was calibrated with water samples and high-precision salinometry carried out on board during the cruise. Careful processing of the entire data ensembles then allows calibration of T, C, and S to the required accuracy.

Each mooring was re-deployed within less than 24 hours of recovery, due to the short time at sea available. This was only possible by having enough equipment at hand to deploy at least one complete mooring without “turning around” any recovered instruments. This had required purchases of new microcats. Later during the cruise, instruments from the first recovered moorings could be re-used for new deployments. New acoustic releases had also been purchased since for the previous deployments releases loaned from Germany and other groups at SIO had to be used.

Another new instrument used in the new deployment was the Nortek Aquadopp current meter. This will replace the rotor RCM instruments used until now to capture the near-shore part of the boundary current not covered by the geostrophic estimates between the deep moorings. Seven newly purchased Aquadopps were used, but in parallel with a set of borrowed RCM current meters, since the Aquadopps are still unproven (in our applications) and cross-calibration with the long existing timeseries is desirable.

Apart from the Aquadopp additions, the moorings were re-deployed in a nearly equivalent configuration as in the previous period, but now with purely NOAA funded equipment (except for the co-located RCM current meters). The configuration is still sparser than desirable, so that more instruments will need to be purchased from future funds. The tables below give information about the PIES and moorings deployed and the material contained in them. The mooring designs are shown in Figures 4-6. Note that PIES remain deployed for nominally 4 years.

Table1. PIES Deployments during cruise RB-07-02, April 2007, and OC 449/1, July 2008.

Site	***PIES s/n***	***Position***	***Water Depth***	***Depl. Date***
MOVE 3	197 SIO	16N21.36 60W29.33	4955m	15-Apr-2007
MOVE 3	200 SIO	16N20.29 60N29.31	4900m	22-Jul-2008
MOVE 2	127 IFM	15N59.28 56W56.29	4943m	23-Apr-2007
MOVE 1	180 SIO	15N27.04 51W31.62	4965m	24-Apr-2007
MOVE 7	128 IFM	12N15.47 57W12.07	4454m	17-Apr-2007

Table 2. Mooring Deployments during cruise OC 449/1, July 2008.

Site	***Mooring ID***	***Position***	***Water Depth***	***Depl. Date***
MOVE 4	MOVE4-08	16N20.00 60W36.45	3005m	22-Jul-2008
MOVE 3	MOVE3-08	16N20.30 60W30.30	4960m	22-Jul-2008
MOVE 1	MOVE1-08	15N26.60 51W30.85	4990m	25-Jul-2008

Table 3. Mooring Instrumentation and Equipment.

Site	*Aanderaa RCM*	*Nortek Aquadopp*	*Seabird 37 MicroCat IM*	*Acoustic Release*	*17" Float*
MOVE 4	4	4	-	2	40
MOVE 3	3	3	21	2	67
MOVE 1	-	-	15	2	45

The Aanderaa RCM are loaned by collegues at Ifremer in Brest/France and at IFM Hamburg/Germany.
Each Mooring is equipped with 2 Elkins Titanium Swivel, in total 6 swivel are deployed.
Each Mooring has a Top-Float (Aluminum Frame with 2 Benthos Floats), equipped with an Argos-Beacon, a VHF-Radio-Transmitter and a Xenon-Flasher.

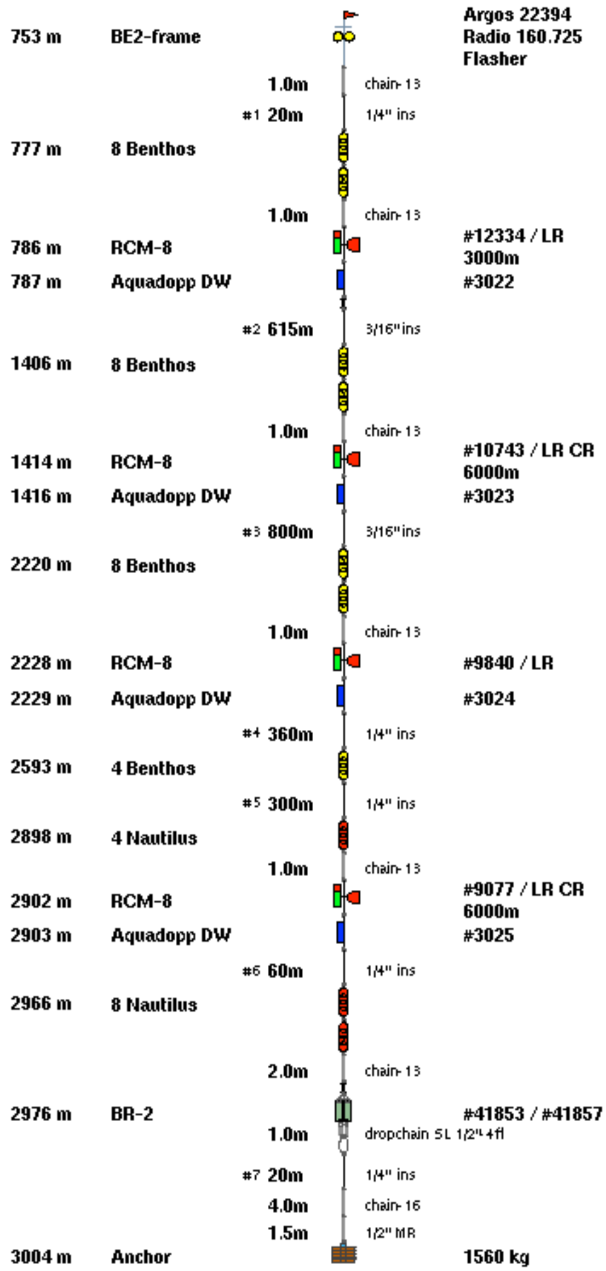

Figure 4. Design of mooring MOVE4 with each instrument and its depth noted.

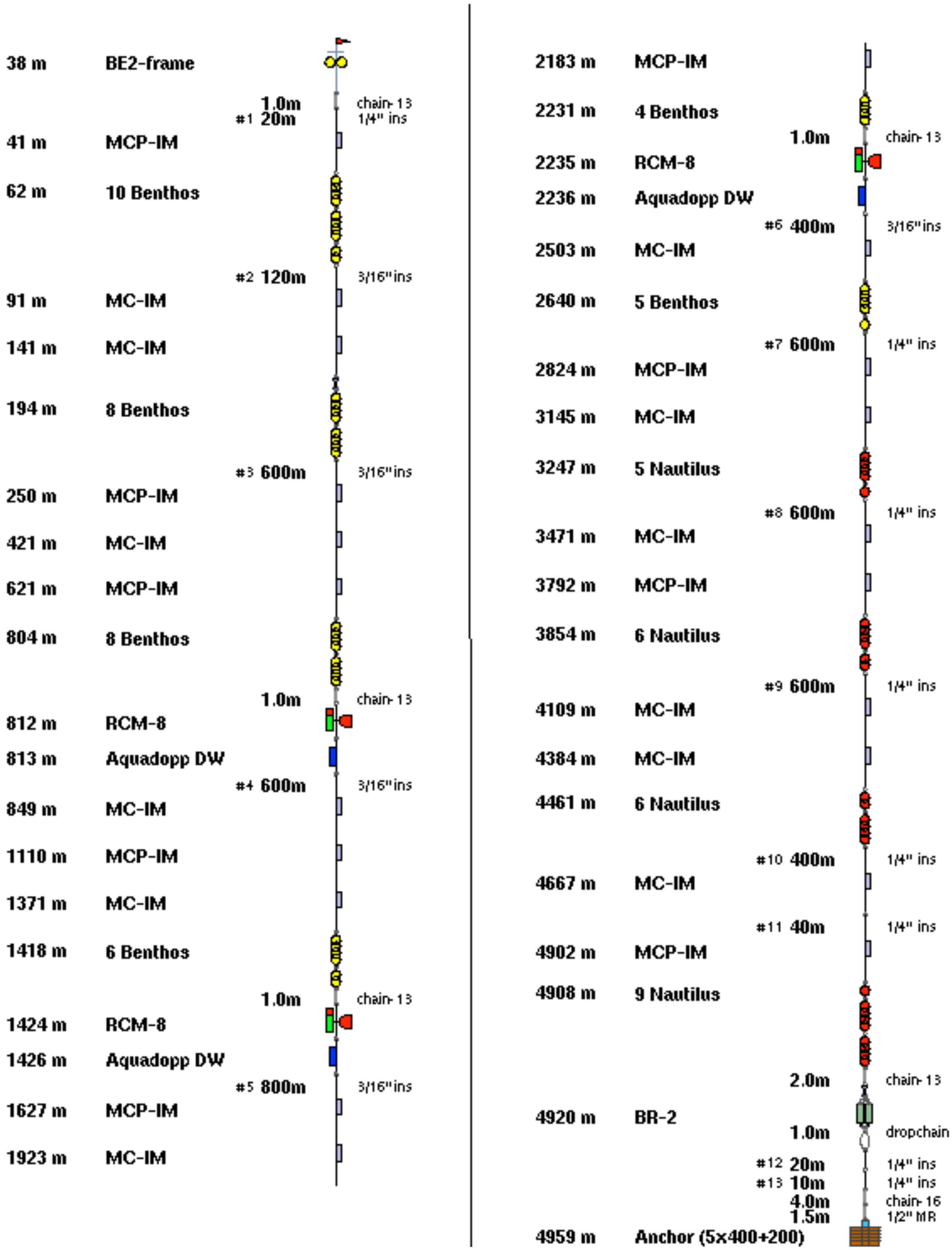

Figure 5. Design of mooring MOVE3 with each instrument and its depth noted.

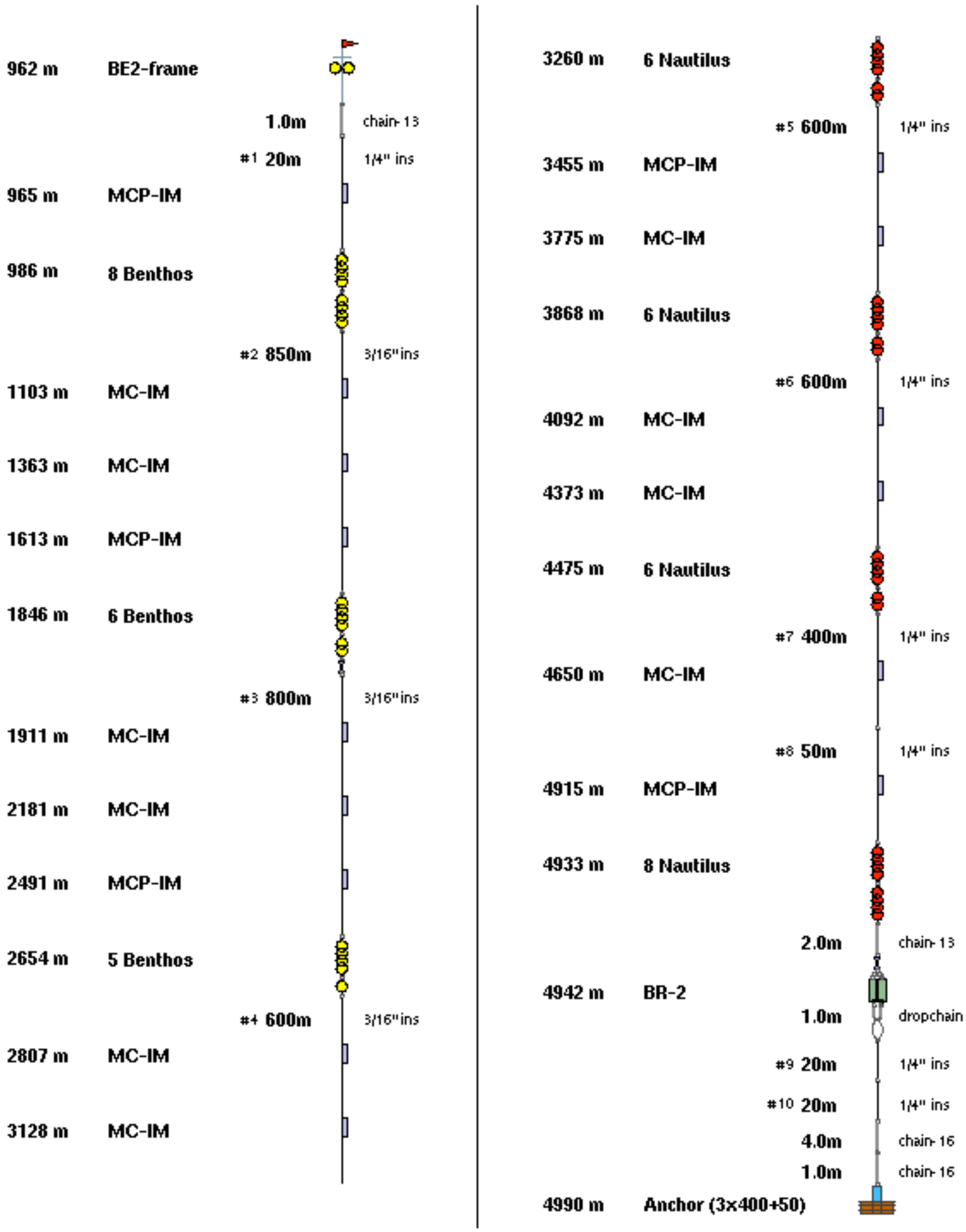

Figure 6. Design of mooring MOVE1 with each instrument and its depth noted.

After the cruise, work concentrated on analyzing the data in order to obtain useful and reliable estimates of the various transport components in the deep southward return flow of the meridional overturning circulation (MOC), i.e. the transport in the NADW (North Atlantic Deep Water). Since we now had an unprecedented 8-year timeseries at hand, a special effort was made to prepare a complete record of data for the annual NOAA system review meeting in Silver Spring.

One component of the transport is the part shoreward of the geostrophic section spanned by the deep moorings M1 and M3. This component is captured with the current meters on moorings M3 and M4. Since there are some gaps, and in the last deployment much fewer current meters were available (all needed to be borrowed) than previously, statistical estimates were constructed for the more sparse phases, based on the long timeseries with the full array. It was found that the error was acceptably small, and an 8-year timeseries of this “boundary transport” could be calculated. It is shown in Figure 7.

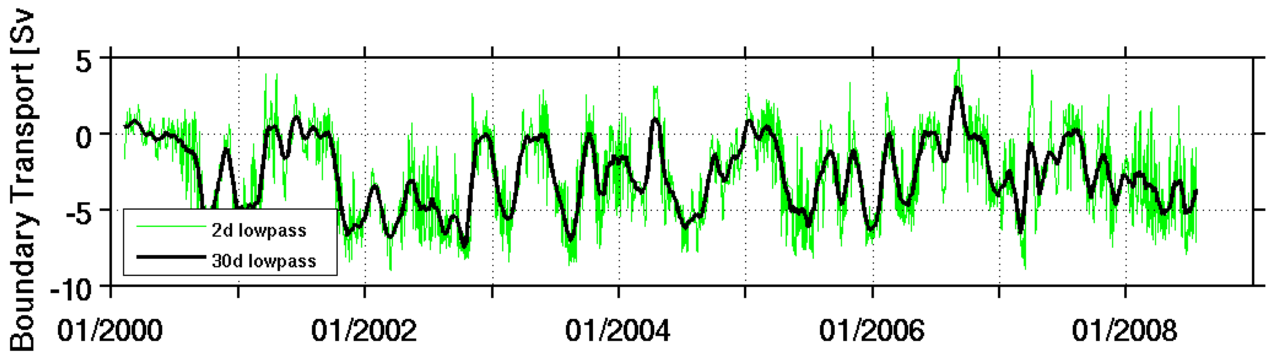

Figure 7. Transport (in Sv) of the boundary component of the NADW flow, i.e. the part between the continental shelf and mooring M3, estimated from the current meters in the moorings.

Another component is the “internal” transport calculated from the geostrophic pressure differences between moorings M1 and M3, derived from the density profiles at each mooring (from the T/S timeseries recorded by the microcats). This gives a transport relative to a pressure level, in our case initially 5000db. The excellent data set at hand now also allows an 8-year computation of this component, shown in Figure 8.

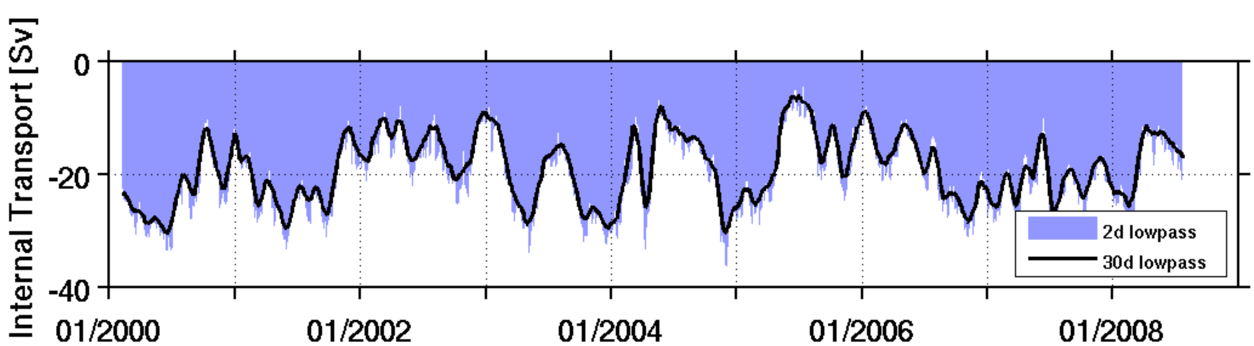

Figure 8. Transport (in Sv) of the internal (dynamic height derived) geostrophic transport of the NADW between moorings M1 and M3.

The third component of the flow is more problematic, since we rely on bottom pressure measurements that are not absolute, and thus for each deployment cycle the mean needs to be removed. As a result, long-term multi-annual variability cannot be determined at present (we will address this in the future with longer overlapping deployment of PIES). In addition, the failure of the PIES during 2006-2007 (reported manufacturer-related battery problem) resulted in a 2-year gap in the bottom pressure data. The available timeseries of transport fluctuations resulting from this "external transport" is shown in Figure 9.

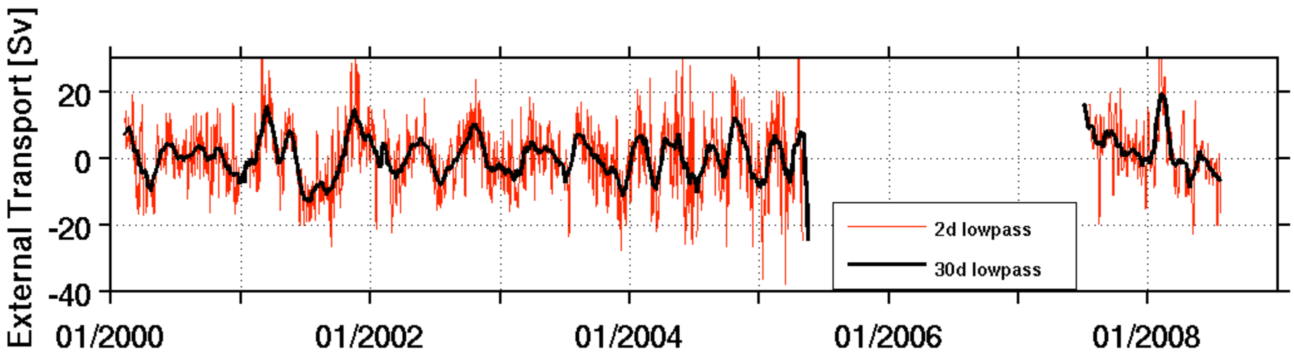

Figure 9. Transport (in Sv) of the "external" (bottom-pressure derived) component of the NADW flow, between moorings M1 and M3.

In order to obtain absolute transports, it was assumed that the long-term flow at the interface between the AAIW and the NADW is zero, since those water masses spread in opposite directions. This assumption had been shown to be valid in the initial phases of MOVE where 10 moorings with current meters were available from the joint deployment together with the GAGE project (M.McCartney). If this reference level is chosen to make the internal transports absolute, and the boundary transport is added, our current best estimate for the total absolute NADW transport over 8 years results, and is shown in Figure 10.

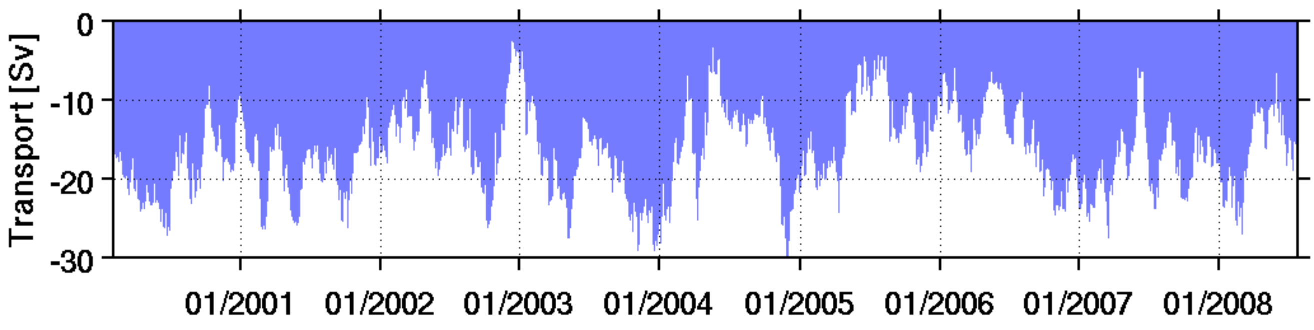

Figure 10. Absolute internal plus boundary transport through the MOVE section. The long-term mean is -14.9Sv (southward).

Careful trend analyses have been performed on the timeseries in Figure 10, and it appears that there is a significant decreasing transport intensity present with 80% certainty. However, there are still poorly understood sensitivities to the reference level chosen to make the internal transports absolute, and this a topic of ongoing work.

Integrated Boundary Current Observations in the Global Climate System

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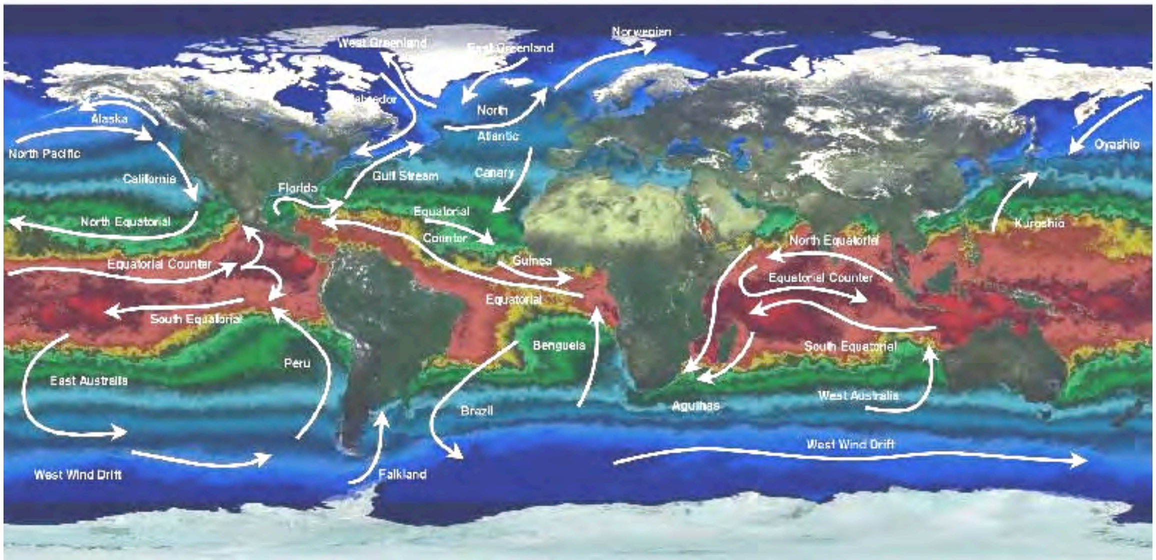
1. Project Summary



The current national and international ocean observing system for climate consists of several components, none of which are designed for capturing intense, concentrated, or deep circulation systems. Therefore, additional approaches and infrastructure are needed for observing western and eastern boundary currents, throughflows/overflows, and deep circulation regimes.

The goal of the current CORC project is to develop, demonstrate, and implement a system that can fully monitor the intensity (mass and heat transports) of most boundary currents in a sustained and routine mode, delivering indicators about the state of those regimes in near-realtime. To this end we will merge several technologies and techniques that have been used by the P.I.'s in the past, and that were partly developed in prior CORC phases. These include:

- *end-point moorings* (with CTD sensors throughout the water column and bottom pressure sensors) at the ends of a section to determine the dynamic height difference, and thus geostrophic transports, as a time series.
- *underwater gliders* to estimate the heat transport through a section, by providing the horizontal (and vertical) distribution of heat content and its correlation with the flow.
- *inverted echosounders plus bottom pressure (PIES)* distributed along the section to be monitored. These will yield 2 vertical integrals (e.g. dynamic height and heat content) at each location, providing the depth (and time) coverage along the section that the gliders can not.
- *data telemetry* for the PIES and (subsurface) moorings using acoustic modems between these and the gliders. In very high (surface intensified) current regions, the gliders may need to remain submerged on one of the round-trip crossings each time. In this case, a navigation capability will be needed in the gliders to pass within close enough proximity of the PIES and moorings.

- *data assimilation* for determining heat and flow distributions, and thus the full mass and heat transports, that are consistent with all the data types collected, with satellite altimetry, with the forcing fields (wind) and with up/downstream and offshore information.

The pilot and testbed application is being carried out in the California Current which has large climate and socio-economic relevance and does not have a routine monitoring system. Operation along CalCOFI line 90 in southern California assures synergy with other programs, and coincides approximately with the high resolution XBT line PX31 which are contributing comparison data and connect sampling to the basin interior. In addition automated surface drifter releases will quantify the eddy variability and the Ekman flow in the boundary current region.

Later in the project, implemention of the system in the climatically highly relevant western boundary current of the low-latitude western Pacific is planned (which feeds the Equatorial Undercurrent through the Solomon Sea). This is already partially under way with regular glider deployments there.

2. PROGRESS REPORT

2.1. Glider Measurements in the South Pacific

Goal: There is a relatively direct oceanic connection between the subtropical South Pacific and the equatorial zone where air-sea interaction is strong. This connection is potentially important to coupled climate variability on interannual and, even more, on decadal time scales. The goal of this task is to exploit underwater gliders to gather preliminary observations and time series of this subtropical-equatorial connection.

Role in CORC: As the result of a sustained improvement effort within CORC over the last 5 years, the underwater glider Spray is relatively mature and economical to operate and achieves a relatively high success rate. Consequently, gliders are potentially a useful in CORC's overall objective to develop and exploit methods for monitoring climatically important characteristics of boundary currents. Consequently, South Pacific gliders are being used to: (a) test their stand-alone capabilities in boundary current monitoring, (b) to begin a time series of transport the climatically significant oceanic transport, and (c) to survey potential sites for eventually using the full CORC system to observe this current.

Progress:
There are two basic mechanisms by which conditions in the subtropical ocean might impact sea-surface temperature along the equator where air-sea coupling is strong and, consequently, might impact global atmospheric climate. While these mechanisms are potentially active in the ENSO cycle, the case for them playing a central role in decadal climate variability is even stronger. In one mechanism proposed by Gu and Philander,[1] air-sea interaction in the subtropics can change the temperature and/or salinity properties of subtropical surface waters. These anomalies then subduct in the shallow overturning cell and flow below the surface back to the equator where they upwell

[1] Gu, D., and S.G.H. Philander, 1997. Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics. *Science*, **275**, 805-807.

and produce anomalous air-sea fluxes. McPhadden and Zhang[2] have suggested that a more direct and faster mechanism may be variability of the transport of the subtropical cell that, by modulating advective supply of water to the equator, also affects the properties of water upwelled on the equator.

In the South Pacific, as depicted in Figure1, the South Equatorial Current (SEC) carries water into the Coral Sea and directly past New Guinea in the Solomon Sea. Some of the flow into the Coral Sea turns eastward south of New Guinea and then enters the Solomon Sea. Our initial studies, in cooperation with W. Kessler (PMEL) and the IRD laboratory in Noumea, New Caledonia, began with a pair of glider cruises across the SEC between New Caledonia and Guadalcanal, Solomon Islands, roughly along 160^{o}E. Results reported by Gourdeau et al[3] include the zonation of the SEC into jets.

Although logistically more difficult, a more direct measure of the subtropical-equatorial connection is the flow from the SEC through the Solomon Sea toward the equator. The western boundary current (New Guinea Coastal Undercurrent, NGCUC) in the Solomon Sea links the SEC to the equatorial zone with an equatorward flow of water at densities near that of the equatorial undercurrent that upwells on the equator. In 2007 CORC began an exploration of transport through the Solomon Sea using underwater gliders. The goals are to find a suitable section through which to measure the equatorward transport and to begin a time series of these transports. Figure 2 shows the glider cruises completed in 2007 and 2008.

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[2] McPhadden, M.J., and D. Zhang, 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature*, **415**, 603-608.

[3] Gourdeau, L., W.S. Kessler, R.E. Davis, J. Sherman, C. Maes and E. Kestenare, 2008. Zonal jets entering the Coral Sea. *J. Phys. Oceanogr.* **38**, 715-725.

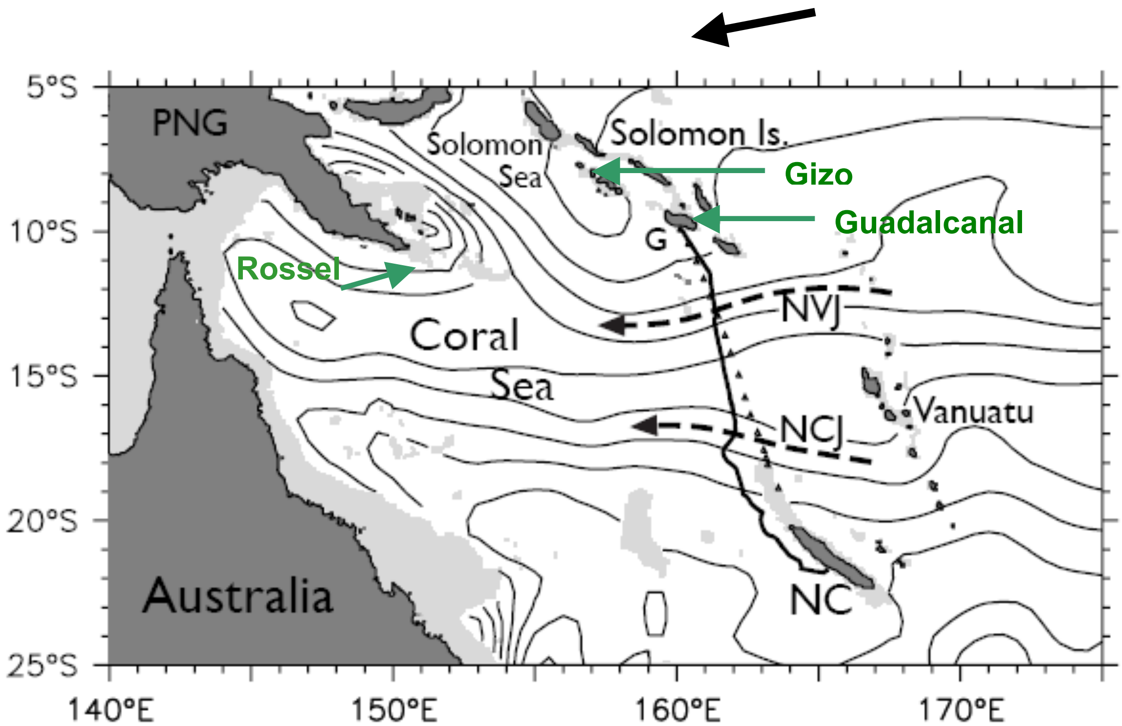


Figure 1. Flow from subtropical South Pacific toward the equator. NCJ and NVJ denote jets in the SEC. Solid line from New Caledonia (NC) and Guadalcanal is track of Spray glider. Green labels are termini of ongoing glider sections in the Solomon Sea.

Figure 2 shows substantial cruise-to-cruise variability both in the basin interior and in the western boundary current. The most unusual circulation was seen in the February-July 2008 cruise during a La Niña. In rough agreement with the Sverdrup transport of the anomalous winds, the South Equatorial Current and the flow into the Solomon Sea were weak. This made glider progress so slow that we barely completed the cruise before power was exhausted.

Transports from 2007-08 are plotted in Figure 3. Transport is the double integral with depth and distance along the measured section of the velocity normal to the section toward the equator.

The *x* integral begins at Rossel Island (the easternmost of the New Guinea archipelago) and ends at the Solomon Islands. Transits in both directions are included. Transport is computed from measured depth-average velocity typically spanning the upper 600 m. Interpretation of Figure 3 requires care because the sections are far from straight (currents are frequently too strong to maintain a track) so the distances to the same point along two sections are quite different.

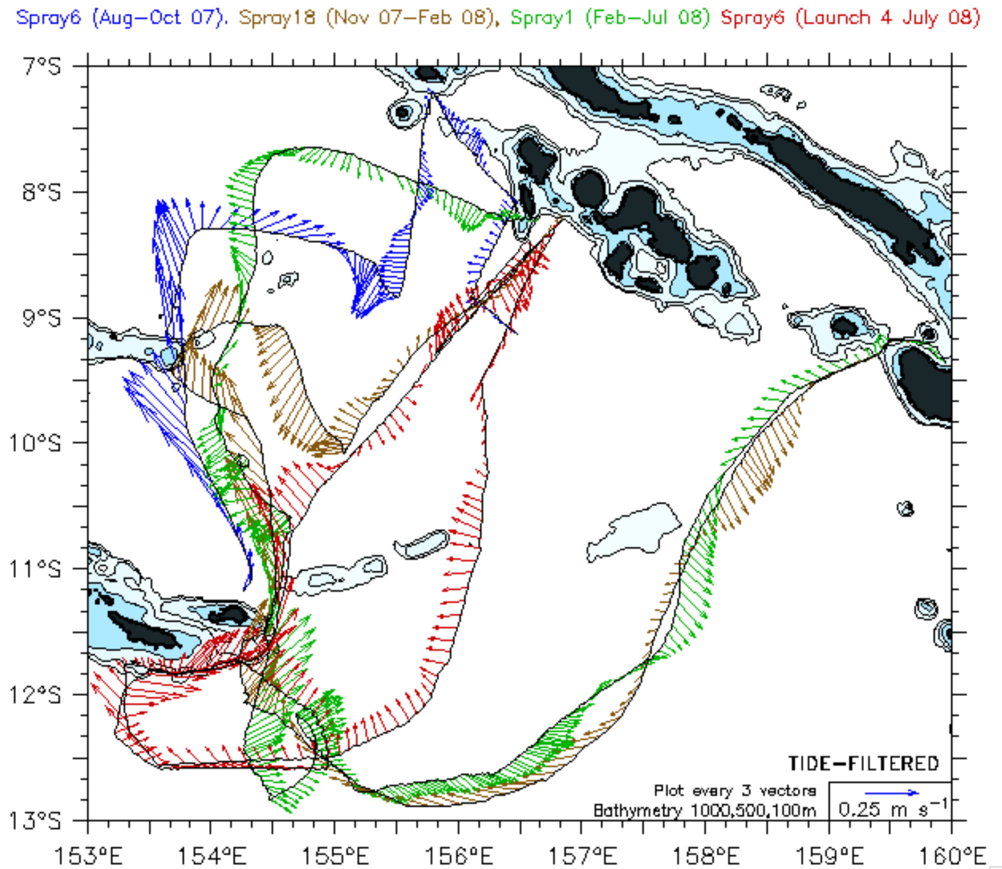


Figure 2. The four Solomon Sea glider cruises completed in 2007 and 2008 (figure by W. Kessler, PMEL). The first cruise (blue) was deployed at Rossel Island and effectively ended at Gizo. Cruises 2 and 3 are from Gualdalcanal to Rossel to Gizo. Cruise 4 (and cruise 5 not shown) were Gizo-Rossel-Gizo. Arrows show the depth-averaged velocity between the surface and 600 m depth. Currents on cruise 3 (green) during La Nina had anomalously low equatorward transport. The top legend gives each cruise's time period.

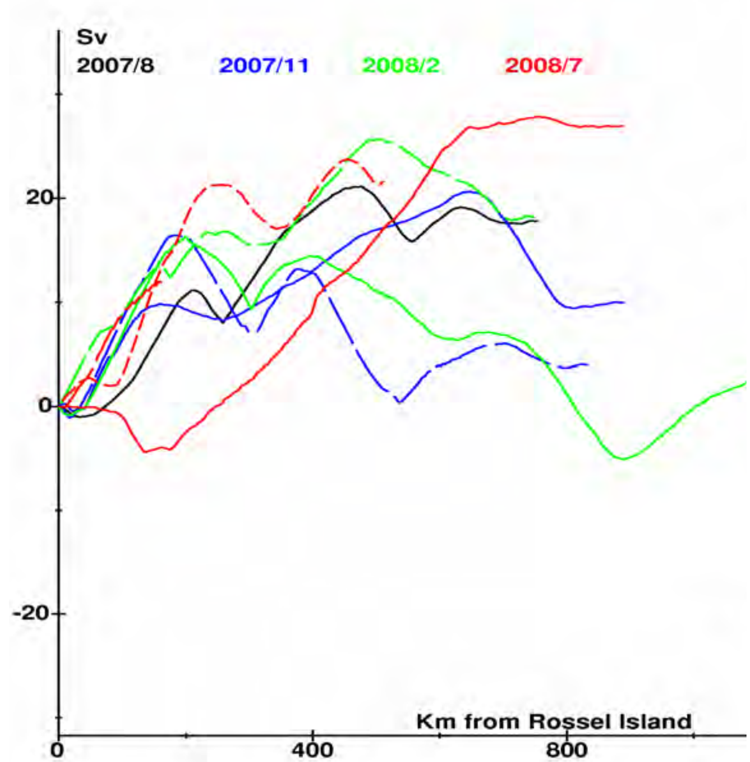


Figure 3. Volume transport Q(X) (in Sverdrups) integrated from the Rossel Island on the western boundary. Transport is based on measured depth-average velocity to ~600 m. The value for the largest distance plotted is the net equatorward transport above 600 m. Colors refer to cruises begun on the year/month given at the figure top. The dashed blue and solid green curves are from June-July 2008 during La Nina conditions. The largest transport variations appear to be in the ocean interior rather than the western boundary current.

The results in Figure 3 show that the transport associated with the strong western boundary current (NGCUC) is reasonably constant between the different sections but interior transport varies markedly. The largest change is between June-July 2008, when the net equatorward transport above 600 m essentially vanished, and August-September 2008, when there was strong northward transport (the figure misrepresents the distance of the flow from the western boundary because the glider was southwest of Rossel Island for the 150 km before reaching the western boundary). Because we have observed only one year and do not know the seasonal cycle of the Solomon Sea, it is dangerous to ascribe causes but the period of minimal transport was a period of La Nina conditions in the western tropical Pacific.

2.2. Glider Measurements in the California Current

Goal: The California Current System (CCS) was chosen as the operational site for developing our suite of techniques for monitoring boundary currents for because it is logistically convenient and because there is known to be significant climate variability of the CCS, which has at least strong statistical connections to the ecosystems and fisheries production. The goals of glider operations in the CCS are threefold: (a) provide a platform for acoustic transponders to report results from subsurface instrumentation, (b) provide continuous time series of offshore sections of velocity, temperature, salinity, chlorophyll fluorescence as a proxy for phytoplankton abundance, and acoustic backscatter as a proxy for zooplankton abundance along the section defining our testbed (CalCOFI Line 90), and (c) in order to explore alongshore coherence of fluctuations of the CCS, maintain a similar continuous time series on CalCOFI Line 67 off of Monterey CA.

Role in CORC: In addition to the intrinsic interest in the related variability of physical and biological conditions within the CCS, gliders are integral to CORC in three ways: (a) they carry acoustic transponders to report results from subsurface instruments (surface mooring are impossible in many strong boundary currents), (b) they provide spatially extensive reference observations to interpret the point observations from moorings along Line 90, and (c) they provide some alongshore sampling to understand which climate variations in the ocean are connected between Southern and Central California, supplementing the spatial information that comes from VOS sections, altimetry, surface drifters, and CalCOFI sampling, all of which will help constrain the CORC data assimilating model of the CCS.

Progress:
Figure 4 shows the network of CalCOFI Lines. Gliders have been operated under CORC on Lines 90 or 93 since April 2005. Biological sensors were added in October 2006 when sampling on Line 80 was begun under separate funding. Sampling on Line 67 began in April 2007 and became continuous in April 2008.

Two types of Spray gliders are operated in the California Current System (CCS). ADP-Sprays are fitted with Seabird CTDs, 750 kHz Acoustic Doppler Profilers (ADP) that are calibrated for backscatter, and Seapoint Chlorophyll Fluorometers, also regularly calibrated with chlorophyll-a solutions. This sensor suite observes (1) absolute velocity profiles by combining vehicle set and drift with the ADP velocity shear, and through geostrophic calculations, (2) chlorophyll fluorescence, which serves as an indicator of the lowest trophic level affected directly by physical forcing, and (3) acoustic backscatter, which serves as an indicator of zooplankton and forage-fish that prey on phytoplankton and are prey for commercially valuable fish. Under other funding, a nitrate sensor is being installed on gliders to better observe the bottom-up physical forcing of phytoplankton through availability of nutrients. In Transponder-Sprays the ADP is replaced by a Benthos acoustic modem matched to transponders on moorings and PIEs.

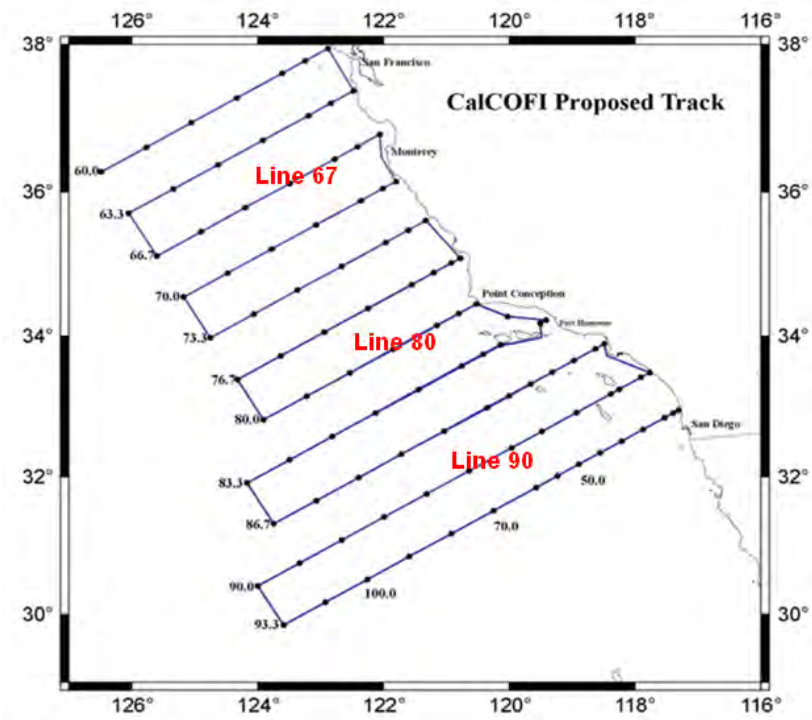


Figure 4. The full CalCOFI survey grid. CORC gliders continuously observe the length of Lines 67 and 90 while Line 80 is continuously observed under separate funding. Spray gliders sample T, S, absolute velocity, acoustic backscatter, and chlorophyll fluorescence.

A preliminary analysis of data on CalCOFI Lines 80, 90 and 93 appeared in *Limnology and Oceanography*[4]. The length of the record available when this analysis was completed was insufficient to clearly define even an annual signal but some aspects of the flow were clear. First, the California Undercurrent is frequently the big signal over the first 100 km from shore and its seasonality is more complex than a simple appearance of the Davidson Current in winter. Second, poleward flow is typical of the entire CCS below 250 m. Third, the eddies in the CCS are frequently powerful (0 to 500-m average velocities of 30 cm/s), sometimes remain trapped in a location for many months, and are a major organizing feature for the phytoplankton and zooplankton. Statistical descriptions of some of these features are shown in Figures 5 and 6.

Although the depth average flow in is still affected by eddy variability, the nearshore Undercurrent and a second, weaker poleward flow is evident near 120^0W on Line 90 and near 122^0W on Line 80. These flows are nearly undetectable in relative geostrophic flow referenced to 500 m, explaining why the extent of poleward flow has been underestimated in earlier work based on hydrography.

Figure 6 is an offshore section of mean velocity computed from geostrophic shear referenced by the depth-average velocity measured directly from the set and drift of the glider. This shows that both the poleward flows seen in depth average flow (Figure 5) are manifestations of largely subsurface undercurrents.

[4] Davis, R.E., M.O. Ohman, B. Hodges, D.L. Rudnick, J.T. Sherman, 2008. Glider surveillance of physics and biology in the southern California Current. *Limnol. Oceanogr.* **53**, 2151-2168.

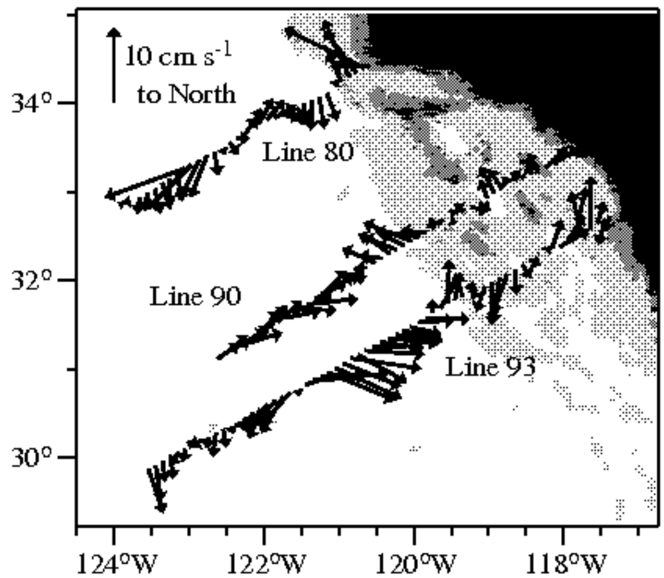


Figure 5. Annual average of the depth-average velocity from the surface to 500 m depth from about 3 years of glider data.

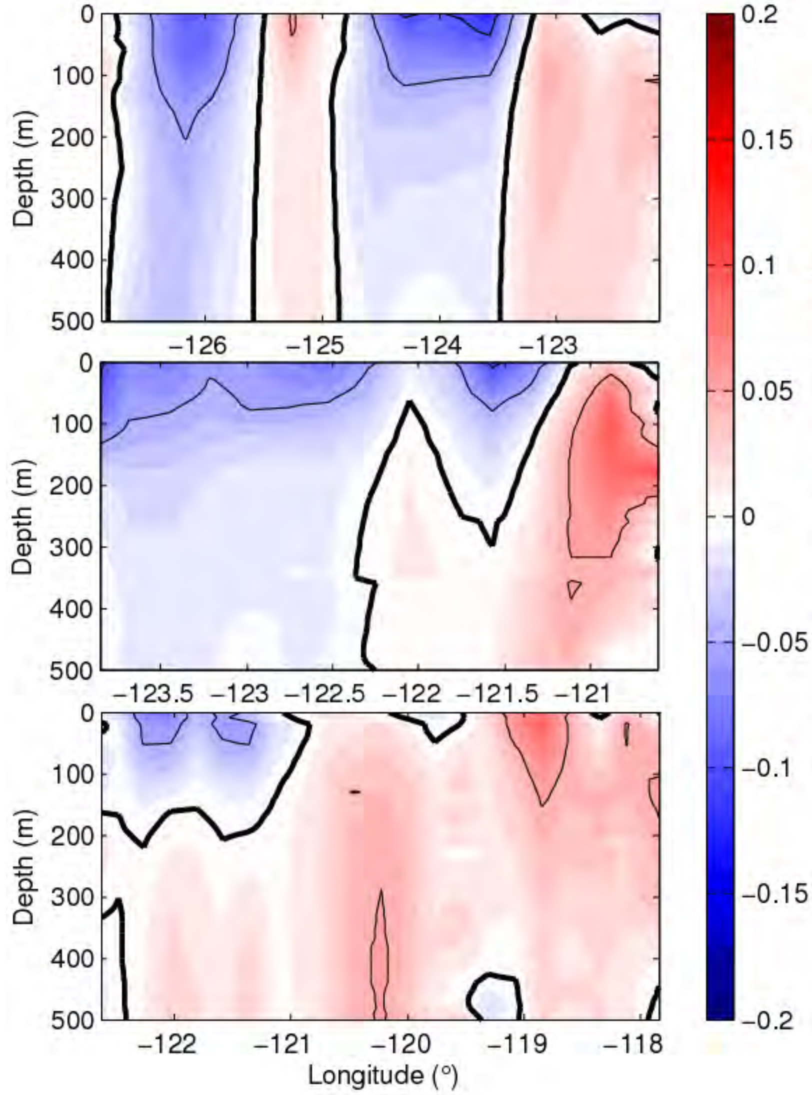


Figure 6. Sections along Lines 66 (top), 80 (middle) and 93 (bottom) of mean poleward flow (cm/s) based on geostrophic shear referenced by measured depth-averaged flow (in m/s). The California Current is the shallow fresh equatorward flow largely above 200 m that is apparently split into two branches. Near the continental slope, the depth-intensified poleward flow at all depths is the California Undercurrent of warm, salty water. Offshore there is a second poleward flow that had previously only been hinted at in hydrographic data. Neither poleward flow is clear in the geostrophic shear.

Figures 7 and 8 show the variability of the depth-averaged flow between glider transects, as well as the distribution of time-depth averaged flow and the cumulative transports, at each of the three locations.

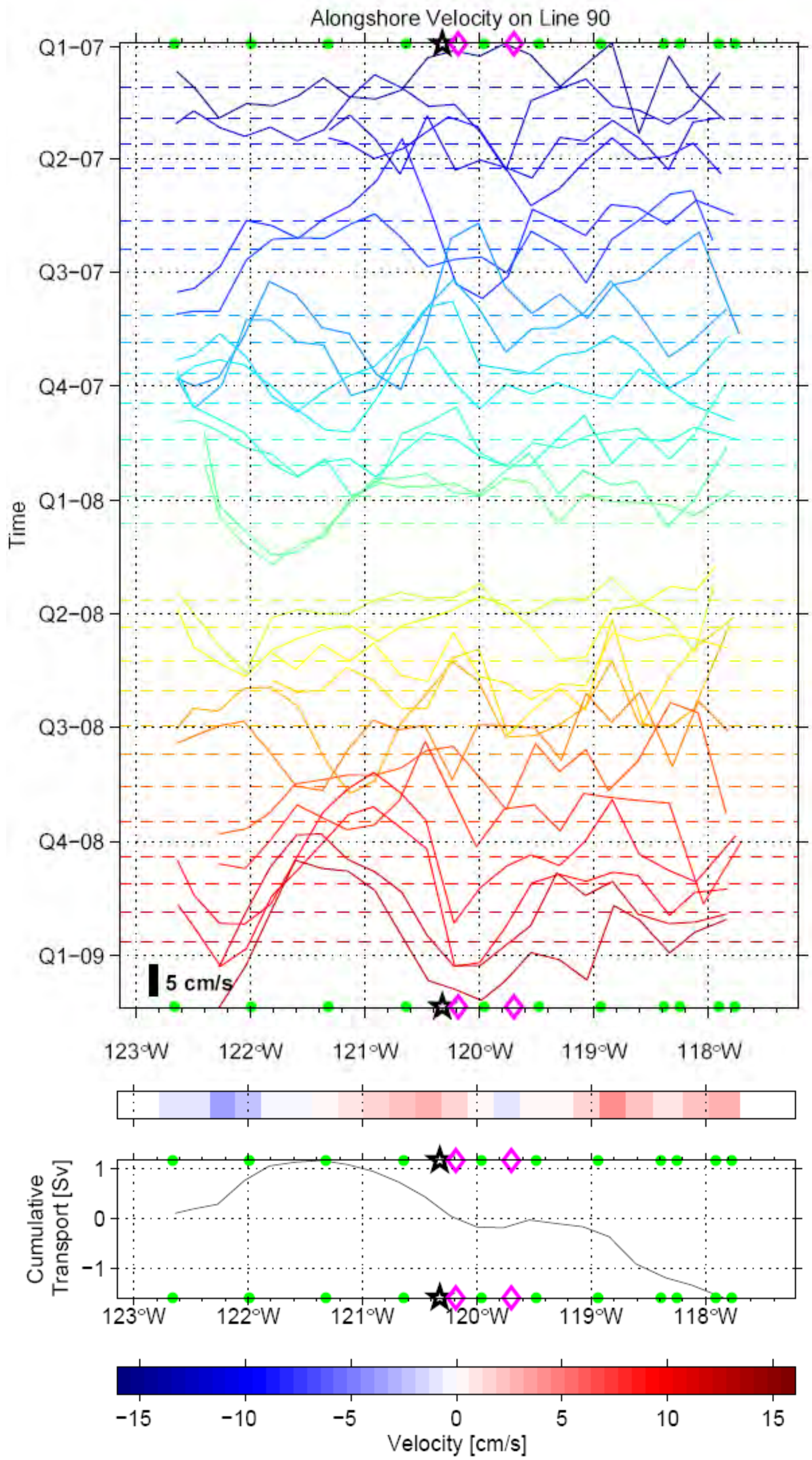


Figure 7. Top panel shows depth averaged flow along each glider transect on line 90. The pink diamonds mark the 1000m and 3000m isobath location, the black star is the inner CORC-1 mooring. The color strip in the middle gives the distribution of the time-mean depth-averaged flow across the section.The bottom panel is the cumulative transport set to zero at the 3000m isobath. All currents are taken over upper 500m.

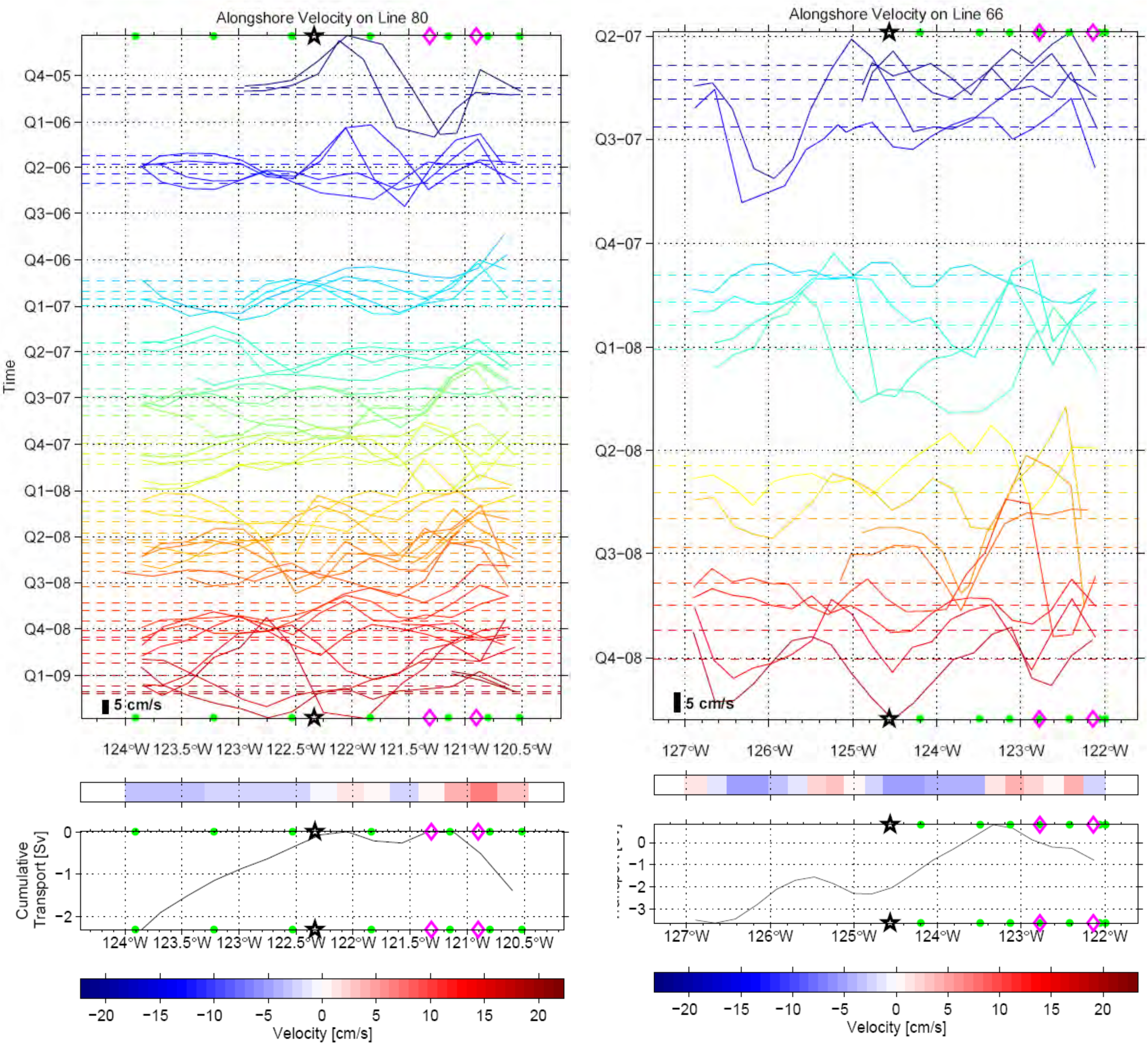


Figure 8. Same as Figure 7 but for CalCOFI line 80 (left) and line 66 (right).

The depth-averaged velocity sections in Figures 7 and 8 often show large changes in the flow distribution from one transect to another, highlighting the fast timescales in the boundary current regime. After averaging all the available transects, a patterns emerges, which is equal to the depth integral of Figure 6. As expected, the main undercurrent cores are located against the continental slopes (3000m-1000m isobaths), but there are indications of more offshore flow cores. The cumulative transport shows that on lines 90 and 80 the gliders miss much of the more offshore southward flow of the California Current, which should be typically 4 Sv or more. At line 66 it seems that the glider section captures more of the main equatorward California Current. More discussion on the offshore extent of the California Current and its sampling will be found in later sections.

2.3. Technological developments for acoustic data retrieval

Goal: High temporal resolution and deep water column coverage is being pursued with endpoint moorings and bottom-mounted PIES (pressure+inverted echsounders). For the PIES, an attractive data link to the surface is acoustic, and for moorings this is also the case for subsurface moorings (which are more economical and less prone to damage or vandalism). A communication capability between gliders and PIES and subsurface moorings is being developed via underwater acoustic modems.

Role in CORC: The goal of CORC is to deliver data from the integrated boundary current observing system in near-realtime, i.e. every 1-2 weeks, for direct analyses and for feeding data into the assimilation system. Therefore the gliders on the main CORC section are expected to ultimately be equipped with modems to telemeter (relay) the PIES and mooring data to shore during each transect.

Progress:
In year 1 of the project (summer'06-summer'07) the available modem options were researched and the Teledyne Benthos ATM-885 model was chosen, several of them were purchased, with and without pressure case (OEM version), for attachment to the PIES and to the moorings, and also for incorporation into a glider.

A hierarchy of modifications of the PIES instrument was designed and agreed on with the manufacturer (Univ. of Rhode Island, URI), for attaching and later incorporating the acoustic modems to/into the PIES. This requires diverting some of the internal data streams to an extra line/port going to the acoustic modem, which was also implemented with the manufacturer. The present configuration of the modified PIES with an external modem attached, is shown in the foto in Figure 9.

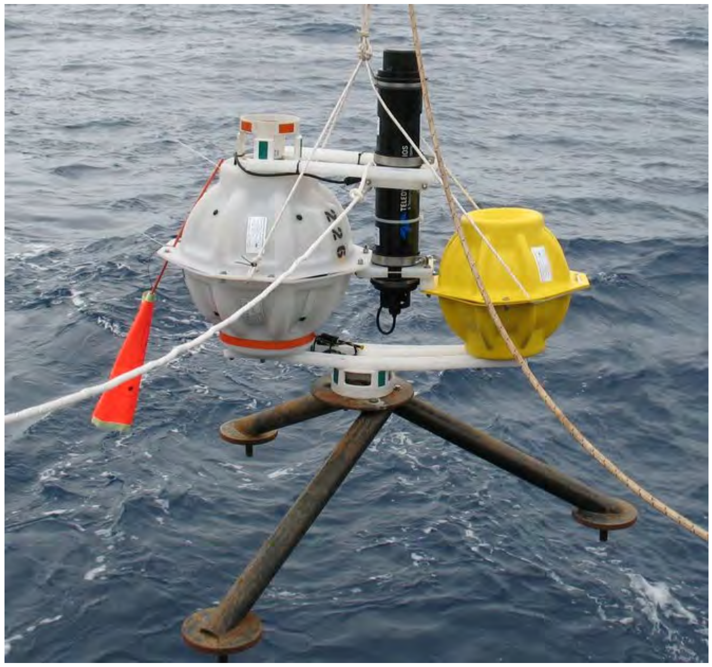


Figure 9. Assembly of the modified PIES (white sphere) with an external modem (black cylinder), mounted onto a stable bottom tripod (together with extra buoyancy, yellow sphere). Foto from them main CORC deployments in September'09.

At the same time, a new controller was designed and built for incorporation into the subsurface moorings. This controller was to collect data from all T/S sensors (microcats) along the entire mooring length via inductive telemetry through the mooring wire, and then pass the data to an external acoustic modem for telemetry to the gliders. The block diagram for this controller set-up is shown in Figure 10.

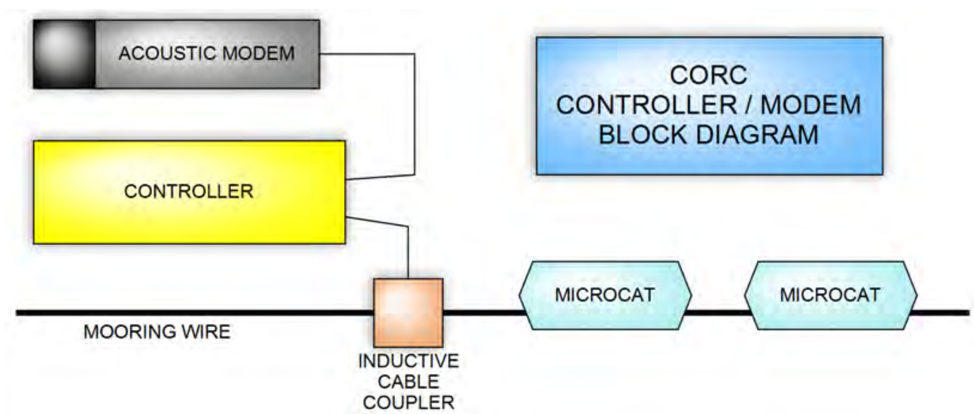


Figure 10. Schematic design of the mooring controller built in year 1.

At the same time, the OEM version of the acoustic modem was incorporated into the glider. The electronics boards were distributed over the available internal space, and the transducer incorporated into the tail section, looking downward, as shown in Figure 11. The glider software was modified to communicate with the modem, and telemeter the modem data back to shore. In addition a long suite of lab/bench/pool tests were carried out to make the different modems (glider, PIES, mooring controller) communicate with each other.

Figure 11. Transducer of acoustic modem incorporated into tail section of the Spray glider.

In year 2 (summer’07-summer’08), in-water field testing was initiated. First a test PIES with a modem assembly was deployed in 900m of water depth 13nm off San Diego, later a test mooring with a controller and two microcats was set next to the PIES. This then allowed a hierarchy of tests to be performed, for communicating with the PIES and mooring from small ships and with the new prototype modem glider. In this period, five opportunities were used to gather experience with the deployed modems.

At the beginning of year 3, in September’08, the first CORC array was deployed across the California Current (see the subsequent section 4), and for this 2 new mooring controllers were built and equipped with modems, and 5 new PIES had the modems added to them. The total of used modems in CORC thus increased to 10, plus several in the lab for development and testing. The glider deployments around the test sites off San Diego were not convincing enough at the beginning of year 3, thus further modifications and test deployments took place. Between fall’08 and the writing of this report, more software upgrades were performed, the test PIES was recovered and redeployed with a latest generation modem, and the modem transducer in the glider was moved to behind the tail fin to be freely exposed to the surrounding water, see Figure 12.

Figure 12. Reconfigured glider tail with modem transducer fully exposed.

After improvements were found with the new transducer position and internal software and the generation 4 modems, a second glider was completed and deployed with this configuration. Trials with this glider around the test PIES were highly successful. The improvement in data success rate at the test PIES off San Diego is shown in the history graph Figure 13.

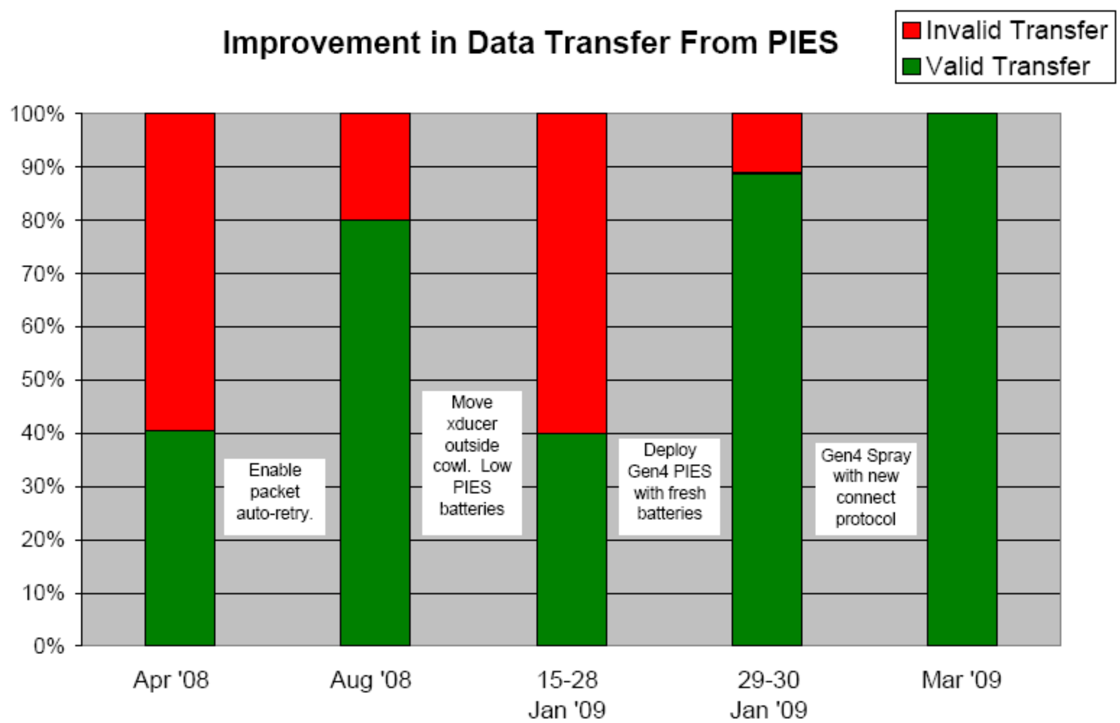


Figure 13. History of success rate at data transfer between Spray modem glider and the test PIES off San Diego in 900m of water depth. It shows the percentage of error-free data transfer once a connection has been established. Some transfers were as far as 5km distant.

At the time of writing both modem gliders are orbiting the moorings and PIES on the main CORC section on line 90 (see below), in water depth of approximately 4000m. For currently not understood reasons, the successful data transfer rate in those conditions is not very high. We are continuing to analyze and assess the diagnostics from those attempts. Some sparse results are presented in the following section.

2.4. Mooring and PIES measurements in boundary currents

Goal: Geostrophic end-point moorings and bottom-mounted PIES (pressure+inverted echsounders) are the only feasible in-situ techniques which can provide rapid enough sampling to avoid aliasing, and which cover the entire water column, in boundary current regimes. Both provide integrals (horizontal and vertical, respectively) and therefore need to be merged with more spatially resolving techniques. The goal is to develop the right technologies and demonstrate their value in boundary current settings.

Role in CORC: In CORC end-point moorings and PIES will be used in conjunction with gliders to fully describe and constrain the circulation and transports in boundary currents. The initial deployment is in the southern California Current, an eastern boundary current. Each setting requires different approaches, and a western boundary environment will be targeted later.

Progress:
In year 2, a test PIES and test mooring was deployed 13nm off San Diego in 900m of water depth, see Figure 14. They were used to gain experience with the modems and test the modem gliders.

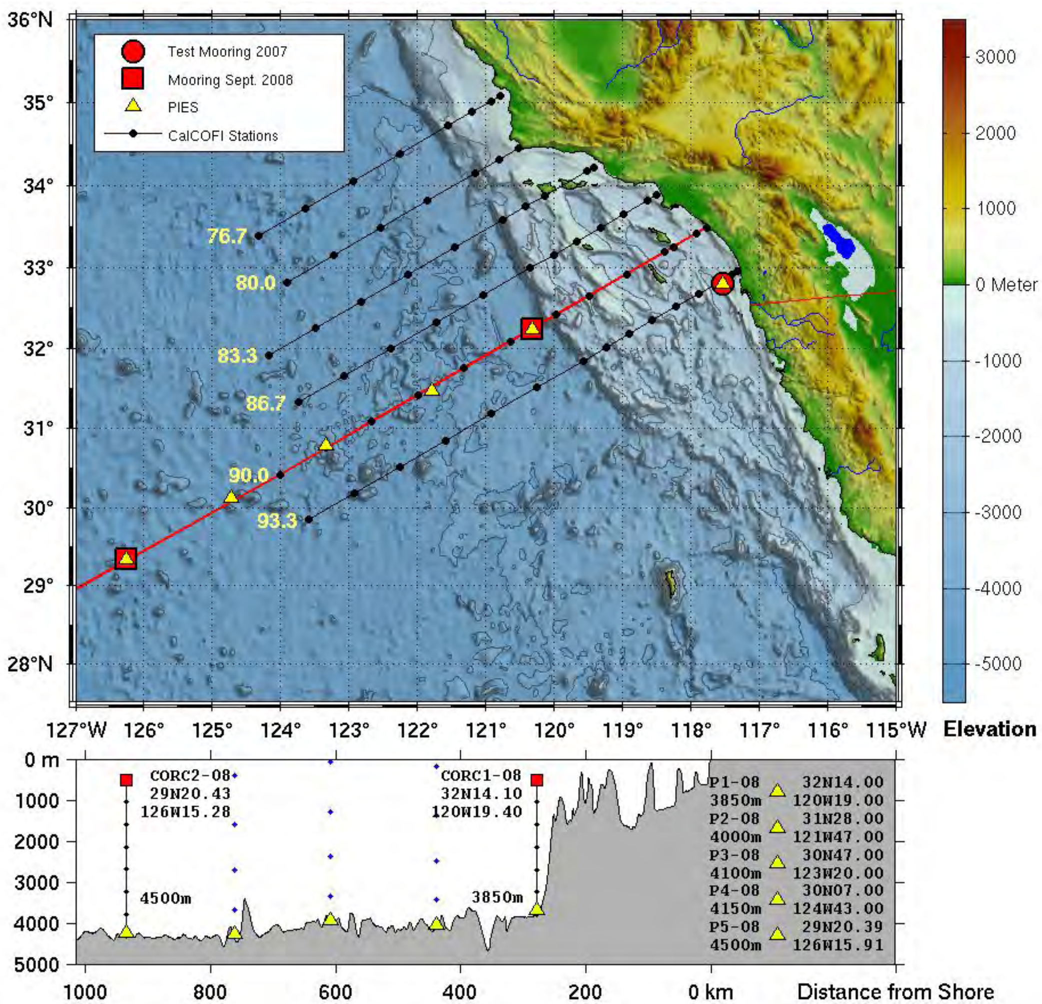


Figure 14. Locations of test mooring/PIES near San Diego on CalCOFI line 93 (red circle, 13nm from coast) and of the initial boundary current mooring/PIES section on line 90 (two red squares for the moorings and five PIES). The bathymetry along the mooring section is shown in the bottom panel.

Much of the spring and summer in year 2 (2008) was used to design and build the two endpoint moorings for deployment on line 90, to improve and build the mooring controllers, to modify, test, and prepare 5 PIES with acoustic modems, to carry out bench and lab tests for the entire communication path, and to prepare for the mooring deployment cruise.

The end-point mooring approach uses moored density measurements throughout the water column (here 15-20 discrete Seabird microcat sensors) to calculate dynamic height, relative to the seafloor or a pressure reference level. It was shown in the MOVE project that with extremely careful calibrations this can be done over the entire watercolumn with such accuracy that at CORC latitudes a mooring pair would determine transports to within 0.2Sv for a 1000m thick layer. Since the California Current is a baroclinic eastern boundary flow system with only moderate flows and largely confined to the upper 500-1000m, we expect the above 0.2Sv to be the approximate accuracy for this flow component (geostrophic transport referenced to a fixed level). The presence of deeper flow can be tested with shear estimates from the density data in the lower water column, and also from the bottom pressure gradients provided by the PIES (giving a measurement of the integrated flow near the bottom).

The original intent was to have mooring-based density measurements only from the seafloor to about 1000m, and to use the vertical integral from the PIES or profiles from the glider data for the upper 1000m. However, initially gliders will only pass by the moorings every few weeks, thus giving insufficient temporal resolution to complete the mooring measurements in the upper layer. Simulations for the skill of the PIES traveltime measurements were then carried out with ARGO data, and revealed that the correlation between acoustic traveltime (from the PIES) and dynamic height (needed for transport estimates) was very low due to high salinity variability in the region. Figure 15a shows scatter in 0-1000m dynamic height of +/-5dyn cm resulting mainly from salinity effects to which the acoustic traveltime measurement is not sensitive. This drove the mooring design to go as close to the sea surface as feasible, i.e. 50m or less. As Figure 15b shows, the scatter then is reduced to 1dyn cm. Over the 50m layer where that uncertainty applies, this results in a transport error of approx. 0.1Sv.

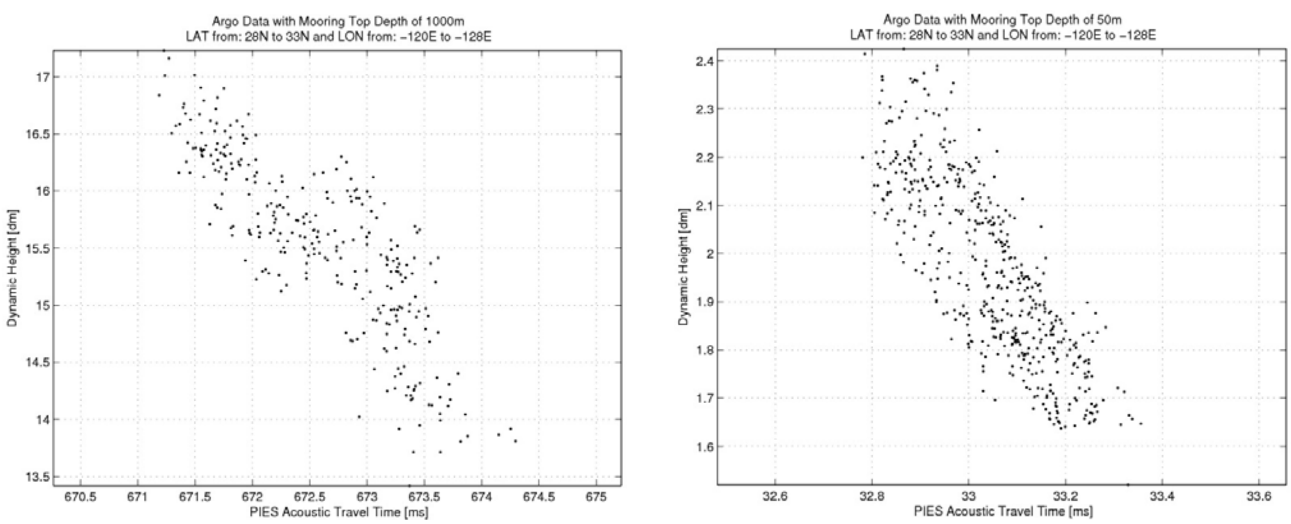


Figure 15. Simulation from ARGO float data of relation between dynamic height and PIES acoustic traveltime measurement, for (a) 0-1000m (left) and (b) 0-50m (right).

The resulting mooring design for the endpoint moorings is shown in Figure 16. They carry 14 and 15 microcats, respectively, reach to within 30m of the sea surface, and have the controller at 800 and 1800m depth to test the impact of controller depth on the glider communication. Both controllers communicate inductively with all microcats and pass the data to an attached acoustic modem.

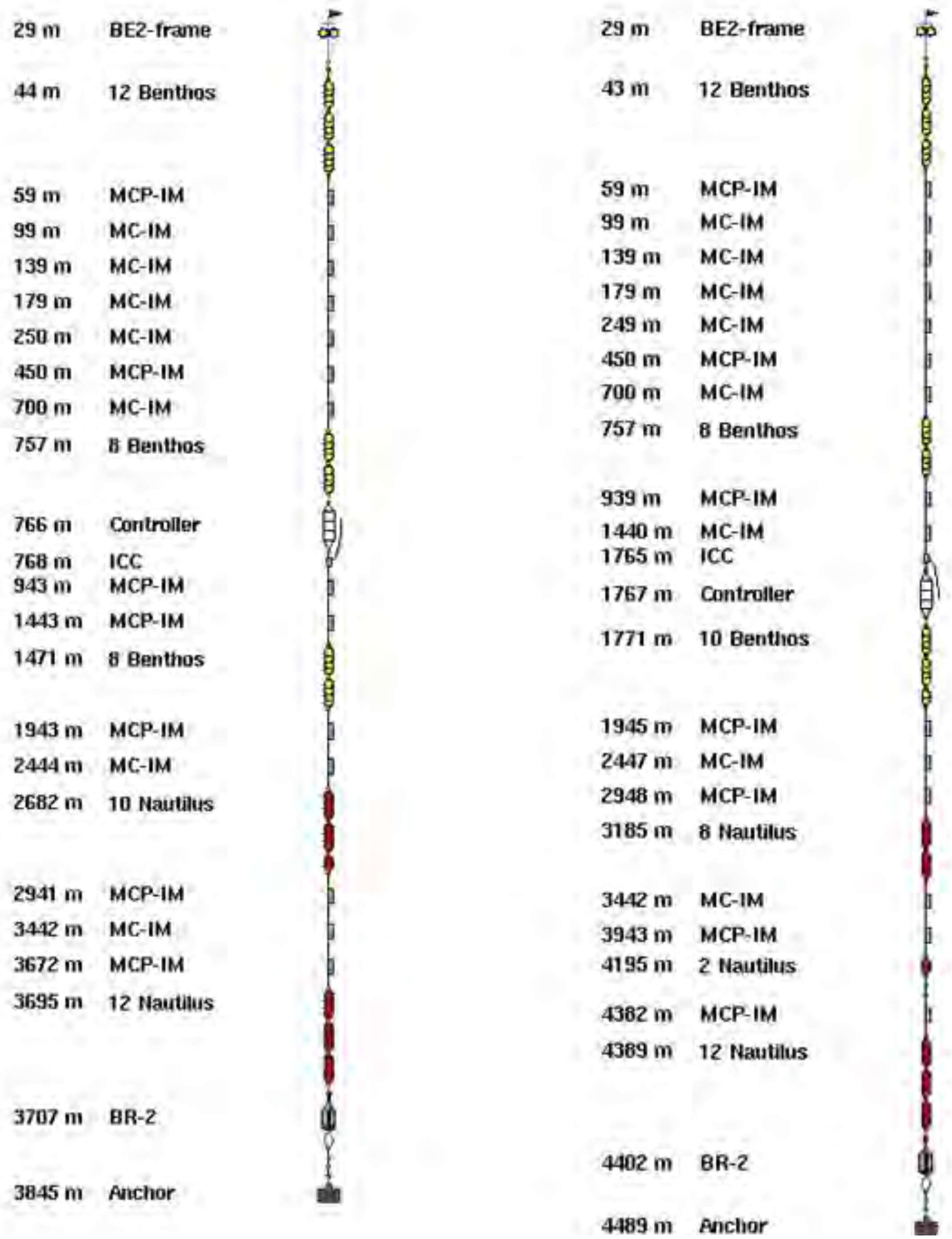


Figure 16. Design of the two endpoint moorings as now deployed on line 90 (see Figure 14). The left column shows the instruments depths, MC and MCP are microcat T/S sensors, Benthos and Nautilus are flotation, ICC is the inductive modem coupler, BR is the acoustic release.

A goal for the end-point mooring placement was to make the transport section longer than the CalCOFI line 90 since it was clear that the CalCOFI sampling misses much of the California Current. One constraint was shiptime, since extending the mooring/PIES section much beyond 1000km distance from shore would have required several more days of transit. The compromise geometry for the first demonstration deployment is shown in Figure 14, with a mooring separation of approximately 700km and a total distance from shore of close to 950km. That figure shows the CORC array as deployed in September 2008 including 5 PIES along the section. It required 6 days of shiptime from/to San Diego to install this. The adopted length makes sure that the core of the California Current is captured, but future implementations may need a longer section. The actual positioning of the moorings during the cruise was made very difficult due to extremely rough and irregular bathymetry, making placement of the anchor in a depth known to about 10m (necessary to reach the 30m below the surface with the top instrument) very challenging.

During deployment of the moorings, the inductive communication with the microcats already in the water (and being towed behind the ship) was continuously tested to verify functioning of the inductive loop and bypasses. After deployment, acoustic communication was established with the controller of one of the moorings, and one data cycle from the entire suite of microcats was successfully downloaded from the ship. The resulting profiles are shown in Figure 17.

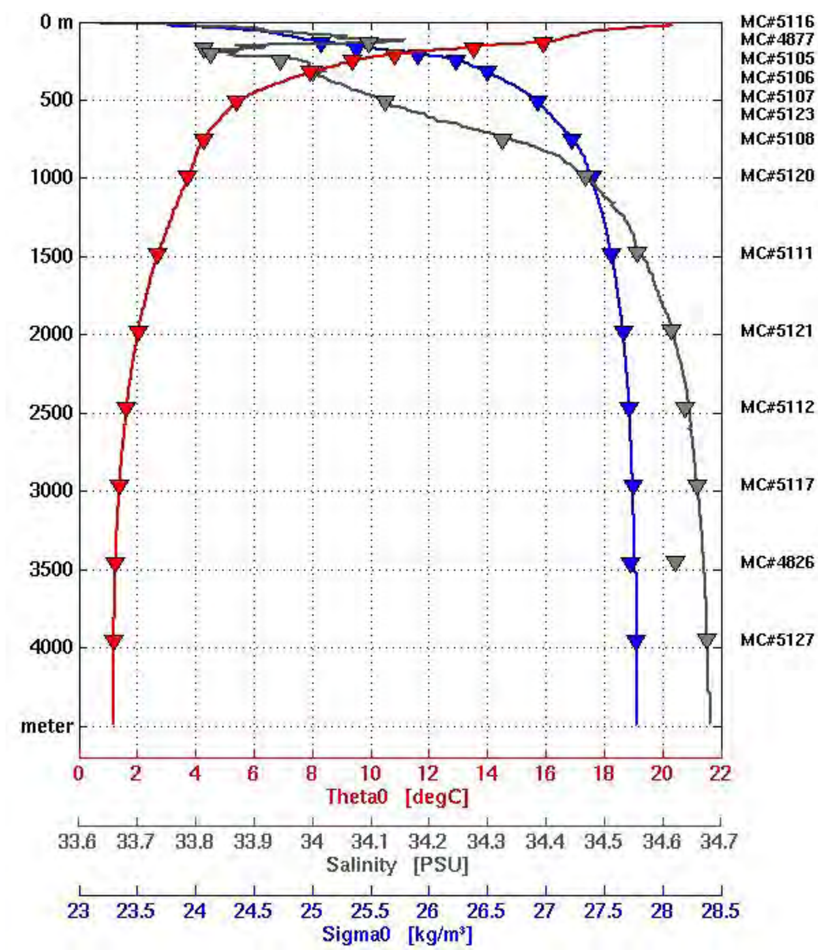


Figure 17. T, S, and density data recovered from the 14 mooring microcats (triangles) 30min after anchor dropof the offshore mooring, plotted together with a continuous profile from a comparison CTD cast nearby. The microcat data were collected by the mooring controller via inductive communication along the mooring wire and then passed to an attached acoustic modem. From there, the data were downloaded acoustically from the research vessel. The top instruments have not yet settled at their near-surface target depth.

At the time of writing, only very limited datasets from the now 6 months long mooring and PIES deployment are acoustically available. Some data from the inner mooring CORC-1 could be downloaded during a recent cruise, and a modem glider retrieved a partial dataset from the innermost PIES (P1). If one assumes that at the far offshore end no or small variability in dynamic height or bottom pressure exists, these data can be converted into velocities or transports, to give a feel for the expected variability (see Figures 18, 19). The figures show that the shear relative to 500 or 950db implies baroclinic transport changes of 2-3Sv (which may be eddies). The bottom pressure time series from the PIES suggests barotropic variability of order 3Sv per 500m layer.

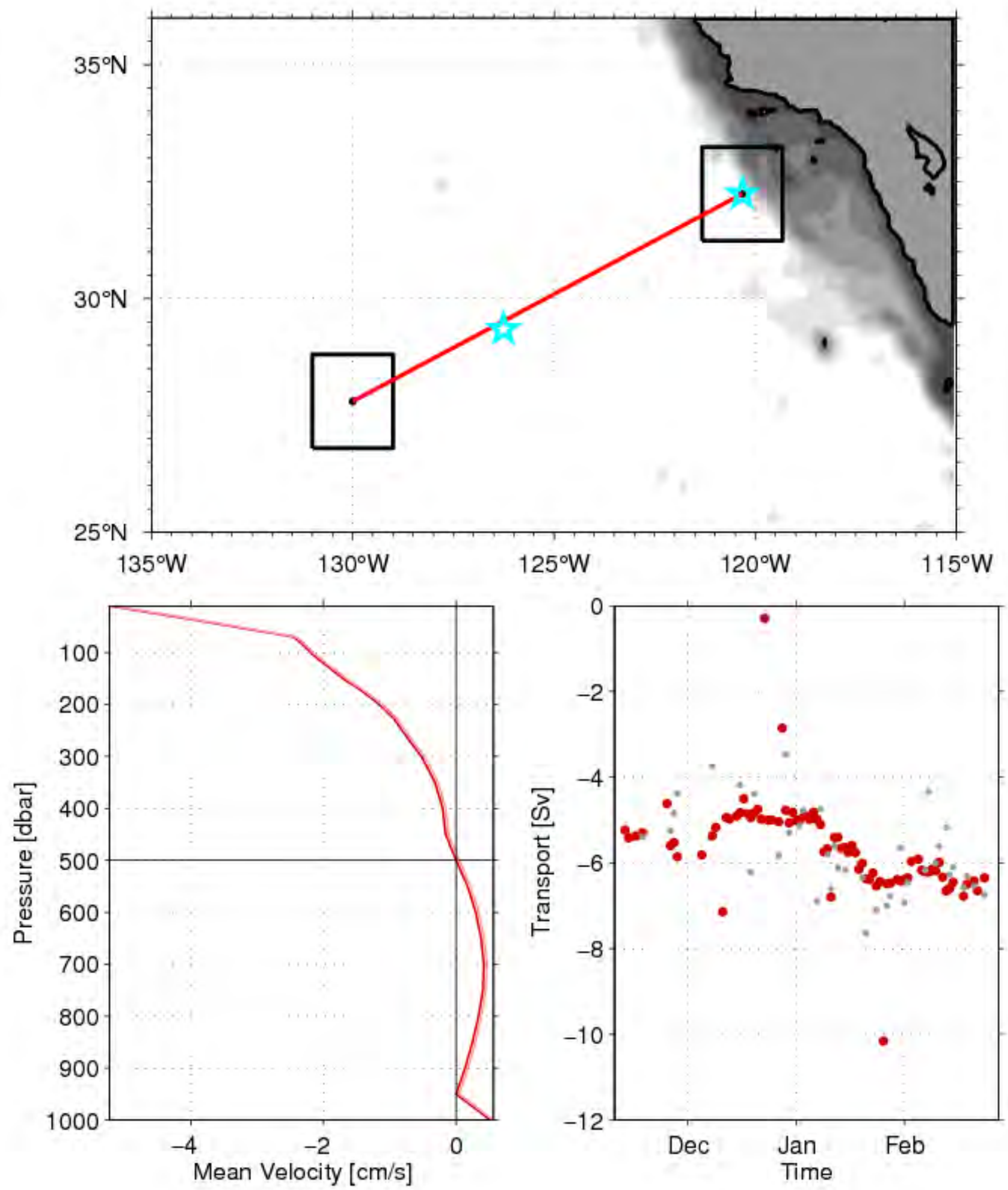


Figure 18. Geostrophic currents computed from a preliminary geometry with the eastern CORC-1 mooring and a constant climatology (SIO Argo Climatology, J. Gilson) at the western end. Transports across the red line are computed. Acoustically downloaded CORC-1 (eastern star) data are used to compute dynamic height there. Data from the outer mooring (western star) is unavailableat present, hence it is replaced by the climatology at a convenient location further offshore. Bottom left: mean velocities across the section,relative to 500db (dark) and relative to surface flow climatology (light). The curves are indistinguishable. Bottom right: transport time series over the top 500m layer, relative to 500db (red) and over the top 950m relative to 950db (grey). All data are raw and uncalibrated, hence the noisy appearance.

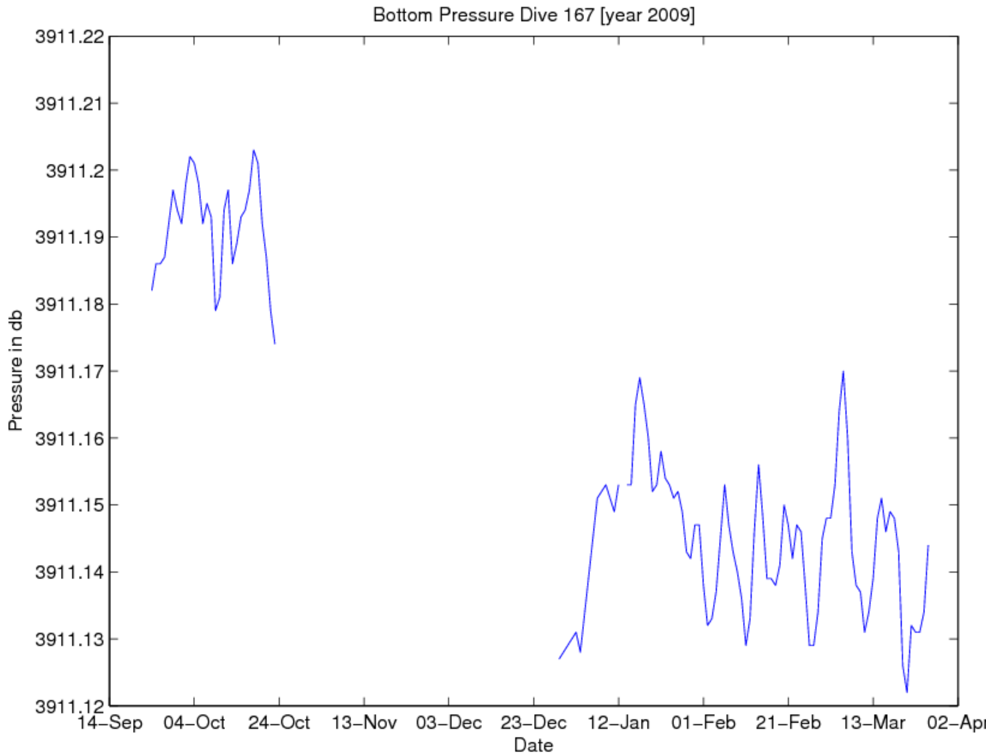


Figure 19. Bottom pressure from easternmost PIES, downloaded by modem glider. Daily averaged and detided data, showing a range of 4cm equivalent sea surface height over short periods, suggesting a fluctuating barotropic flow component (the large difference between the two data segments is likely to be slow drift of the pressure sensor).Each cm translates into 0.7Sv over a 500m thick later when taken as a difference with an unchanging offshore site. Thus this signal would add another 3Sv variability to the 0-500m transport changes shown in Figure 18.

2.5. XBT data in support of the California Current observing system

Goals: High-resolution XBT data have been collected for many years and provide an important data base for boundary current observations. The XBT lines across the California Current will be analyzed to provide complimentary information for CORC. Another goal was to evaluate a 2000m (LMP5-T1) XBT for ocean boundary current and ocean interior sampling.

Role in CORC: Analysis of HRX data from PX37 and PX37S (Figure 20), including temperature, salinity, and geostrophic velocity and transport, together with Argo data over the northeast Pacific, will allow the more intensive CORC measurement program along CalCOFI Line 90 to be placed in the context of the larger eastern subtropical North Pacific domain.Specifically the analyses will help define the offshore extent of the California Current and determine how much of its transport is beyond the usual offshore end of CalCOFI Line 90. Comparison of transport and variability variability of the California Current off Southern California (Line PX37S) with that off Central California (Line PX37) can estimate the degree to which transport variability is correlated alongshore. This will help to assess how representative a single section like the CORC mooring/PIES/glider line is. Optimal merging of HRX lines with Argo data in the ocean interior will guide methods to combine the CORC boundary current observations at high spatial/time resolution with the large-scale interior observations.

Progress:

a) Analysis of PX37 and PX37S lines and interior ARGO data

The High Resolution XBT Network (HRX) collects eddy-resolving temperature transects along commercial shipping routes. Most lines are sampled on a quarterly basis, with temperature profiles from 0-800 m at horizontal separations ranging from 50 km in mid-ocean to 10 km near ocean boundaries. Two HRX transects cross the California Current system (Figure 20). These are lines PX37 (San Francisco-to-Honolulu) and PX37S (Long Beach-to-Honolulu). The latter is in close proximity to CalCOFI Line 90. Line PX37 has been sampled continuously since 1992.

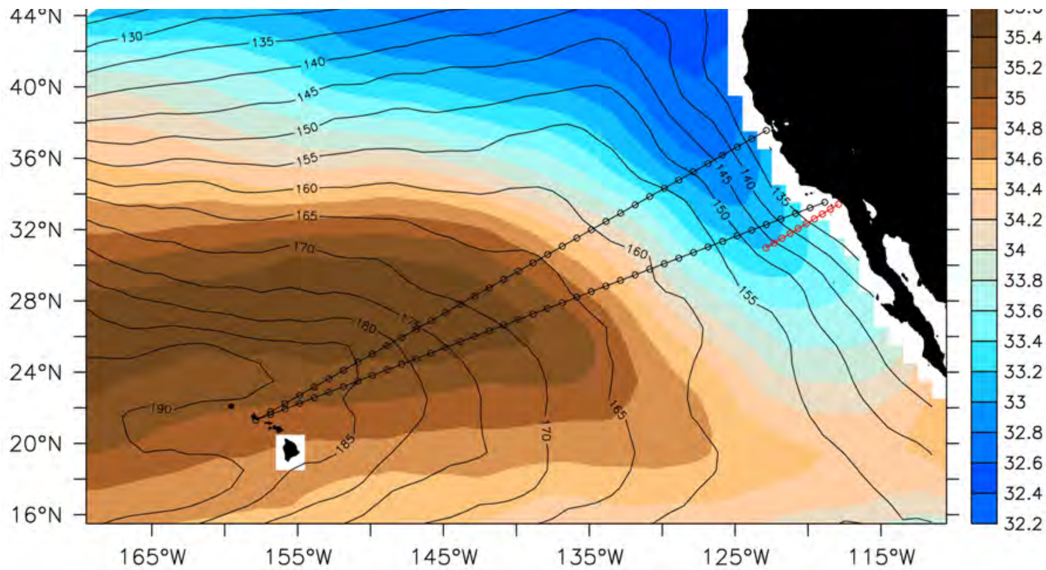


Figure 20. HRX Lines PX37 (Honolulu-San Francisco) and PX37S (Honolulu-Long Beach) are shown in relation to CalCOFI Line 90 (red), and to the mean sea surface salinity and mean dynamic height of the sea surface from Argo (0/2000 dbar).

Analysis is proceeding concurrently on the three datasets (Argo, HRX, CalCOFI). Analysis of Argo data (Figures 20 and 21a) indicates that using either the maximum horizontal gradient in surface layer salinity or the minimum in southward geostrophic velocity suggests the offshore end of the California Current is located at about 129-130^{o}W. A significant fraction of the Current is beyond the end of CalCOFI Line 90.

The cumulative transport shown in the top panel of Figure 21 does not show a strong change in slope at the transition from the boundary current to the interior. This is due to the deep-reaching and wide-spread background flow (green colors) which causes much of the cumulative transport, to which the shallow and slightly enhanced boundary current flow adds little transport, at least in this analysis.

Geostrophic velocity on large spatial scales are similar in multi-cruise averages from HRX data (Figure 21b) and multi-year averages from Argo. But Argo does not sample close enough to shore to observe the poleward countercurrent, nor does it capture small spatial-scale features in the mean field. There also appears to be persistent northward flow around 130^{o}W in the HRX data.

In support of CORC sampling has recently begun (November 2008, Figure 22) along HRX Line PX37S (previous sampling from Fiji to Long Beach, PX31, ended in mid-2007 when the ship changed its routing). Line PX37S includes XCTD profiles because of the importance of the salinity field as a tracer and in geostrophic velocity calculations.

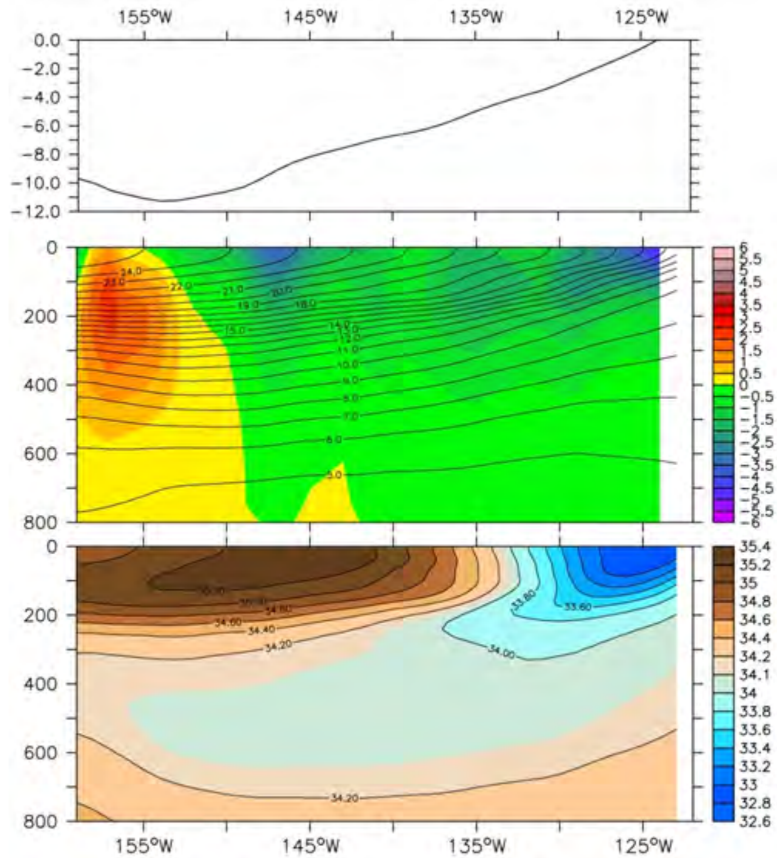


Figure 21a. 2004-2008 mean ARGO data along PX37 yielding cumulative geostrophic 0-800m transport in SV (top), geostrophic flow(cm/s) and temperature (middle), salinity (bottom). Geostrophic flow relative to 800db.

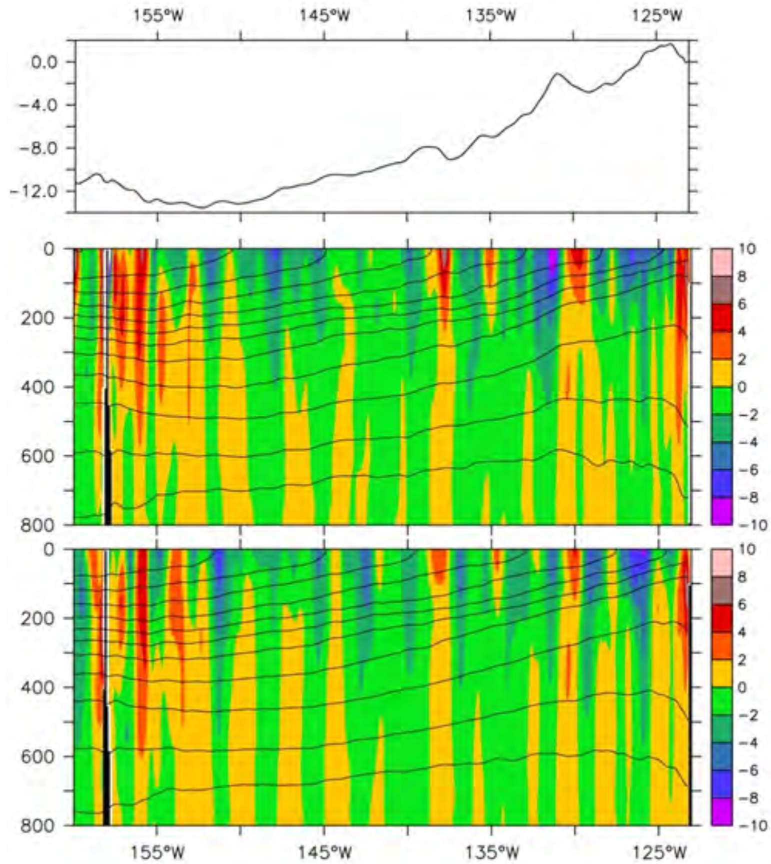


Figure 21b. Similar to 21a but from PX37 XBT data. Top: Transport integral (Sv), 2004-2008 21-cruise mean. Middle: T and velocity (cm/s), 2004-2008, 21 cruise mean.Bottom: T and v, 1993-2003, 46 cruise mean.

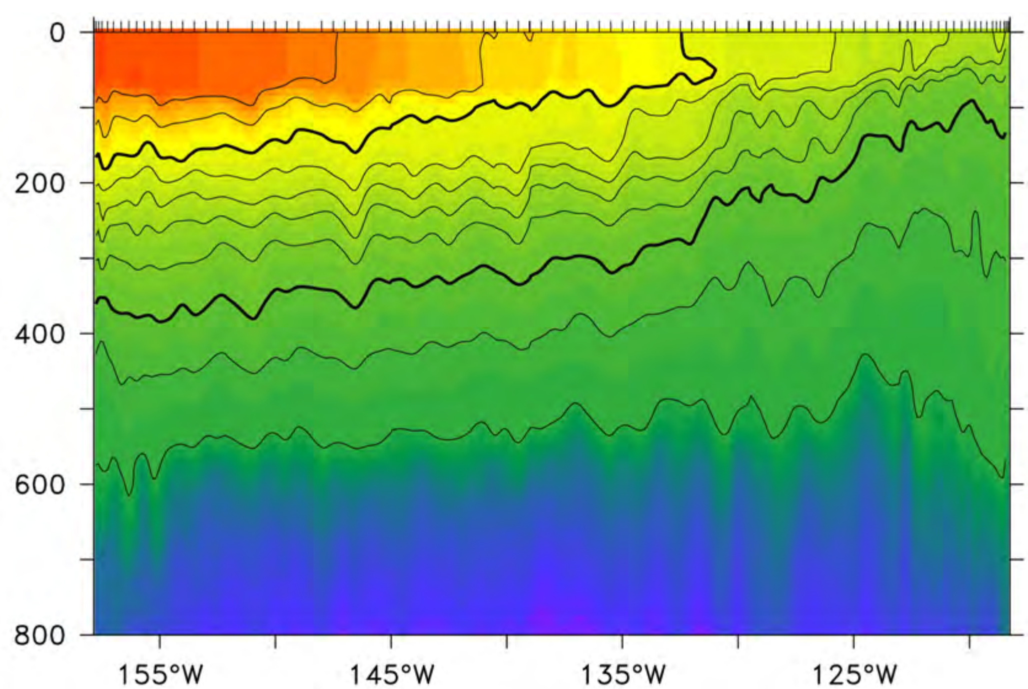


Figure 22. Temperature transect along PX37S, Honolulu to Long Beach, November 2008.

b) Evaluation of 2000 m (LMP5-T1) XBT for ocean boundary current and ocean interior sampling:

Present sampling with expendable bathythermograph (XBT) probes at high ship speeds is limited to 800 m. A new XBT probe (LMP5-T1) is under development by Lockeed Martin Co (formerly as Sippican Corp) to provide research-quality temperature versus depth measurements to 2000 m at ship speeds of 20 knots. The HRX program is assisting this development by testing prototype LMP5-T1 probes.

If the effectiveness of the LMP5-T1 could be demonstrated, combining it with Deep Blue XBT and Argo float data would have widespread usage in the HRX Network for ocean circulation and heat transport estimation.

Development of the LMP5-T1 probe by Lockeed Martin has been suspended, and the company is marketing a deep analog probe rather than the planned research quality probe. We will therefore not be further testing or acquiring LMP5-T1 probes, and will instead use residual funds for XCTD sampling that is badly needed along line PX37.

2.6. Surface drifter observations in boundary currents

Goals: The objectives are to utilize historical and real-time drifter, ADCP, hydrographic and satellite sea level data to construct maps of surface circulation of ocean boundary regions that transport ocean properties and thermal energy across latitudes. A novel contribution is the development of a bottom-release technology for surface drifters,

Role in CORC: The special contribution of the drifter data is to provide spatial patterns of near surface circulation that surround the data lines occupied by moorings, PIES, XBTs and gliders in CORC. Drifters will be deployed from ships of opportunity (in the CALCOFI region and Solomon Sea) and where ships do not visit on a regular basis, drifters will be positioned by a newly developed mooring system on the ocean floor, to be released at preset times. Presently, the period of 1993 to 2008 is being analyzed to form a 15-year time mean, which will be followed by analyses that describe the evolution of the circulations systems that accompany or influence climate change. The near surface data provided by this effort will be provided to the CORC data assimilation effort.

Progress:

a) Analysis of historical observations in the Southern CCS:

The hydrographic data from 1949-2008, the SVP drifter data from 1985-2008, the satellite altimeter from 1992-2008 and ADCP data from CALCOFI ships were combined to compute comprehensive horizontal maps of velocity along CALCOFI Lines 77-93. These analyses produce time-mean horizontal maps of surface circulation in the southern portion of the CCS and vertical sections along CALCOFI Lines (Figure 22).

The data on Line #90 shows significant ageostrophic velocity component normal to Line #90 line in water depths shallower than 100m (Figure 22). The spatial structure of ageostrophic velocity cannot be entirely due to wind driven Ekman currents because the wind along Line #90 does not have a spatial structure commensurate with the location of the spatial structure of the ageostrphic current patterns. Data on Line #90, as well as the other CALCOFI lines where ADCP data is available, is being inspected to determine whether interaction with the wind and the relative vorticity of the time mean circulation might lead to these anomalies.

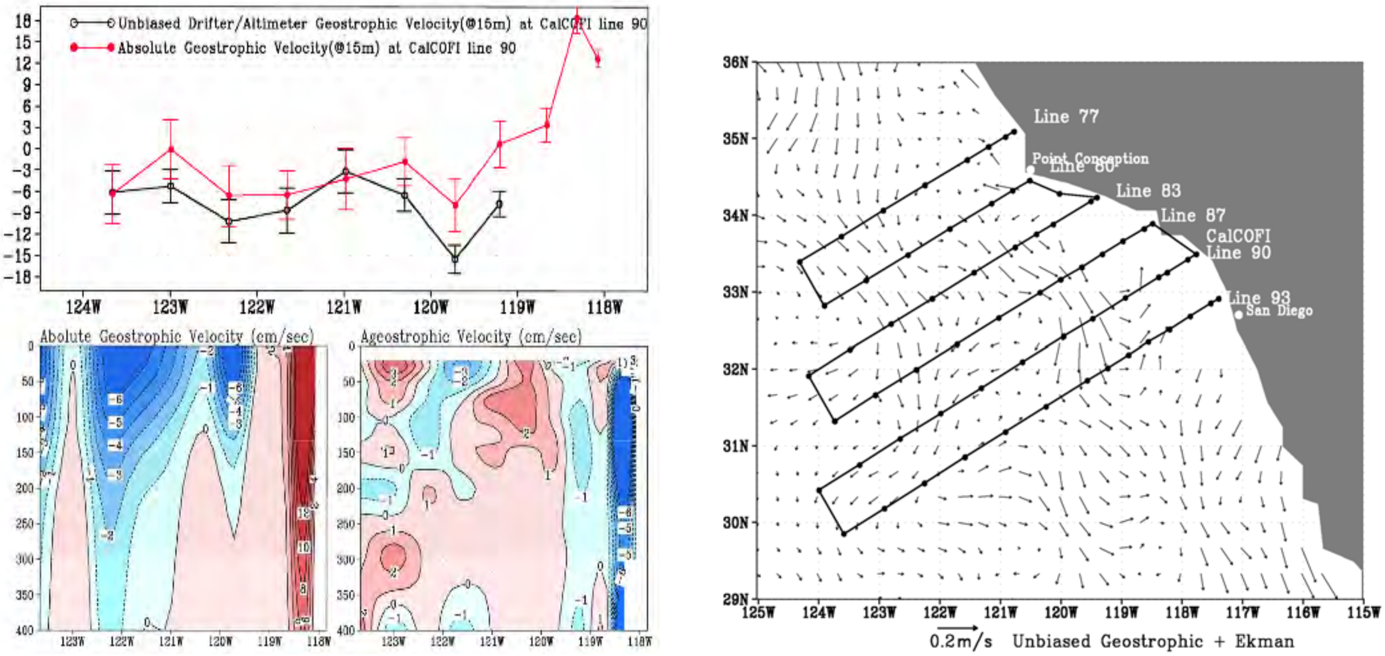


Figure 22. The 15m depth drifter/altimeter velocity component normal to Line #90 (black) and the 250m relative to ADCP geostrophic velocity component from CALCOFI (upper panel). The geostrophic velocity relative to ADCP data at 250m (middle left panel) and the ageostrophic velocity from ADCP measurements (middle right panel lower panel). The 15m velocities derived from drifter and altimeter data (bottom panel). It is apparent that Line #90 is imbedded in a complex flow pattern with at least three cores of southward flow and a northward current along the coast.

Analysis has also been completed for the time variable EOF's of the transport, surface velocity and hydrographic properties (not shown). We anticipate having complete description of Line 90 completed with FY'08 funding.

b) Analysis of the surface circulation of the Solomon Sea

Drifters have been deployed in the western tropical Pacific since 1988. The historical ensemble of tracks (Figure 23 top panel) reveals currents in excess of 50cm/sec in the Solomon Sea and the passage from the northeast into the Solomon Sea between New Ireland and Buka Island. The average 15m-depth velocity (Figure 23 bottom panel) shows that there is an inflow of surface water through this strait that makes up the surface water of the New Guinea Current. No apparent connection of the New Guinea Current appears to the circulation of the Coral Sea. This is in marked contrast what is implied by water mass distributions and direct flow measurements below the surface, where a direct link the Coral Sea conditions is established. More comprehensive definitions of the Solomon Sea circulation patterns and its time evolution is an objective of CORC in which drifter observations will be playing an important role. Our analysis of this region is not complete because we have not combined the drifter data with altimeter and wind observations, but these tasks will be completed in the next several years.

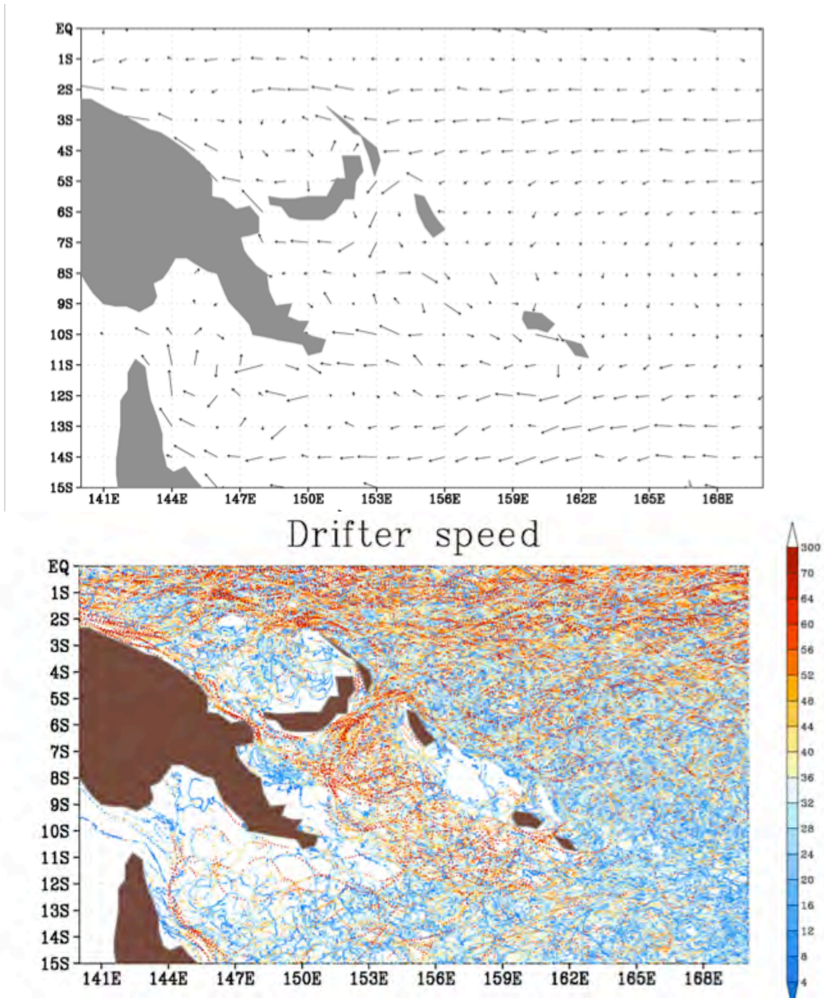
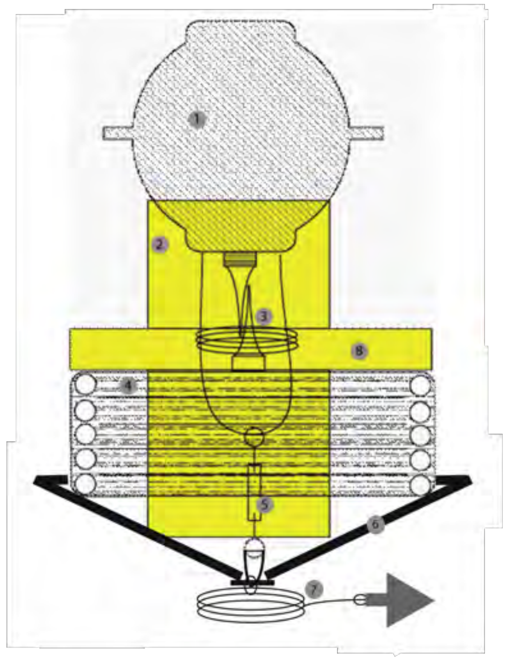


Figure 23. Historical drifter tracks in the vicinity of the Solomon Sea (top panel) and the ensemble mean velocity at 15m-depth on 0.25º resolution (bottom panel). Note the strong inflow of surface water into the Solomon Sea from the northeast and the anticyclonic gyre in within the basin.

c) Construction and testing of bottom release system for drifters

We have built four test drifters that are to be moored to the bottom and will be released at preset times, Figure 24. Test in 10m-depth pool at Scripps were continued in the ocean off Scripps pier. Numerous electrical and electronic problems have been identified and corrections are being implemented. We anticipate the first deployment of 6 units in the deep ocean along line 90 within six months. The long-term objective is to place arrays of such drifters in regions where regularly time spaced ship deployment is not practical.

Drawing 1.1 Packaged Long Term Bottom Release Mooring



1) Surface Sphere
2) Sonotube Mount
3) Carrot, burn wire, and excess tether setup
4) Drogue
5) Tensioner and shackle system to calibrate mount
6) Conical cap for mounting package, anti-tumbling during deployment, and anti-skating during mooring phase
7) Thimble, excess tether, and anchor setup

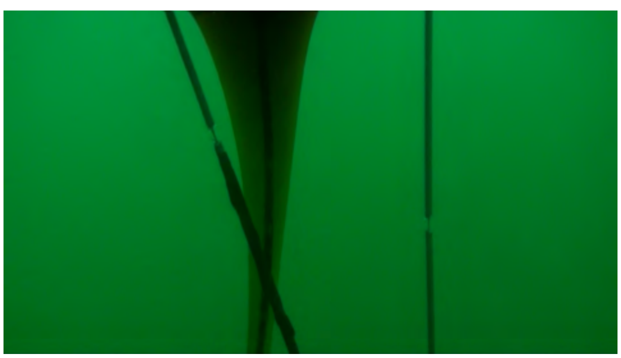


Figure 24. The schematic on the left shows the initial design of the timed-release mechanism and ocean bottom-resting configuration for drifters. Burn wire technology was adopted from geophysics research group at SIO that forms the connection to a low cost resting pod on the ocean bottom. The new drifter configuration float is a 4000m pressure resistant Benthos glass sphere with a thru-hull cable to the burn wire. The burn circuit works well in the laboratory. Underwater tests in the OAR salt-water pool are continuing to be problematic in stabilizing the entire configuration of the float, drogue and the anchor. We anticipate a series of test is the first two weeks in January to solve problems.

The underwater photograph (lower green panel) taken on 3/20'09 shows a burn wire test at 30m of water depth off Scripps Pier. Note that both wires that are holding the mooring in place have burned their stainless steel strength members and the remaining cotton cord around which the wire was wound is ready to break. Upon rupture, the drogue deployed correctly and the ARGOS transmitter started working correctly.

d) Deployments of drifters within CALCOFI

The project is focused on the analysis of historical Lagrangian surface current data collected off the Central and Southern California coasts, and additional data collection with SVP surface drifters. The research will provide new insight into the connection between continental shelf flows and the larger scale California Current located further offshore. Dr. Carter Ohlmann at the University of California at Santa Barbara supervises this activity.

The following two tasks have been performed during the period:
• Historical CODE drifter data for the study region have been obtained and organized.
• SVP drifters (27) have been purchased and a deployment plan is being developed.

Historical drifter data collected as part of the MMS funded Santa Barbara Channel – Santa Maria Basin circulation study (SBC-SMB) and through the Global Drifter Program (GDP) have been obtained and organized. The SBC-SMB dataset is comprised of observations from 536 CODE style drifters drogued at a depth of one meter. The drifters were launched within the SBC-SMB between October 1992 and December 1999, but moved throughout the southern branch of the California Current system. Mean track length is 25.8 days and the longest track length is 89.9 days. The intermittent ARGOS position data have been filtered for erroneous position records, linearly interpolated to a 6-hour time grid, and velocity values computed as a first difference in position.
A set of 27 SVP drifters (drogued at 15 meters) has been purchased from Technocean Inc. (Cape Coral, FL). The drifters are expected to arrive at UCSB within the next few days. Development of codes to obtain the drifter position data from Service Argos in near-real time has begun. Obtaining data from sampling units will help guide the deployment of subsequent units. Historical drifter tracks have been examined to identify flow features that characterize the circulation and will guide deployment of the 27 units. The historical drifter data and model results published by Dong et al. (in press) show a somewhat persistent sub-mesoscale cyclonic gyre centered near 33.5° N, 119.5° W. The feature may be significant for material retention in the Southern California Bight circulation and may be an initial "target" for drifter deployments.

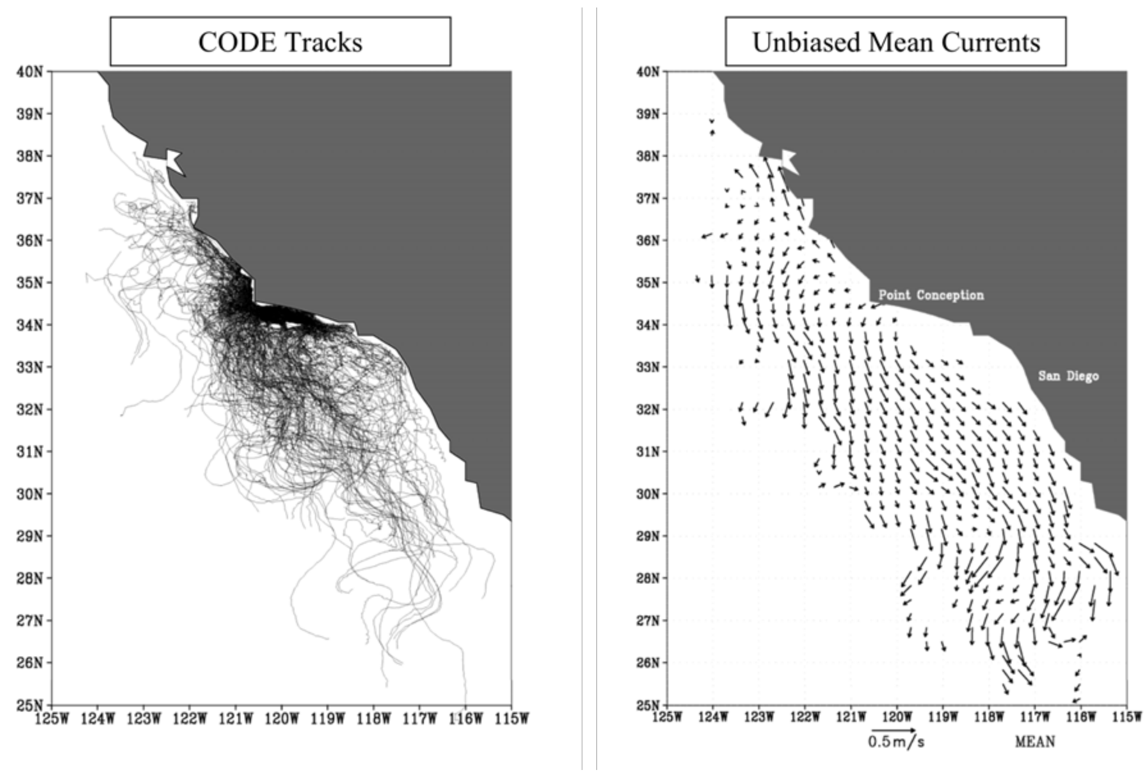


Figure 25. CODE drifter tracks within the CALCOFI region (left panel) and the 'unbiased' 1m-depth average surface current (right pan. Comparison with SVP data at 15m-depth velocity is ongoing.

2.7. Modeling and assimilation of CORC data in the California Current

Goals: Our primary goal is to provide a physical way to merge the datasets together using a regional model of the CCS to come up with a detailed picture of the current system, both upstream and downstream of the primary sampling line. The synthesis will cover the intense years of observations, and provide a testbed for sampling plans. The assimilated results will show space and timescales of the variability for term-by-term analysis of heat, salinity, momentum, and vorticity balances.

Role in CORC: Our role in CORC is to tie the various observation programs together, to provide a coherent synthesis that all PIs can use to evaluate their observations and do further analysis. We should be responsive to PI interests in providing analysis to work in collaboration to write papers, to optimize the observation network, and to construct routine products and indicators.

Progress:

a) MITgcm/ECCO assimilation

A paper on the modeling and assimilation in the tropical pacific from the previous CORC project was accepted to the Journal of Atmospheric and Ocean Technology, and an article on the completed assimilation for the year 2000 is in revision at JGR. The tropical pacific assimilation showed that eddy-resolving assimilation could work for periods as long as a year in the energetic tropical circulation. In addition, the MITgcm/ECCO system was validated as a tool for analysis. This same tool has been applied to eddy-resolving assimilation in support of the observations in the CCS.

The same system was applied to a 1/10 degree and 50 level grid of the CCS, using satellite SSH and SST observations for a proof-of-concept demonstration, and the iteration converged well, although because of the use of ECCO boundary conditions, the assimilation was done for 2003, before the new sampling in the CCS.
The MITgcm/ECCO system has been significantly changed twice since we began the CCS assimilation, and we have upgraded twice and are now using the newest version of the model and the ECCO assimilation package. This version is run by Matthew Mazloff and the set-up isnearly identical to his successful 1/6 degree Southern Ocean State Estimate (SOSE), Figure 26.

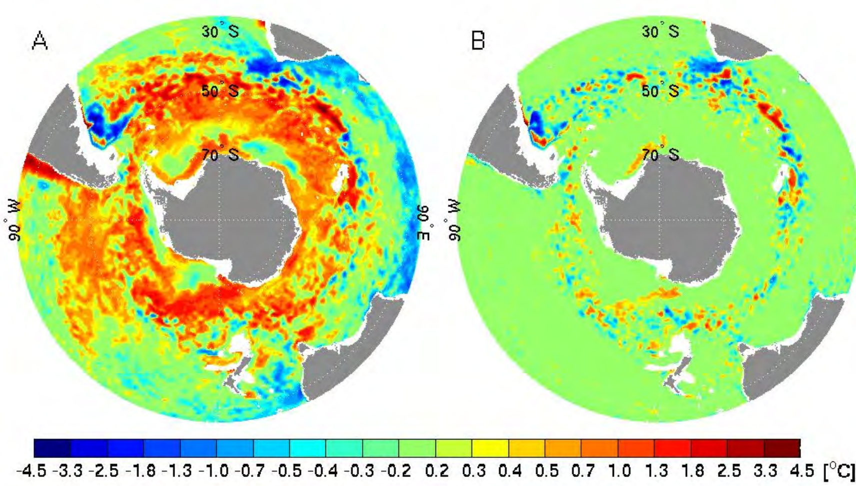


Figure 26. Successful eddy-resolving assimilation over 2 years with MIT/ECCO model at similar resolution as the CORC model in a very dynamic region. Time average of model solution minus observations [^{o}C] for the best guess forward model solution (left) and after 23 iterations of assimilation (right). Observations are combined mean from infrared (AVHRR) and microwave (TMI AMSR-E) radiometers.Exponential color axis.

In addition to the code updates, we have implemented new features, notably an Ensemble Kalman Filtering option to complement the adjoint-based 4DVAR assimilation already in use. We have also extended the system to accommodate non-ECCO models (notably HYCOM) as boundary conditions, since the available assimilated ECCO ocean states lag behind the current time. We have been evaluating the HYCOM estimate in a few regions, starting with the local San Diego region, and the assimilated model output seems to have useful skill.

One of the data sources in the monitoring array are inverted echo sounding with bottom pressure (PIES), which measures round-trip travel time between the bottom-mounted instrument and the surface. This is processed by some investigators using a "gravest mode" method that assumes a dominant mode of variability. We intend to instead use the bottom pressure and vertical integral of sound speed as a constraint on the assimilating model, but this has meant the enabling of integral observations, which have not yet been used in the ECCO system. We have investigated the problem, and it should be possible to add these data to the assimilation by adjusting the cost function without large changes to the code.

The latest version of the CCS model is 1/16 degree and 72 levels, a large improvement in resolution over the previous versions, and embedded in a new global 1 degree state estimate from MIT-ECCO (with thanks to Gael Forget, Patrick Heimbach, and Carl Wunsch) that extends through 2007. To assimilate data into 2008 and 2009 we will need to use different boundary conditions if MIT ECCO does not produce an updated solution. To address this we expect to use HYCOM or just to repeat the older boundary conditions, since they will be altered by the assimilation in any case. We have experimented with boundary conditions from assimilated HYCOM in other regions, and have had some success with model runs, so it seems to be a viable option (Figure 27).

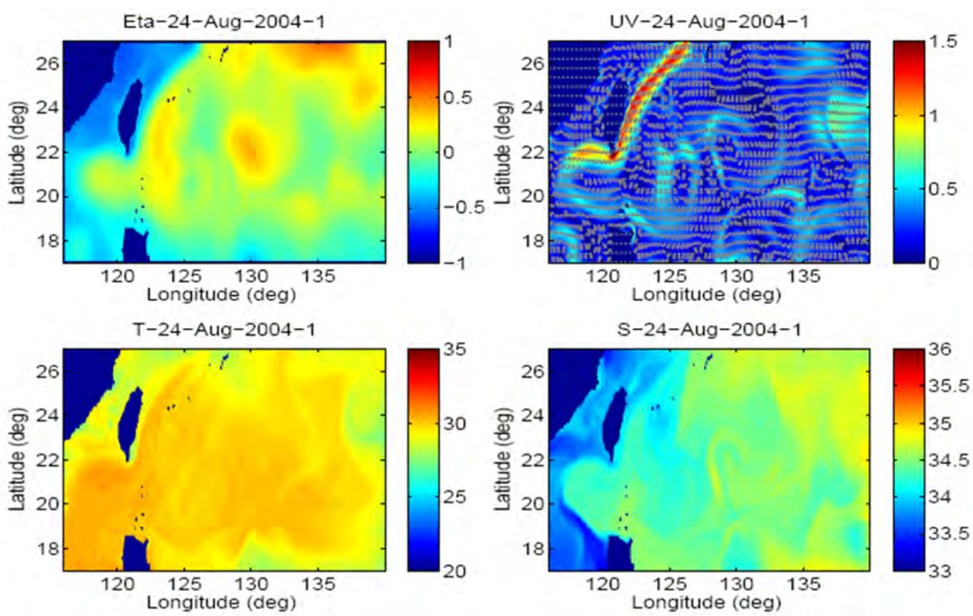


Figure 27. Example of successful regional MIT/ECCO run with original bathymetry, using HYCOM as intial and boundary condition, here for the region off Taiwan (panels show full domain SSH, surface velocity, SST, and SSS).

Much time was spent on debugging and recreation of local modifications to the code, since many features changed. Not all local modifications have been transferred to the new code yet, but while that is underway we are beginning hindcast experiments using the in-situ observations from CalCOFI, Argo, and Spray gliders to evaluate the model skill.

In addition to the MIT-ECCO boundary conditions and initial conditions the reference (starting) model run before assimilation is forced by NCEP reanalysis winds. We continue to evaluate wind products for the California region, including the NCEP reanalysis, NCEP operational NAM, Navy

COAMPS, and UCLA/JPL WRF. None of these products is perfect, and differences in time coverage make it difficult to do long model runs with a single forcing product. In addition, several forward runs have been made to examine sensitivity to mixing parameterizations.

The in situ observations have been compared with the forward model run (Figure 28), and the differences for the downscaled assimilated system are encouragingly small, (see Figure 29) although significant improvement is still possible. The reference run is also useful for observing system simulation experiments (OSSE) to evaluate the observation strategies used in CORC and the validity of dynamical assumptions, such as geostrophy for transport estimates.

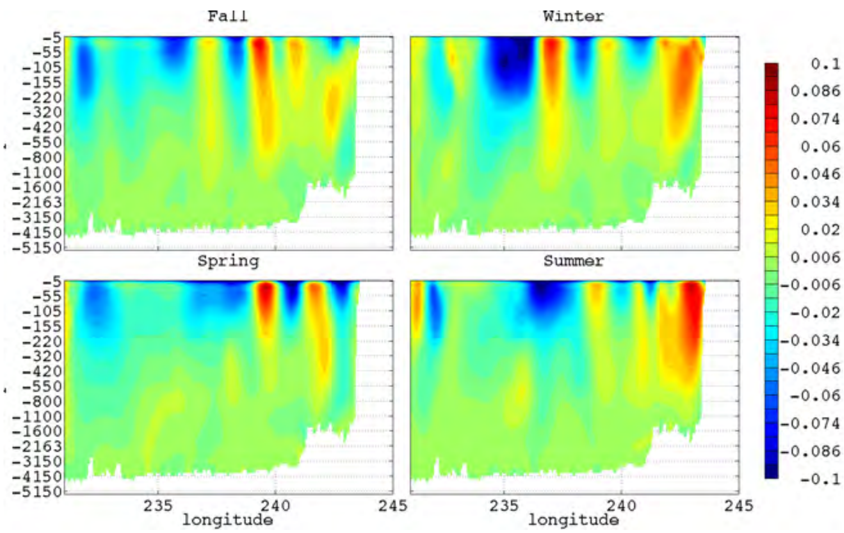


Figure 28. Forward run (no assimilation) of the MIT/ECCO CORC model, with boundary/initial conditions from the global ECCO model, after 1 year. Shown is the meridional velocity across 31S for four seasons. The California Current core (blue) and the northward undercurrents are reminiscent of the glider transects in section 1.

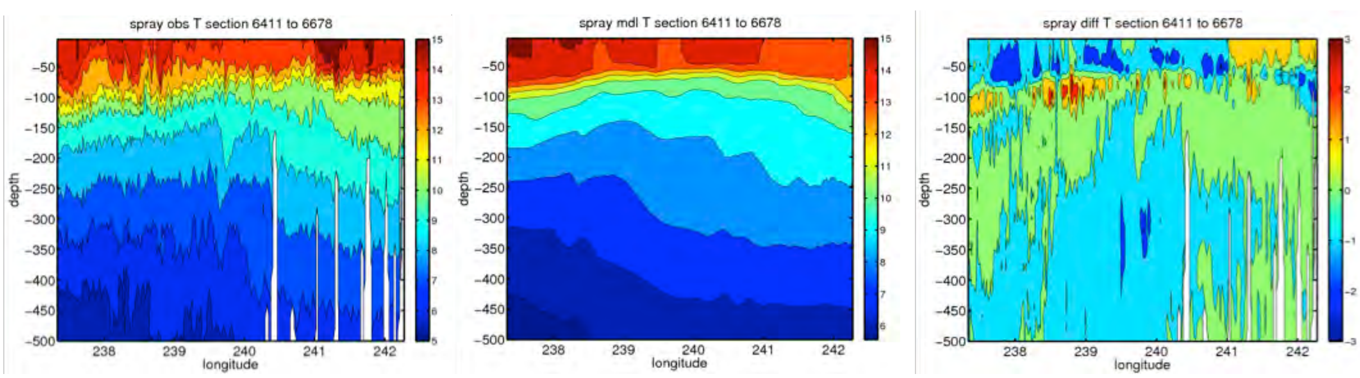


Figure 29. Forward run (no assimilation) of the MIT/ECCO CORC model, with boundary/initial conditions from the global ECCO model, after 1 year. The three panels show temperature for a Spray section on Line 90; 19 Jan 2007 to 17 Feb 2007. The first panel is observed temperature, the second is model temperature, and the third is observation - model misfit. Contour interval is 1 degree C. The agreement is remarkable since the glider data are not assimilated into the global ECCO model which provided the initial/boundary conditions. Thus this is an independent data set.

The result of the assimilation should provide a dynamically-consistent synthesis of the disparate observations, including those made as part of the project and can be compared with the analyses produced by the PI's making the observations. The state estimate will be dynamically consistent in that the assimilation will produce an adjusted set of controls: initial conditions, boundary

conditions, and forcing that can be used with any model (or model resolution) to perform an integration without internal forcings driving the model to the observations.
Tests of robustness will include re-running the forced forward run at higher resolution and applying the adjusted forcing to another model (e.g. ROMS in the case of MITgcm assimilation).

b) ROMS

As a complement to the MITgcm assimilation, adjoint-based assimilation using ROMS is also being implemented for the CCS. ROMS is an S-coordinate (terrain-following) model, in contrast to MITgcm, which is z-level. This allows ROMS to maintain vertical resolution of near-bottom variability, which can be an advantage in coastal regions. In addition, ROMS includes more turbulence closure options than the MITgcm, some of which are thought to be useful in shallow water and coastal regions. It will be useful to compare and contrast the results from these different options. ROMS can now adjust initial conditions (IC) and forcing, but the adjustment of open boundary conditions (OBC) are not yet possible, in contrast to MITgcm, which can adjust IC, OBC, and forcing. In preliminary experiments, ROMS shows strong growth of the adjoint sensitivity (related to model nonlinearities and chaos) over a 1-month period, compared to several months for the MITgcm. These differences are likely due to viscosity differences, but they remain to be explored.

c) Statistical analysis

As a prelude and supplement to the dynamical-model-based assimilation, statistical analysis of the CalCOFI time series has been carried out in order to elucidate links between the observations and climate indices such as SOI, NPO, PDO, and CCS upwelling indices. Work is underway to complete the climatology, including objective interpolation to make smooth maps of larger-scale components such as mean and annual cycle amplitudes and phases (Figure 30).

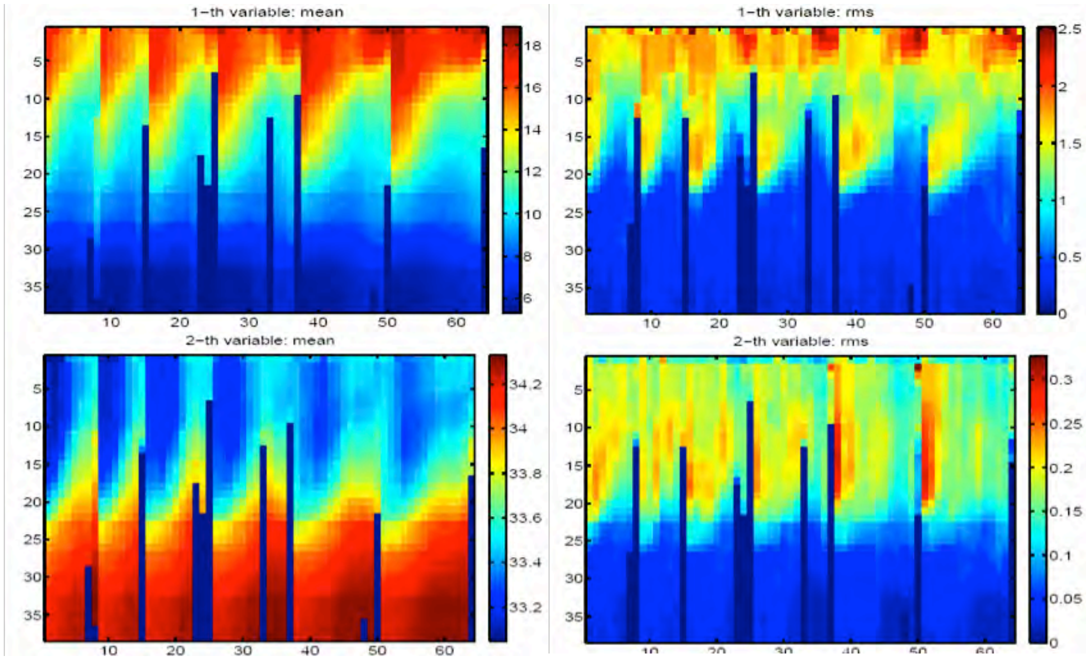


Figure 30. Mean temperature (top left) and salinity (bottom left) for the 25 years of the 64 CalCOFI repeat stations. The cross-shore isotherm tilt is clear in each of the CalCOFI lines. The mean salinity shows the saline undercurent water, tilted up against the coast showing the long term balance between upwelling of the salty deep water and mixing of the surface fresh water of the southward-flowing current. The right panels show total RMS variability for temperature (top) and salinity (bottom) for the CalCOFI stations, including the annual cycle. The variability decreases sharply in the cold and salty deeper water below 200m offshore and about 100m inshore. Salinity variability inshore is less strongly trapped to the surface, but the gradient in variability is sharp, and there is little variability below 200m relative to the surface.

3. NEXT STEPS

In year 4 of the project we will migrate the California Current monitoring system to full operation and start to produce indices and assimilation products. The Solomon Sea efforts will be focused on exploring details about the circulation system for planning a future integrated system there including moorings.

In the Solomon Sea we intend to maintain one glider on the section between Rossel Island and Gizo at all times (requiring a deployment every 3 to 4 months). The first analysis product will be an extended time series of volume, heat, and freshwater transport toward the equator. As the record grows it will be possible to refine the annual cycle and define specific anomalies, perhaps including June 2008. Beginning July 2009 we plan to put a second glider in operation on other transects with the dual purposes of exploring suitable sites for any eventual CORC moorings and partitioning the net transport toward the equator into specific pathways. Collaborator W. Kessler is initiating a modeling program for the area and the comparison of observations and model results will help us refine the limitations of glider monitoring and contribute to CORC's developing picture of the capabilities of different approaches to monitoring boundary currents.

In the California Current, the glider observations will focus on the transport and partitioning of both the equatorward cold-fresh California Current and the poleward warm-salty Undercurrent. Analysis is now underway to summarize our observations of these currents to date as part of the Ph.D. thesis of Robert Todd. He has identified various cores of the CCS and is exploring their time variability. Seasonal cycles and anomaly patterns are being constructed as well as time series of transport. The CCS measurements are also describing how eddies and fronts organize the biology as marked by chlorophyll and acoustic backscatter measurements and provide a baseline for detecting climate-scale variability in the ecosystem. In cooperation with zooplankton biologist Mark Ohman we are seeking compact descriptions of both large-scale and eddy-scale variability in the biology and physics.

Continuous sampling of a single glider will continue on Line 67. Continuous sampling with one ADP-Spray will be continued on Line 90 and sampling will be extended further offshore to reach the CORC mooring at the end of the Line. Our two modem-Sprays, and three additional units to be completed this year, will be placed in service providing acoustic data relay of the mooring and PIES data and more frequent sampling of T, S and chlorophyll.

The acoustic data recovery and transmission via the modem gliders will be made more robust, and as back-up option alternative modems will be tested.

In fall 2009, the moorings and PIES from line 90 will be recovered and all data will be in hand then. Based on the ongoing analyses from gliders, XBTs, mooring/PIES data, and altimetry, such as those presented above, an improved layout of the end-point mooring section and the PIES will be decided. It seems clear that we will have to extend the present length of the section across the California Current, enhance the existing 5 PIES with additional instruments depending on a study of the dominant scales that need to be resolved with these systems. The ARGO and XBT analyses such as those in Figure 3, seemed to suggest an “edge” of the California Current around 130°W. This choice is also supported by contouring the mean surface dynamic topography from blended drifter/altimeter analyses (e.g. Maximenko&Niiler) and the SSH variability, Figure 31. Around 130°W on extensions of CalCOFI lines 80 or 90, there is a minimum in southward surface flow and also the SSH variability has decayed to a minimum there. Offshore of this limit, the boundary current data will be merged with interior ARGO data, as is being studied at present (see section 2.5).

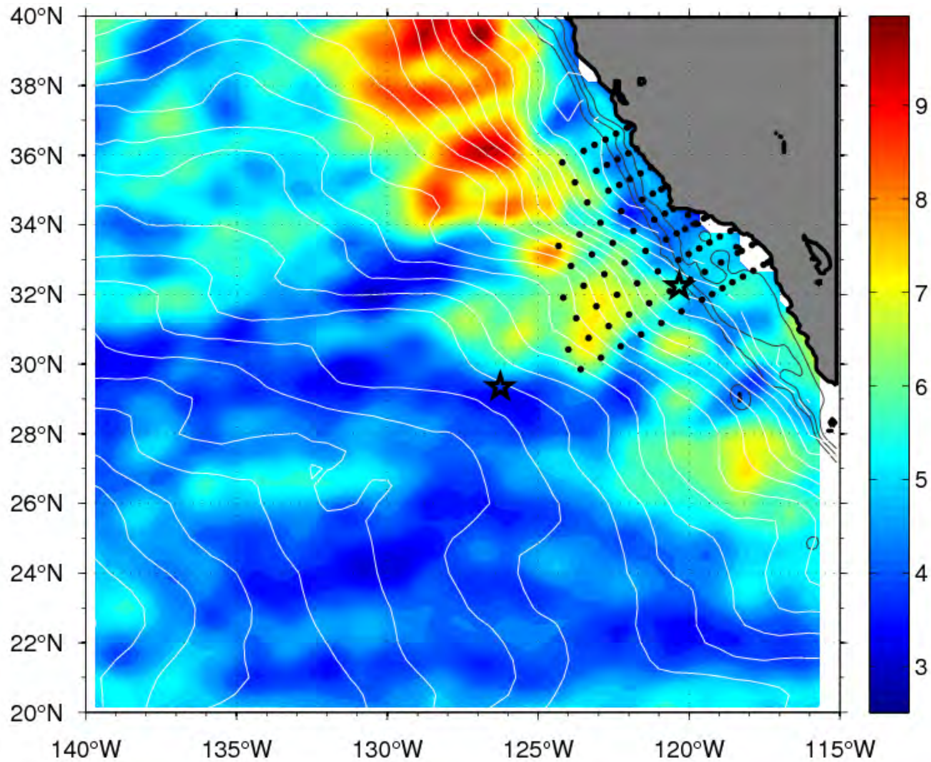


Figure 31. Contour map of rms sea surface height variability in cm (color) from 5 years of altimeter data, and of surface dynamic topography from 6 years of drifter/altimeter data (white contours at 2cm interval). The CalCOFI station grid and the current two CORC moorings are indicated with dots and stars, respectively. At 128-130°W a minimum is found in SSH variability and in the surface flow.

The mooring and PIES (especially bottom pressure) observations will allow to address the more rapid timescales which are not captured or aliased by the glider and XBT data. In addition these timeseries will for the first time quantify the deep flow and its variability (as suggested from Figure 19 and some model results, the flow below 1000m may not be negligible).

The data will be quality checked and used for quantitative analysis of the transports. Data from the moorings, PIES, and gliders will be merged for direct estimates of the transports in near real-time. The telemetered data will also be prepared and provided for assimilation into the model described above in section 2.7. From these data integration activities we will begin to produce indicators and assimilation products in a quasi-operational manner.

For the XBT/ARGO data, work during the coming year will focus on integration of datasets, including Argo, High Resolution XBT, CalCOFI, and CORC glider transects. After defining the offshore extent of the California Current, the transport and variability of the current will be combined with the interior datasets. Fine spatial resolution in the HRX and CORC glider data will enable temperature and velocity fields to be estimated at finer resolution nearshore and more smoothly offshore. A research goal, working with the CORC data assimilation modeling effort, is to study interannual variability in the salinity budget of the salinity minimum in the California Current, including interannual variability due to changes in the salinity of source waters, in the strength of alongshore advection, and in coastal upwelling. The re-initiated sampling of the Honolulu-Los Angeles XBT line will also be maintained, which is supported by the non-CORC XBT grant but directly contributes to the CORC objectives.

For the surface drifter work, analysis of the CALCOFI region, including all the lines that have ADCP will continue. The objective is to provide the CCS model initialization and assimilation velocity fields from both CODE and SVP data sets. The emphasis will be expanded to include real time velocity data sets. In addition, we will build, deploy and test 6 pop-up drifters for the CALSOFI Line 90 deployment in 2009 and starting in 2010 begin to provide pop-up drifters for the Solomon Sea and other CORC relevant areas.

Manpower and computer power are now in place for construction of a multiyear state estimate for the CCS region using glider, mooring, drifter, float, and remotely sensed observations. The assimilation window will be as near to the current time as possible depending on the availability of boundary conditions and forcing fields. The results will be shared with the observation PI's to do analysis and to plan future observational approaches. Studies of the boundary currents in the western pacific will also take place using the output from the tropical pacific model.

The result of the assimilation should provide a dynamically-consistent synthesis of the disparate observations, including those made as part of the project and can be compared with the analyses produced by the PI's making the observations. The state estimate will be dynamically consistent in that the assimilation will produce an adjusted set of controls: initial conditions, boundary conditions, and forcing that can be used with any model (or model resolution) to perform an integration without internal forcings driving the model to the observations.

4. OUTLOOK

In the California Current, we expect to have a sufficient understanding of the cross-shelf scales and flow distributions, the variability, the transports, and the along-shore coherence, to leave in place an efficient monitoring system for the southern California Current by the end of the current CORC phase. It may turn out that it makes most sense to move the mooring/PIES section from line 90 to line 80. In that location, there would also be optimum synergy with the additional carbon/ecosystem moorings planned there.

The assimilation system will be fully running and producing products and indicators for the state of the California Current, including its mass, heat, freshwater transports, its eddy activity, and possibly forcing of carbon and biological processes.

In the last year of the current CORC phase we plan to turn attention to a more comprehensive implementation of the integrated observing system in a western boundary current, most likely the Solomon Sea. The appropriate blend of observing techniques is likely to be different there, compared to the eastern boundary current off California. Reasons are very swift flows which sometimes make it impossible for gliders to reach a specific location, large barotropic and deep-reaching flow components (which require methods other than gliders or XBTs), and rapidly changing eddying flows which strongly alias glider transects. Also the surface flow, as measured by drifters, may show rather different distributions compared to the subsurface current systems. If gliders cannot reliably reach moorings/PIES for acoustic data downloads, it may be necessary to employ surface moorings. Suitable locations in terms of geometry and current intensities will be explored by gliders, drifters, and in collaboration with field work by French collegues.

An example of a flow section derived from a glider crossing of the Solomon Sea is shown in Figure 32. It shows a boundary current of 20-40cm/s in the upper 100m, and 10-20cm below that. Those conditions would allow deployment of an endpoint surface mooring, to capture the full time variability and depth extent of the flow through the Solomon Sea.

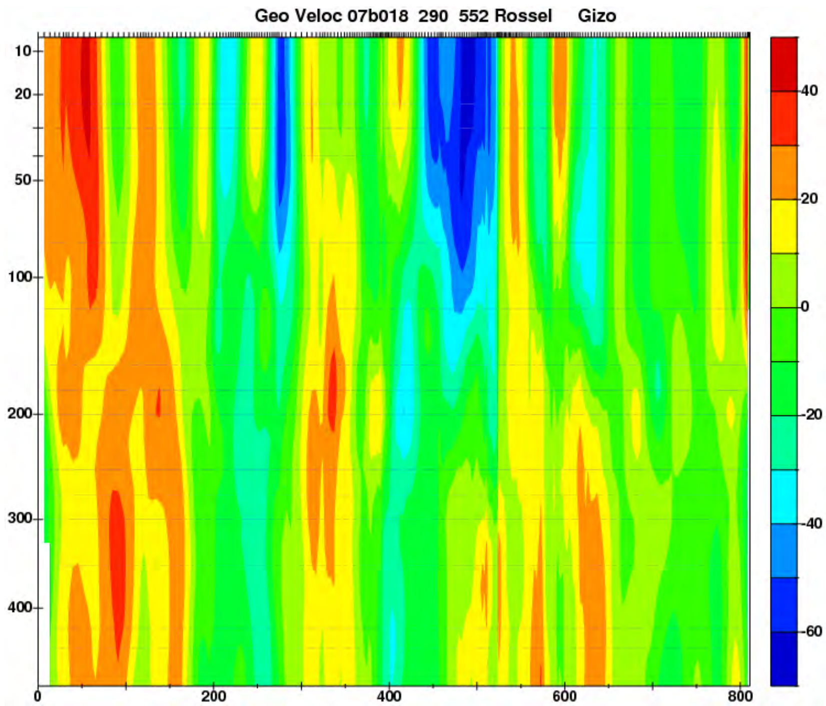


Figure 32. Geostrophic flow referenced to directly measured 0-500m average from a glider section across the Solomon Sea (Rossel to Gizo, see Figure 1). It shows a strong equatorward flow near the boundary, and generally strongly barotropic current distributions.

Glider Sampling of the Solomon Sea

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1. PROJECT SUMMARY

The Solomon Sea Glider Project has two principle objectives: first, to demonstrate newly-developed glider technology as a sustainable means of measuring swift western boundary currents, and second, to use this new instrument to monitor the inflow towards the equator from the South Pacific, which is thought to contribute to the variability of El Niño.

Ocean gliders are small autonomous vehicles based on Argo float technology (see http://www-argo.ucsd.edu/FrAbout_Argo.html/), whose only propulsion is to pump oil in and out of an external bladder. This makes the glider sink and rise in the water, and with its wings it slowly glides forward. It typically dives to 700m depth over 3-4 hours, gliding about 25 kilometers per day, while reporting its data and receiving instructions by satellite each time it surfaces. Although the glider moves slowly, it uses very little power and operates unattended for 4 to 6 months, so it covers a substantial distance. It measures profiles of temperature and salinity, and the current velocity is inferred from the glider's motion. The glider has three important advantages over previous technology: it can be deployed and recovered entirely by small boats near shore, making the operations much cheaper and more flexible than a research ship; it makes continuous observations for much longer periods than is practical for a research ship; and it makes densely-spaced profiles right up to the coast. For these reasons, ocean gliders are likely to play a large role in climate monitoring of the ocean, especially for sampling narrow coastal currents. The Spray glider used in this project is designed and built by the Instrument Development Group at the Scripps Institution of Oceanography, funded by NOAA's Climate Program Office as a new tool for the climate observing system. All aspects of the program are a collaboration among scientists and engineers at NOAA/PMEL, Scripps, and the French laboratory IRD in Noumea, New Caledonia.

The Pacific Ocean circulation encompasses a great overturning cell in which cool, salty water sinks in the subtropics, flows at depth towards the equator, and upwells back to the surface in the eastern equatorial Pacific. Variations of the cell produce slow changes in the temperature of equatorial water, which can then influence the occurrence and strength of El Niño events. Because El Niños affect weather of the entire Pacific and beyond, fluctuations of the overturning cell play a major role in the year-to-year and decade-to-decade variations in climate.

Observations show that perhaps 70% of equatorial upwelling due to the overturning cell originates from the South Pacific, with a large fraction arriving via the narrow boundary currents in the Solomon Sea. (Such powerful western boundary currents are analogous to the Gulf Stream, but flow towards the equator in the tropics). However, measuring these currents has lagged other elements of the circulation because the region is remote and difficult to work in, with strong narrow filaments of current flowing among a complex network of islands and reefs; as a result there have been only sparse measurements that have barely outlined the circulation. Producing a time series of this system is recognized as one of the most important challenges in gaining a full picture of the climate of the Pacific.

The Solomon Sea glider project began in mid-2007, and has conducted four deployment cycles (as of October 2008) in continuous rotation since then. Each round-trip mission lasts 3-4 months, crossing the Solomon Sea to within 5km of the coast on each side. In this initial year, the program has demonstrated first, that gliders are capable of sustained sampling of this piece of the climate system relatively cheaply, and second, that the Solomon Sea boundary current system supports dramatic variability, seen especially associated with the La Niña cold event of early 2008. During FY 2009, we propose to continue deployments, pointed towards establishing an ongoing operational monitoring capability, and to use the accumulating glider data to diagnose the circulation in connection with climate model simulations.

2. ACCOMPLISHMENTS

Work done during FY 2008 was aimed at beginning the observations and establishing the local infrastructure for longterm operations.

All previous South Pacific glider work had been one-off experiments done from research vessels and tied to their availability, but the goal of ongoing monitoring requires the ability to work from shore, using local boats and resources. The Solomon Sea glider project began in July 2007, with a deployment from a French ship (R/V Alis, out of Noumea, New Caledonia) off the coast of Papua New Guinea (PNG). This initial deployment represented a commitment to recover the glider from the Solomon Islands in October without any outside assistance. We had never worked on the ground in the Solomon Islands before, so the principal task in FY 2008 was to establish a local infrastructure for these operations. Initial Papua New Guinea and Solomons EEZ clearances had been obtained for the first deployment, but longterm clearances required substantial negotiation.

The program manager (Kessler) traveled to the Solomon Islands in October 2007 to survey ports, and to arrange boat charters, suitable work and storage spaces, customs clearances, and shipping. The port of Gizo was chosen for the operations, as it gives the shortest cross-Solomon Sea distance, has a reliable local charter service and domestic air and sea transport. He also established cooperative liaison with local authorities and with the Solomon Islands Meteorological Service. He spent a week in Port Moresby, PNG, negotiating an extended EEZ clearance for the glider to sample in their national waters. PNG authorities are generally suspicious of international researchers and a requirement of the clearance is that we be available to explain the data and findings to government (weather service) and other local stakeholders.

Recovery/deployment operations were conducted in October 2007, and in February and July 2008 (another is about to get underway in early November 2008). Two people are required for this work. The at-sea glider is steered (remotely) to Gizo and recovered by small boat. It is inspected, dismantled, the internally-stored (engineering) data downloaded, and the instrument prepared for shipping back to the US. The new glider is received from customs, transported to Gizo, assembled and tested, and deployed. All four missions to date have been completed successfully.

Glider oceanographic data (temperature and salinity profiles, and velocity) are received and processed at the Scripps Institution of Oceanography. The initial (raw) data is available online at
http://spray.ucsd.edu/cgi-bin/archive_init.pl?start_archive=ARCHIVE+DATA.
Although these data remain experimental and not appropriate for routine (operational) use, we are

working towards producing a quality-controlled, delayed-mode data set that would be available on the web and suitable for validation of models.

The initial year of work has been successful in three respects: First, the glider has been shown capable of navigating this environment of swift currents amid a complex network of reefs and islands, while making measurements of currents and water properties that can describe the circulation and its variability. This is proof of concept that the technology is suitable for measuring this current system and was the principle objective of the initial year of the program. Second, the operations can be accomplished by a small crew relatively cheaply, and an ongoing infrastructure for operations out of the Solomon Islands has been established. This is essential for the glider's use as a sustained monitoring tool. Third, the year of sampling encompassed the entire sequence of the 2007-2008 La Niña event, and showed the very large signatures of the event expressed in the boundary current variability. This demonstrates that a monitoring program is likely to yield important information about the climate system of the Pacific.

The initial year also showed intense eddy activity in the Solomon Sea that stretches the limits of the glider sampling. To evaluate the extent of aliasing by these eddies, we have directed the glider on several loops in which it is steered back and forth over the same course repeatedly, so the variations on short timescales can be measured and diagnosed. These signatures are being compared with high-resolution model simulations, which can aid both the interpretation of the glider measurements and also evaluate the models fidelity at fine scales.

3. PUBLICATIONS AND REPORTS

Gourdeau, L., W. S. Kessler, R. E. Davis, J. Sherman, C. Maes and E. Kesternare, 2008: Zonal jets entering the Coral Sea. *J. Phys. Oceanogr.*, **38**, 715-725.

Note: This publication describes initial tests of the glider in the nearby Coral Sea, during the year leading up to the Solomon Sea program. This was an essential pilot study of the potential of the Spray glider to operate in nearshore swift boundary current regimes, and to adequately sample the scales involved. It demonstrated the glider's ability to measure both the absolute vertically-average currents and the relative geostrophic currents to within a few km of the coast. This proved crucial in the identification of a previously-unknown boundary current feature, the 80-km-wide North Caledonian Jet.

High Resolution Climate Data From Research and Volunteer Observing Ships

Christopher. W. Fairall,
NOAA Earth System Research Laboratory, Boulder CO

1. PROJECT SUMMARY

This project involves the measurement of direct high-resolution air-sea fluxes on one to two cruises per year and the development of a roving standard flux measuring system to be deployed on a series of NOAA and UNOLS research vessels to promote the improvement of climate-quality data from those platforms. An adjunct task is maintenance and operation of the C-band scanning Doppler radar and the stabilized wind profiling radar on the NOAA ship *Ronald H. Brown*. Because buoys and most ships and satellites rely on bulk methods to estimate fluxes, another aspect of this project is the use of direct measurements to improve the NOAA/COARE bulk flux algorithm. Originally one cruise was the annual TAO buoy tending cruise to 95 and 110 W on the *Ronald Brown*, but that has been discontinued in favor of an annual cruise to the equatorial Atlantic Ocean with Dr. Bob Molinari (AOML) as part of the African Multidisciplinary Monsoon Analyses (AMMA) and Saharan Dust studies. The second cruise, which also occurs in the fall, is the annual excursion to turn around the Stratus climate buoy at 20 S 85 W. A full suite of direct, inertial-dissipation, and bulk turbulent fluxes are measured along with IR and solar radiative fluxes, precipitation, and associated bulk meteorological properties. This effort represents a partial transition of research from the OGP CLIVAR PACS program to operations under the Climate Observations Program (COP).

The project development is the result of a recent NOAA-sponsored workshop on high-resolution marine measurements (Smith et al., 2003, *Report and Recommendations from the Workshop on High-Resolution Marine Meteorology*, COAPS Report 03-01, Florida State University, pp38) which identified three important issues with the planned NOAA air-sea observation system: 1) the need for a data quality assurance program to firmly establish that the observations meet the accuracy requirements, 2) the need for observations at high time resolution (about 1 minute), 3) and the need to more efficiently utilize research vessels, including realizing their potential for the highest quality data and their potential to provide more direct and comprehensive observations. For seasonal time scales, the net air-sea flux (sum of 5 flux components) must be constrained within 10 Wm^{-2}. Buoys and VOS systems are required to operate virtually unattended for months, so considerations of practical issues (e.g., power availability, instrument ruggedness, or safe access) are balanced against inherent sensor accuracy and optimal sensor placement. As discussed above, an important function of the in situ measurements is to provide validation data to improve NWP and satellite flux fields. Here, high time resolution and more direct observations are invaluable for interpreting surface flux measurements and diagnosing the source of disagreements; such information can be provided by suitably equipped research vessels (R/V). Thus, the accuracy of buoy and VOS observations must be improved and supplemented with high-quality, high time resolution measurements from the US R/V fleet (which is presently underutilized). The necessity for both high time resolution and high accuracy places extreme demands on measurements because some sources of error (such as the effect of ship flow distortion on wind speed) tend to average out over a large sample. To accomplish this task will require a careful intercomparison program to provide traceability of buoy, VOS, and RV accuracy to a set of standards.

This project directly addresses the need for accurate measures of air-sea exchange (Sections 5.2 to 5.4, *Program Plan for Building a Sustained Ocean Observing System for Climate*. The project is a joint effort by ESRL and Dr. Robert Weller of the Woods Hole Oceanographic Institution (WHOI). NOAA COP funds the ESRL component and Dr. Weller is seeking NSF fund for the WHOI component. The ESRL Air-Sea Interaction Group website can be found at: http://www.etl.noaa.gov/et6/air-sea/. ESRL also cooperates with Dr. Andy Jessup (APL University of Washington) on radiative sea surface temperature measurements, Dr. Frank Bradley (CSIRO, Canberra Australia) on precipitation, Drs. M. Cronin and N. Bond (PMEL) on buoy-ship intercomparisons and climate variability analysis, and Dr. Mike Reynolds (DOE BNL) on radiative fluxes. A new website is under construction for this project (High Resolution Climate Observations http://www.esrl.noaa.gov/psd/psd3/air-sea/oceanobs/). An associated website (http://www.esrl.noaa.gov/psd/psd3/wgsf/) contains a handbook on best practices for flux measurements plus a database of high-resolution flux data. This work will be closely monitored by the WCRP Working Group on Surface Fluxes (WGSF) which is chaired by C. Fairall. This will give the project high visibility in the CLIVAR, GEWEX, and SOLAS programs. This project will be managed in cooperation with JCOMM (and other) panels as per instructions of Mike Johnson.

2. ACCOMPLISHMENTS

For the *Ronald Brown* C-band and wind profiler radar project, major maintenance was performed in August 2008 in Charleston, SC, right before the NOAA CPPA VOCALS cruise planned October-November 2008.

ESRL completed three research cruises. The preliminary raw and processed data from these three cruises can be found at ftp://ftp.etl.noaa.gov/et6/cruises.

*The Bob Molinari buoy deployment cruise in the Atlantic in the spring of 2008 (this is the *PNE/AMMA-Saharan Dust* cruise) on board the R/V *Ronald H. Brown*. This cruise was essentially cancelled because of problems with the *Brown* but we manned the cruise and took data on the Uruguay to Charleston transit.

*The NOAA IPY ICEALOT cruise on the R/V *Knorr* (http://saga.pmel.noaa.gov/Field/icealot/). The portable flux standard was installed on the *Knorr* in Woods Hole, MA. The cruise was from Woods Hole, to Tromso, Norway, and back to Iceland. The principal goal of the cruise was to study aerosol-cloud interactions in the Arctic. We also used the cruise for the first intercomparison of the flux standard with a UNOLS ship.

*The joint ESRL/WHOI cruise to the climate reference buoy (25 S 80 W) on board the *Brown* in October 2007. Our role in this cruise is to provide standard observations for the WHOI flux reference buoy and to quality check the R/V *Brown* sensors. We worked with Bob Weller to perform a fairly comprehensive check of radiative flux measurements from the deck of the *Brown*. This included ESRL and WHOI Eppley radiative sensors, the Brown IMET sensors, and a new set of Kipp & Zonen (K&Z) sensors. We also operated the newly developed ESRL pitch-roll stabilized platform with K&Z sensors mounted on it. This comparison has uncovered a bias difference of about 3% between the Eppley and K&Z sensors (see Figure 1). This represents a possible error of 5-10 W/m^2, which exceeds the allowed uncertainty in the surface radiation budget to meet the standards of the flux reference sites. A batch of these sensors was calibrated at the BSRN calibration facility in Boulder over the summer of 2008, but we have not yet resolved the conflict.

ESRL also made two trips to the Coastguard/NSF icebreaker *Healey* to advise on installation and sensors for their new meteorology observations system. We placed sensors on board for a one-week test cruise in January 2008. We worked with the SAMOS group at Florida State University concerning quality control of data from the *Healy*. A preliminary report on this was given at the SAMOS/GOSUD conference in Seattle in June 2008.

In 2007 we produced a synthesis of the main results of the previous five years of strategic observations in the form of three scientific publications. In 2008 we produced a synthesis flux and boundary layer **data set** from the Stratus cruises to the WHOI buoy at 20 S 85 W which is now publically available (http://www.esrl.noaa.gov/psd/psd3/synthesis/). This data set is intended for quality assurance and context for interpreting the buoy observations at this site but the principle reason for this synthesis set is to provide easy to use but very accurate observations for model and ocean data assimilation guidance.

Considerable progress was also made on developing the portable flux standard and implementing ship and buoy intercomparisons for quality assurance. Production of the roving flux standard is now complete. The portable standard was deployed in spring of 2008 (see above).

The PI of this project has been chair the WCRP Working Group on Surface Fluxes (WGSF) since 2003. He also serves on the International Geophysical Union International Climate Dynamics and Meteorology Working Group A (Boundary Layers and Air-Sea Interaction). In 2004 he was invited to join the SOLAS Focus 2 (air-sea flux physics) Working Group to develop the Surface Ocean-Lower Atmosphere Study (SOLAS) International Implementation Plan and has been named to the US SOLAS Advisory Group. In 2008 he joined the CLIVAR High Latitude Flux Working Group (http://www.usclivar.org/hlat.php).

3. PUBLICATIONS

Kara, Birol, Alan J. Wallcraft, E. Joseph Metzger, Harley E. Hurlburt, and C. W. Fairall, 2007: Wind stress drag coefficient over the global ocean. *J. Clim.*, **20**, 5856-5864.
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ftp://ftp.etl.noaa.gov/user/cfairall/oceanobs/pubs/fy08/

Weller, R.A., E.F. Bradley, J. Edson, C.W. Fairall, I. Brooks, M.J. Yelland, and R.W. Pascal, 2008: Sensors for physical fluxes at the sea surface: Energy, heat, water, and salt. *Ocean Sci. Discuss*., **5**, 327-373.
ftp://ftp.etl.noaa.gov/user/cfairall/oceanobs/pubs/fy08/

Ghate, Virendra P., Bruce A. Albrecht, Christopher W. Fairall and Robert A. Weller, 2008:

Climatology of marine stratocumulus cloud fraction in the South-East Pacific using surface longwave radiative flux observations. *J. Clim.*, to appear.

De Szoeke, S.P., C.W. Fairall, and S. Pezoa, 2008: Ship observations coasting South America in the tropical Pacific Ocean. *J. Clim.*, to appear.

4. CONFERENCES

29^{h} Session of the Joint Scientific Committee for the WCRP, World Climate Research Program, Arcachon, France, 31 March–4 April 2008. Presentation: The WCRP Working Group on Surface Fluxes. (http://wcrp.wmo.int/documents/JSC29FinalReport.pdf)

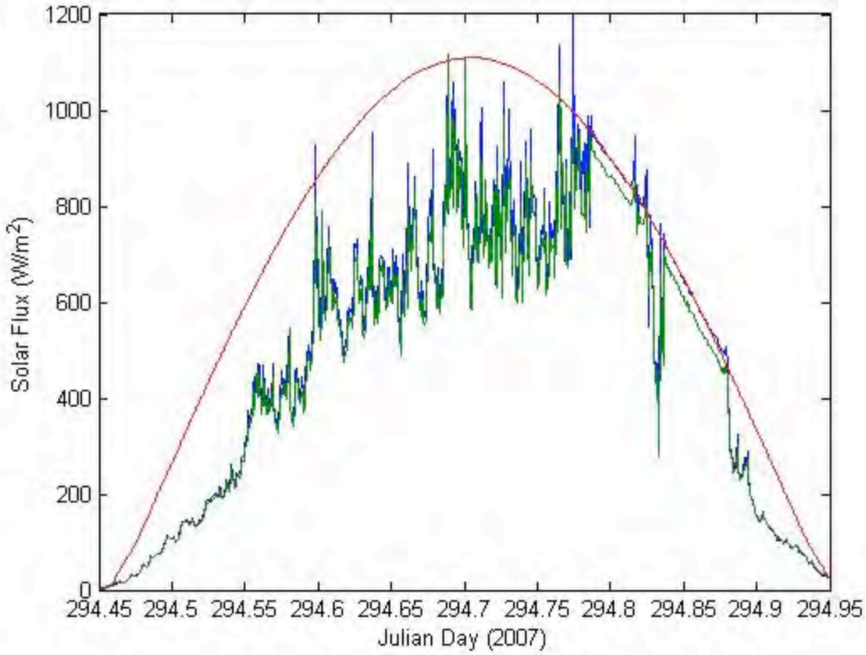
Symposium on Observing the Turbulent Atmosphere: Sampling Strategies, Technology, and Applications. NCAR, 28-30 May 2008, Boulder, CO. Invited talk: *Turbulence measurements for surface-layer micrometeorological studies over sea and sea ice.*

2nd Joint GOSUD/SAMOS Workshop, Seattle, Washington, USA, 10 - 12 June 2008. *Shipboard Meteorological Measurements: Interpretation and Quality Assessments.*

Office of Climate Observation 5th Annual System Review, NOAA, Silver Spring MD, 2-5 September 2008. Poster presented: *The ESRL Portable Seagoing Flux Standard: Preliminary Quality Assessments from Healy and Knorr.*

WCRP WOAP-III meeting, Boulder, CO, 29 Sep.-1 Oct. 2008. Talk presented: *Report on the Working Group on Surface Fluxes: Present Status and Future Plans.*

5. FIGURES



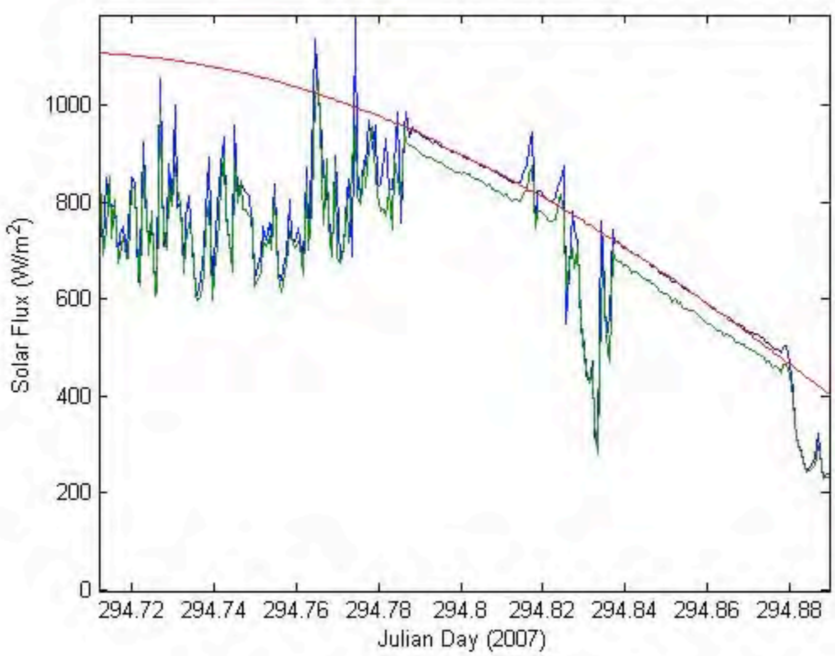


Figure 1. Solar flux vs time at 1-min resolution on from the WHOI flux reference site at 20 S 85 W Julian Day 294: red line – clear sky flux model; blue line – mean of two K&Z sensors; green line - mean of five Eppley sensors. The lower panel is a detail from JD 294.71 to JD 294.89 (4.3 hrs). Clear periods are indicated by very smooth traces of the time series and values near the clear-sky flux model (e.g., between 294.78 and 294.82). Note the green line is about 3% lower than the blue line.

Assimilation, Analysis and Dissemination of Pacific Rain Gauge Data: PACRAIN

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1. PROJECT SUMMARY

Tropical rainfall data taken over both land and ocean is particularly important to the understanding of our climate system. Not only is it a tracer of latent heat, it is vital to the understanding of ocean properties as well, such as latent and sensible heat flux, salinity changes and attendant local ocean circulation changes. In addition, rain gauge observations from low-lying atolls are required to conduct verification exercises of nearby buoy-mounted rain gauges, most of which are funded by NOAA's Office of Climate Observations' (CPO) program.

This project supports the effort to "build and sustain the global climate observing system that is needed to satisfy the long-term observational requirements of the operational forecast centers, international research programs, and major scientific assessments". We also are continuing in our role as the Surface Reference Data Center (SRDC), a core program that supports the Global Precipitation Climatology Project (GPCP) and the Global Energy and Water Cycle Experiment (GEWEX). Our current and future efforts include expanding our mission to collect, analyze, verify and disseminate global rainfall data sets and products deemed useful for Operational Forecast Centers, International Research Programs and individual researchers in their scientific endeavors. Housed in the Environmental Verification and Analysis Center (EVAC) at the University of Oklahoma, the EVAC/SRDC has built upon work from past NOAA-supported projects to become a unique location for scientists to obtain scarce rain gauge data and to conduct research into verification activities. These data are continually analyzed to produce error-assessed rainfall products and are easily assessable via our web page (http://pacrain.evac.ou.edu/). We're also actively involved in research of the tropical rainfall process using data obtained from this project.

Scientists need only to access the PACRAIN web site <http://pacrain.evac.ou.edu> to obtain the most comprehensive Pacific rainfall data set anywhere in the world. The Surface Reference Data Center web site <http://srdc.evac.ou.edu> contains validation data for various regions. Many of these regional data sets are impossible or impractical to obtain elsewhere. The EVAC/SRDC serves the research community by actively working with individual countries in environmentally important locations to help provide them with infrastructure, education and other short and long-term support. The return on this investment by NOAA has been significant in terms of enabling EVAC/SRDC to provide the scientific community with critical, one-of-a-kind rain gauge data sets and to have established ongoing mutually beneficial relationships that should lead to future collaborations. Past successes with this strategy have proven very worthwhile on a cost-benefit basis.

Due to the importance of tropical Pacific rainfall data to climate research and operational and climate forecasting we work collaboratively with the Pacific Island Global Climate Observing System (PI-GCOS) program to effectively and efficiently match the areas of commonality among both CPO's and PI-GCOS's objectives. One of these common areas is the strengthening of the existing Pacific observation climate network for both atmosphere and ocean.

Specifically, we seek to collect all available rain gauge data 1) in environmentally critical locations (e.g. tropical Pacific), 2) where dense rain gauge networks exist and 3) where agreements can be made to help construct rain gauge networks in these critical locations. These data are assimilated, homogenized, and error-checked and then made available to the general research community.

To create the most comprehensive Pacific raingauge database possible it is necessary to continue to work closely with the Pacific meteorological services to help them sustain high their quality gauge networks. One of our most successful efforts during the last few years was (and is) the implementation of a large network of new manual-read rain gauges and automatic data-logger equipped tipping bucket rain gauges located on various atolls and islands managed by the local Pacific meteorological services. A total of approximately 60 automatic, high quality tipping bucket gauges are being operated by various Pacific Island meteorological services. We currently are collecting the data in tip format and converting it to 1 minute resolution. One of new efforts this year has been to conduct research using the tipping bucket data. The research this year has one of the first articles on stochastic modeling tropical rain rates. His paper was published in the International Journal of Climatology.

Our Pacific educational program, SPaRCE (http://sparce.evac.ou.edu/) contributes in a direct way to the PACRAIN database through the contribution of Pacific schools taking manual read daily rain gauge measurements while learning about the importance of weather and climate. Underlying these projects is the long-term effort to help build the capacity of the all the PNMS to better serve their constituents. This will ultimately result in the PNMS being able to self-sustain their data networks. We continue to contribute to this effort by providing what we can in terms of needed supplies, education and communication infrastructure (e.g. involvement in the Radio/Internet; i.e. RANET project) until the PNMS become completely self-sustainable. We also work collaboratively with the Secretariat for Pacific Regional Environmental Programme (SPREP) which is located in Apia Samoa. SPREP acts as a communication conduit through which we communicate and collaborate with the different PNMS. This project is continually in the process of implementation with a portion of the total number of gauges on operational status, some currently being shipped to the Pacific and some needing maintenance. We work particularly close with the New Zealand Meteorological Service and the attached PI-GCOS Technical Support Project to accomplish the later objective.

The PACRAIN data set has been used by many researchers for a variety of purposes (e.g. Delcroix et. al, 1996, Pingping Xie et al., 2007). The uses include incorporate into climate models, climate studies, and the verification of satellite rainfall algorithms.

It is our belief that by working directly with local Pacific island meteorological services, we bring tangible benefits to the global climate research community through data base development and enhancement. In turn, the local meteorological services also benefit directly through enhanced forecast products developed by the scientific community using these critical data sets.

2. ACCOMPLISHMENTS

2.1. Delivering vital rainfall data to the research community through on-line access of the PACRAIN database

Rain rate measurements over open ocean regions are very important in the assessment of satellite rain algorithms climate change and modeling of physical processes. Until recently, no Pacific island rainfall measurements have been available at resolutions less than one hour. Our new MetONE rain gauges tipping bucket gauges are equipped with data loggers and have been donated by the University of Oklahoma for this project. In turn, they have been given to the PI-GCOS Coordinator, headquartered at SPREP, for distribution to the various PNMS. We have deployed over 50 of these gauges throughout the Pacific region during 2008. We are currently receiving rainfall tip data back from many PNMS and these data are inserted into the PACRAIN database. These data are particularly important in the understanding of basic tropical rain systems and consequently, more accurate global climate models. These data are all included in the PACRAIN database.

The achievement of this objective could not be accomplished without the close collaboration of the PI-GCOS Steering Group and the current PI-GCOS Coordinator. Other important collaborative groups are the Global Ocean Observing System (GOOS), the New Zealand Meteorological Service, and the New Zealand Institute for Research in Water and Atmosphere, the Australian Bureau of Meteorology, Meteo-France and the US National Weather Service.

PI-GCOS Tipping Bucket Project Web site and related web sites:
http://pacrain.evac.ou.edu (PACRAIN site)
http://srdc.evac.ou.edu (SRDC site)
http://sparce.evac.ou.edu (Schools of the Pacific Rainfall Climate Experiment, SPARCE)
http://www.pi-gcos.org/ (the P.I. initiated the PI-GCOS web site in collaboration with the GOSIC project at the University of Delaware. It now under the auspices of the NOAA National Climatic Data Center).

Figure 1. Installing a METONE Tipping Bucket Gauge at the Samoa Meteorological Service

2.2. Provide high spatial density world regional rain gauge datasets for use in satellite rainfall algorithm verification

EVAC maintains a database of selected high density raingauge network data for use in satellite rainfall algorithm assessment. Parts of our responsibilities include operating the Surface Reference Data Center (SRDC), which is associated with the Global Precipitation Climatology Project (GPCP). Our tasks in this capacity include identifying and collecting these data sets and making them available to researchers for this purpose. We also conduct studies on the errors involved when comparing satellite and rain gauge data. During 2008 we began research on the rain rate characteristics of tropical rainfall by developing a tropical point process model. The fit of the model at various temporal scales was tested using the data from the tipping bucket gauges.

The results of our research (Figure 2) indicate that the model is able to reproduce the rain rate statistics computed from Tongan METOne gauges quite well. This study would not have been possible without the tipping bucket data. The model now can be further tested at other sites which will allow the assessment the statistical characteristics unique to tropical rainfall.

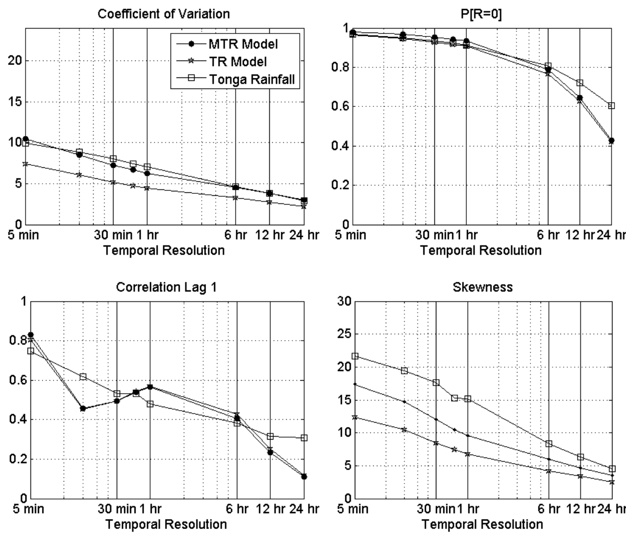


Figure 2. Comparison of the the newly developed rainfall model with Tongan rain rate statisitcs at different time resoltuions.

2.3. Maintain and Improve an Error-assessed PACRAIN Database

The core asset of PACRAIN and SPaRCE programs is the online rainfall database. This database contains historical data from several sources, and is updated monthly with the latest data from three sources: the National Climatic Data Center (NCDC), the National Institute for Water and Atmospheric Research (NIWA) in New Zealand, and the SPaRCE program. Additional updates are done as needed. The *pacusers* mailing list is maintained as a way to disseminate information and provide support to PACRAIN users (http://pacrain.evac.ou.edu/pacusers.html). Database changes are also cataloged online (http://pacrain.evac.ou.edu/changes.html). Some database statistics:

- ~2 million observations
- ~8 thousand observations added each month
- 839 sites
- monthly data with some records beginning in 1874
- daily records begin in 1942

Over the past few years the PACRAIN database has undergone a number of upgrades, and this trend continued in FY 2006. Previous upgrades focused on infrastructure, but the most recent improvements have been to the underlying data. The quality control of PACRAIN data is an ongoing process, and errors are corrected as they are discovered. A comparison of PACRAIN records to satellite data was performed in May to evaluate the accuracy of PACRAIN timestamps.

In addition to specific database upgrades, other routine activities continued throughout the year. The PACRAIN database continues to be upgraded on a monthly basis with data from the Schools of the Pacific Rainfall Climate Project (SPaRCE) project, the National Climatic Data Center, New Zealand Institute for Research in Water and Atmosphere (NIWA), and directly from the individual PNMS. Also, several journal articles have been accepted into print which details the PACRAIN operations and objectives.

2.4. Current Status of PACRAIN Database

- More than 150,000 records added to the PACRAIN database, including almost 50,000 tipping bucket gauge observations.
- The PACRAIN data base was modified to allow for high-resolution tipping bucket gauge data.
- The high resolution tipping bucket gauges incorporating data loggers which are now operational (since last year) are located in these countries:

    - Cook Islands: 4
    - Kiribati: 6
    - Tuvalu: 4
    - Samoa: 3

- A total of 200 plastic rain gauges have been sent to various Pacific Island Meteorological Services.
- New software (a Microsoft Excel add-in) has been developed for use by the individual meteorological services for easy download of tip data from these gauges.
- Enhanced support of the PI-GCOS tipping bucket guge network through technical support and the distribution of supplies (data loggers, batteries, etc.)
- Preliminary design completed for new PACRAIN web site; new database functionality nearly complete

2.5. Survey of PACRAIN Usage

a) User Requests

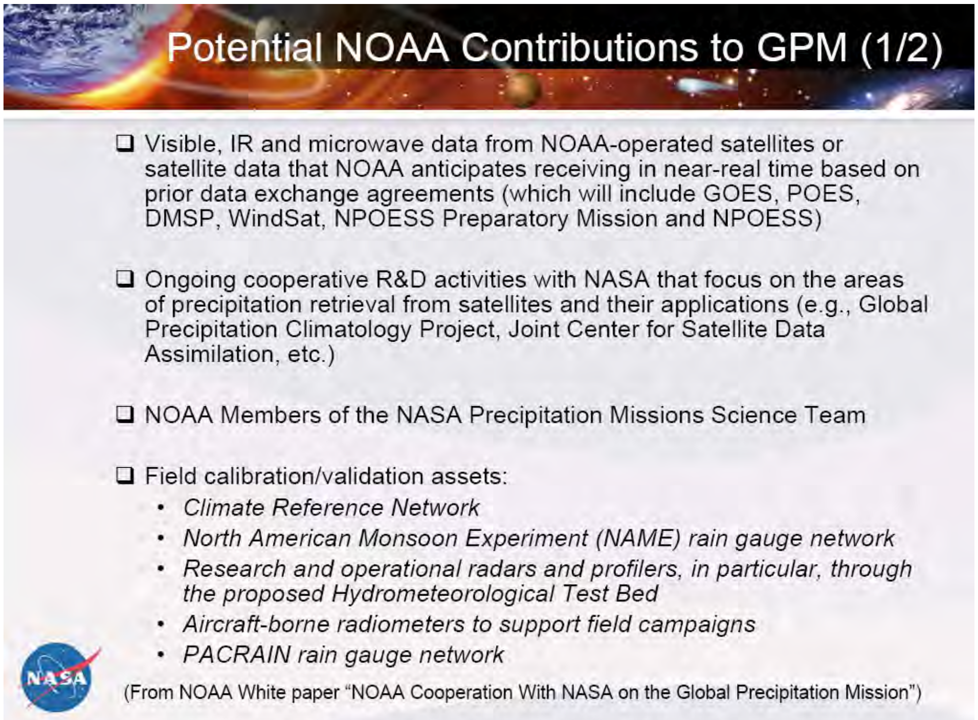
Last year we conducted a survey of the users of the PACRAIN database. We maintain query log on our server which goes back 26 months. In that time, 98 users (distinct e-mail addresses, excluding us) have made 153 queries that returned 45 million records. Almost half of all queries return at least 1000 records. Most users are one-time visitors, and approximately 15% have made more than one query.

The server logs only go back one month. In that time, the full dataset has been downloaded 14 times, and the monthly update has been downloaded 11 times.

b) Institutional Usage

The PACRAIN database is hosted on NASA Goddard's Global Change Master Directory (http://gcmd.nasa.gov/records/GCMD_ATOLL_RAIN_PACIFIC.html) and linked from a number of project web sites such as PI-GCOS: http://www.pi-gcos.org/data_access.htm, UCAR's CISL Research Data Archive (http://dss.ucar.edu/datasets/ds484.0/), the U.S. Global Change Research Information Office (http://www.gcrio.org/datainfo/index.html). The PACRAIN dataset also makes up part (303 stations) of the Global Historical Climate Network (GHCN) (http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php) developed and maintained by NOAA's National Climatic Data Center (NCDC). The dataset forms an intergral part of many international project such as the Global Precipitation Climatology Project (GPCP). There are also many international organizations which link to our server (SOPAC, http://www.pacificwaterefficiency.com/links.html).

The PACRAIN dataset will also form a critical component of NASA Global Precipitation Measurement Program (GPM) (see below).



One of the most important operational use of the PACRAIN dataset is it's inclusion in the CMAP satellite/raingauge merged global precipitation estimates, managed by Pingping Xie from NOAA's Climate Prediction Center (see below).

CMAP

The CPC Merged Analysis of Precipitation ("CMAP") is a technique which produces pentad and monthly analyses of global precipitation in which observations from raingauges are merged with precipitation estimates from several satellite-based algorithms (infrared and microwave). The analyses are are on a 2.5 x 2.5 degree latitude/longitude grid and extend back to 1979. These data are comparable (but should not be confused with) similarly combined analyses by the Global Precipitation Climatology Project which are described in ***Huffman et al*** (1997).

It is important to note that the input data sources to make these analyses are not constant throughout the period of record. For example, SSM/I (passive microwave - scattering and emission) data became available in July of 1987; prior to that the only microwave-derived estimates available are from the MSU algorithm (***Spencer*** 1993) which is emission-based thus precipitation estimates are avaialble only over oceanic areas. Furthermore, high temporal resolution IR data from geostationary satellites (every 3-hr) became available during 1986; prior to that, estimates from the OPI technique (***Xie and Arkin*** 1997) are used based on OLR from polar orbiting satellites.

c) Research Usage

The following list is an abbreviated list of sampled refereed journal articles citing use of the PACRAIN database :

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Greene, J. S., B. Paris, M. Morrissey, 2007: Historical changes in extreme precipitation events in the tropical Pacific region. *Climate Res.*, **34**, 1-14.

Xie, P. P., A. Yatagi, M. Y. Chen, et al., 2007: A gauge-based analysis of daily precipitation over East Asia. *J. Hydromet.,* **8**, 607-626.

Huffman, G.J., R.F. Adler, D.T. Bolvin, G. Gu, E.J. Nelkin, K.P. Bowman, Y. Hong, E.F. Stocker, D.B. Wolff, 2007: The TRMM Multi-satellite Precipitation Analysis: Quasi-Global, Multi-Year, Combined-Sensor Precipitation Estimates at Fine Scale. *J. Hydrometeor.*, **8**(1), 38-55.

Huffman, G.J., R.F. Adler, D.T. Bolvin, G. Gu, E.J. Nelkin, K.P. Bowman, Y. Hong, E.F. Stocker, D.B. Wolff, 2007: The TRMM Multi-satellite Precipitation Analysis: Quasi-Global, Multi-Year, Combined-Sensor Precipitation Estimates at Fine Scale. *J. Hydrometeor.*, **8**(1), 38-55.

Islam, M. N. and H. Uyeda, 2007: Use of TRMM in determining the climatic characteristics of rainfall over Bangladesh. *Remote Sens. Environ.,* **108**, 264-276.

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Xie, P. P., J. E. Janowiak, P. A. Arkin, et al., 2003: GPCP Pentad precipitation analyses: An experimental dataset based on gauge observations and satellite estimates. *J. Climate*, **16**, 2197-2214.

Kummerow, C., Y. Hong, W. S. Olson, et al., 2001: The evolution of the Goddard profiling algorithm (GPROF) for rainfall estimation from passive microwave sensors. *J. Appl. Meteor.*, **40**, 1801-1820.

Adler, R. F., C. Kidd, G. Petty, et al., 2001: Intercomparison of global precipitation products: The third Precipitation Intercomparison Project (PIP-3). *Bull. Am. Meteor. Soc.*, **82**, 1377-1396.

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Adler, R. F., G. J. Huffman, D. T. Bolvin, et al., 2000: Tropical rainfall distributions determined using TRMM combined with other satellite and rain gauge information. *J. Appl. Meteor.*, **39**, 2007-2023.

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Morrissey, M. L. and J. S. Greene, 1998: Uncertainty analysis of rainfall algorithms over the tropical Pacific. *J. Geophys. Res. Atmos.*, **103**, 19569-19576.

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Huffman, G. J., 1997: Estimates of root-mean-square random error for finite samples of estimated precipitation. *J. Appl. Meteor.*, **36**, 1191-1201

Ferraro, R. R., 1997: Special sensor microwave imager derived global rainfall estimates for climatological applications. *J. Geophys. Res. Atmos.*, **102**, 16715-16735.

Lin, B. and W. B. Rossow, 1997: Precipitation water path and rainfall estimates over ocean using special sensor microwave imager and International Satellite Cloud Climatology Project data. *J. Geophys. Res. Atmos.*, **102**, 9359-9374.

Maliekal, J. A. and T. J. Petroski, 1996: Evidence of secular changes in rainfall data from the tropical western and central Pacific over a 20-year period. *Geophys. Res. Letters*, **23**, 2621-2624.

Morrissey, M. L. and N. E. Graham, 1996: Recent trends in rain gauge precipitation measurements from the tropical Pacific: Evidence for an enhanced hydrologic cycle. *Bull. Amer. Meteor. Soc.*, **77**, 1207-1219.

Morrissey, M. L. and J. E. Janowiak, 1996: Sampling-induced conditional biases in satellite climate-scale rainfall estimates. *J. Appl. Meteor.*, **35**, 541-548.

d) Comments from Project Coordinators and PACRAIN USERS

From Dr. George Huffman, Mesoscale Atmospheric Processes Branch, NASA Goddard:
Dear Mark - It was good to catch up with your activities when we chatted at the 88th Annual Meeting of the AMS in New Orleans last week. The group of which I am part, the precipitation research group in the NASA/GSFC Laboratory for Atmospheres, will be very interested in seeing how the tipping bucket gauges work out.

This interest is, of course, a continuation of our long-term interest in, and use of, the PACRAIN data for various comparison and validation activities. As we produce and update the Global Precipitation Climatology Project (GPCP) monthly and daily products, and develop the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA; both in and after real-time), it is critical to understand how well the products are performing. The PACRAIN dataset is unique in providing us with a long, continuous record at many locations across the vast expanse of the tropical Pacific. One recent example is our use of the PACRAIN atoll data in

Huffman, G.J., R.F. Adler, D.T. Bolvin, G. Gu, E.J. Nelkin, K.P. Bowman, Y. Hong, E.F. Stocker, D.B. Wolff, 2007: The TRMM Multi-satellite Precipitation Analysis: Quasi-Global, Multi-Year, Combined-Sensor Precipitation Estimates at Fine Scale. *J. Hydrometeor.*, 8(1), 38-55.

The Kwajalein Island radar and the TAO/TRITON buoys provide additional unique data, but they cover a different scale and region, respectively, and cannot replace PACRAIN or replicate its period of record.

It is important to our work that the PACRAIN data are maintained in a coherent, accessible Web location that minimizes the amount of time we spend dealing with obtaining such data. This allows us to focus on our core activity - combining precipitation estimates from as many sensors as possible to establish a unified global record of precipitation.

Please let us know how the tipping bucket work is progressing.
George

George J. Huffman, Ph.D. (Voice) +1 301-614-6308
Sci. Sys. & Appl., Inc. (FAX) +1 301-614-5492
NASA/GSFC Code 613.1 (Email) george.j.huffman@nasa.gov *new*
Greenbelt, MD 20771 USA (Office) Bld. 33 Room C417

From John Janowiak, Climate Prediction Center:
As for PACRAIN, I think that it's an indispensable data base for calibrating and validating satellite precipitation algorithms. It is a unique resource that provides in situ measurements of precipitation over much of the tropical Pacific, which is a vitally important region where knowledge of rainfall amount and it's distribution is required for many reasons, particularly for assessing model precipitation forecasts. I've used the PACRAIN data to make quantitative assessments of satellite-derived precipitation estimates. These data are also used in CPC's CMAP global precipitation analyses.

John Janowiak
NOAA/NWS/NCEP/Climate Prediction Center
voice: (301) 763-8000 ext. 7537
email: john.janowiak@noaa.gov

From Pingping Xie, NOAA's Climate Prediction Center

Hi, Mark,

Your Pacific atoll gauge rainfall is extremely important for many of the research, development and operational activities at NOAA Climate Predictions. In addition to what have already covered in John's statement, I would like add that we also use your atoll gauge data as part of the inputs to the CMAP merged analysis of precipitation which is widely applied in climate monitoring, climate assessment, climate diagnostics, and climate model verifications. In one sentence, we absolutely need your atoll gauge rainfall data.

Pingping Xie, CPC

Letter from Dr. Thomas Peterson, NOAA's NCDC

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL ENVIRONMENTAL SATELLITE DATA
AND INFORMATION SERVICE
NATIONAL CLIMATIC DATA CENTER
151 PATTON AVE ROOM 120
ASHEVILLE NC 28801-5001

February 4, 2008

Prof. Mark Morrissey
Department of Meteorology
University of Oklahoma
Norman, OK 73019

Dear Prof. Morrissey,

As you know, we were delighted to be able to incorporate your Pacific Island rainfall data set, PACRAIN, into the Global Historical Climatology Network (GHCN) version 2 precipitation data set. Scientists all over the world have been downloading GHCN precipitation data free of charge from http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/ and using the data for a wide variety of analyses.
I just discussed the plans for GHCN version 3 precipitation data set and confirmed that PACRAIN is an integral part of global precipitation data as it provides important observations across a wide expanse of the globe where other sources of in situ precipitation measurements are sparse. In addition to being used in the monthly version of GHCN, PACRAIN has been incorporated into GHCN daily which has been used to provide valuable information on changes in extremes. Both GHCN data sets, which means both daily and monthly versions of your PACRAIN data, were used in analyses presented in the Nobel Prize winning Intergovernmental Panel on Climate Change's Fourth Assessment Report.

Thank you for your valuable contribution to these endeavors.

Regards,

Thomas C. Peterson

A NATIONAL RESOURCE FOR CLIMATE INFORMATION

2.5. Enhancement of Educational Outreach Component of the SPaRCE Program

For the past 15 years the Schools of the Pacific Rainfall Climate Experiment (SPaRCE) project at the University of Oklahoma has been working directly with elementary and high school teachers around the Pacific. During this time, we have also worked informally with the Pacific island meteorological services to aid them with their own local educational outreach projects. However, given the age of the SPaRCE materials there is a need to upgrade them to include more relevant information, e.g. the PI-GCOS program, Global Warming, cyclones, cyclone preparation brochure, etc.

As the meteorological services in the Pacific islands continue to expand and enhance their technological capabilities, there is an increased awareness and appreciation by meteorological service personnel for the need of an educated public. For example, more cooperative climate observer networks are being proposed and implemented in these countries, modeled after the U.S. Cooperative Observers Network (e.g. in Vanuatu, Samoa, and Tonga). There are many challenges in implementing a sustainable cooperative observer program in the developing tropical Pacific island nations, one of which is the availability of easily understood educational materials that can be used by meteorological service personnel in recruiting and training potential observers. In addition, disasters such as the December 2004 tsunami have emphasized the need for a basic understanding of any potentially dangerous phenomenon, such as hurricanes, by the general public. The SPaRCE program is uniquely situated to be able to both continue collaborating directly with schools, and to aid the meteorological personnel in the islands to develop easily understood educational materials that can be used in a variety of circumstances. Additional funding for the SPaRCE program will be used to provide Pacific island meteorological services with low-cost rain gauges for their cooperative observer networks, and to hire a student to work with meteorological service personnel to develop and deliver educational materials aimed at both potential cooperative observers as well as the general public. In addition, these additional materials would be available through the Pacific-RANET project's satellite/internet broadcasts.

2008 Progress Related to the SPARCE Program

Completed:

- Significant update of raingauge data from SPaRCE schools
- Sent 100 new rain gauges and thermometers to schools
- Sent 125 rain gauges to Solomon Islands
- New recruitment documents created (application, teacher survey, site survey, etc.).
- Created a computer data base of schools and addresses.
- Additions to workbook.
- Letters sent to schools in which we have not received data from in over six months. From these letters. Replies with new data and new teachers are currently coming in.
- Development of a workbook supplement to send to schools along with the newsletter so they can add to the existing workbook four times a year.
- Newsletters sent out in March, June, September, and December.
- Mailed out 2009 data sheets with newsletter in September.

Ongoing Activities:

- Rewriting the SPaRCE brochure.
- Contacting various meteorological services for addresses of local schools.
- Working on sending out a large mailing to schools we have had in the past

and new schools (about 150 total + addresses from meteorological services), to join SPaRCE.

- Workbook updates.

3. PUBLICATIONS, WORKSHOPS, AND CONFERENCE PRESENTATIONS

3.1. 2008 Publications

Refereed Book Chapters

Morrissey, M.L. and J.S. Greene, 2007: "'Ground Validation for the Global Precipitation Climatology Project" in "*Measuring Precipitation from Space - EURAINSAT and the future*" Levizzani, Vincenzo; Bauer, Peter; Turk, F. Joseph (editors), 2007, Approx. 745 p., Hardcover ISBN: 978-1-4020-5834-9. P. 381-392.

Gruber, A., B. Rudolf, M.L. Morrissey, T. Kurino, J. Janowiak, R. Ferraro, R. Francis, A. Chang and R.F. Adler, 2007: 'The Global Precipitation Climatology Project" in "*Measuring Precipitation from Space - EURAINSAT and the future*" Levizzani, Vincenzo; Bauer, Peter; Turk, F. Joseph (editors), 2007, Approx. 745 p., Hardcover ISBN: 978-1-4020-5834-9. P. 25-36.

Journal Articles

Morrissey, M.L., 2008: Superposition of the Neyman-Scott Rectangular Pulses Model and the Poisson White Noise Model for the Representation of Tropical Rain Rates. *Journal of Hydrometeorology*: doi: 10.1175/2008JHM1039.1

Morrissey, M.L. and J.S. Greene, 2008: A theoretical framework for the sampling error variance for three-dimensional climate averages of ICOADS monthly ship data, *Theoretical and Applied Climatology*, doi 10.1007/s00704-008-0027-3

Greene, J.S., M. Klatt, M.L. Morrissey, and S. Postawko, 2008: "The Comprehensive Pacific Rainfall Database: An enhanced tool for research and education", *Journal of Atmospheric and Oceanic Technology*, 25, pp. 71-82.

Conference Presentations

Klatt, M., M.L. Morrissey, S. Postawko and J.S. Greene, 2007: "Assimilating tipping bucket rain gauge data into the PACRAIN database", presented at the 88th AMS Annual Meeting, New Orleans, January 24, 2008.

5. Ships of Opportunity

a. SIO High Resolution XBT Transects

b. Ship of Opportunity Program (SOOP), Volunteer Observing Ships, Expendable Bathythermograph (XBT) and Environmental Data Acquisition Program

c. Ship of Opportunity (VOS)

SIO High Resolution XBT Transects

Dean Roemmich, Bruce Cornuelle, Janet Sprintall and Glenn Pezzoli
Scripps Institution of Oceanography
University of California San Diego, La Jolla CA

1. PROJECT SUMMARY

The High Resolution Expendable Bathythermograph (HR-XBT) network was initiated in 1986 along a commercial shipping route between New Zealand, Fiji, and Hawaii. It was subsequently expanded during the 1990's to include basin-spanning temperature transects in all of the oceans. Major partners in the HR-XBT network include Scripps (Pacific and Indian Ocean), NOAA/AOML (Atlantic), and CSIRO (SW Pacific, Indian). Typically, each transect is repeated on a quarterly basis to resolve variability in temperature, geostrophic circulation and transport on annual and longer periods. A technician is on board in order to carry out sampling, with XBT probe spacing at 50 km or less in the ocean interior and as fine as 10-15 km in boundary currents. The ship rider also provides technical support for ancillary programs including improved marine meteorological sensors (VOS-IMET), Argo float and surface drifter deployments, underway thermosalinograph, and water sampling. Figure 1 shows the present transects sampled by the Scripps HR-XBT program and its partners in the Indian and Pacific Oceans. A typical temperature section is shown in Figure 2.

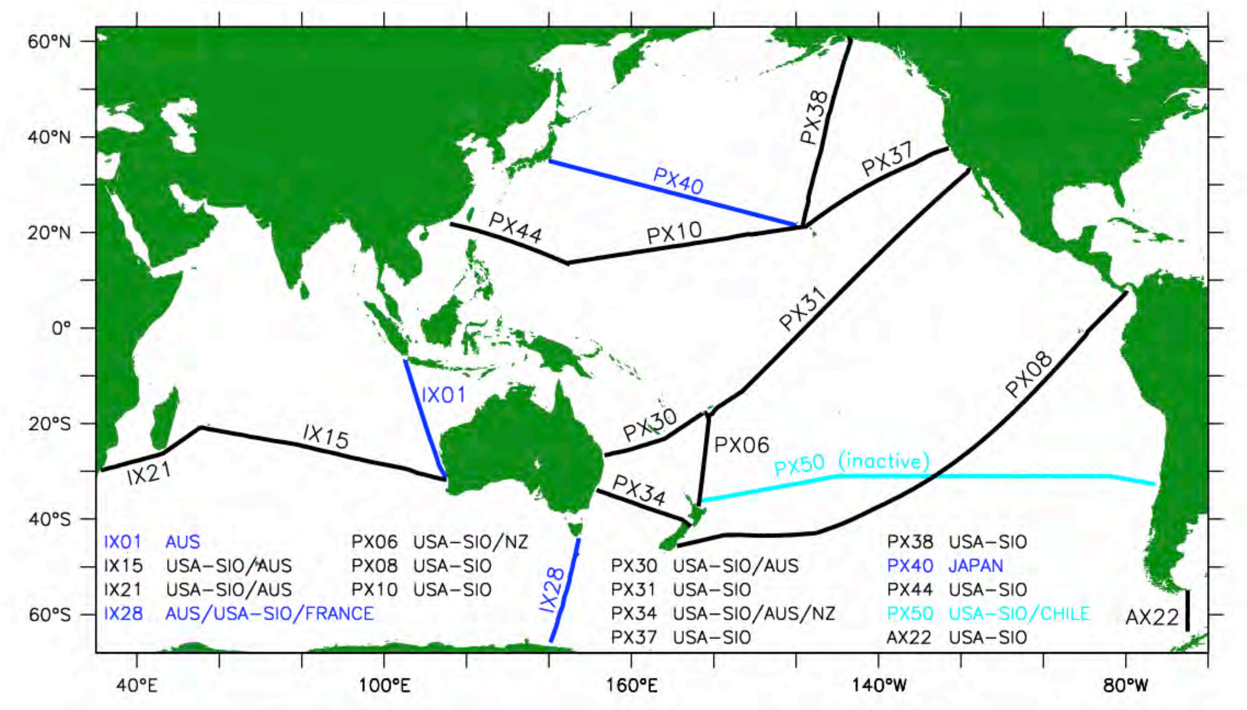

Figure 1. The HRX Network in the Pacific and Indian Ocean. International partnerships are indicated in the notes on the bottom of the figure.

Scientific Objectives

A primary scientific goal of the HR-XBT network is to determine whether interannual variability in the transport of heat by ocean currents is a major contributor to the heat budget of the ocean and hence to air-sea interactions and feedbacks in the climate system. Specific scientific objectives of the HR-XBT program are to:

- Measure the seasonal and interannual fluctuations in the transport of mass, heat, and freshwater across transects which define large enclosed ocean areas.
- Determine the long-term mean, annual cycle and interannual fluctuations of temperature, geostrophic velocity and large-scale ocean circulation in the top 800 m of the ocean.
- Obtain long time-series of temperature profiles at precisely repeating locations in order to unambiguously separate temporal from spatial variability.
- Determine the space-time statistics of variability of the temperature and geostrophic shear fields.
- Provide appropriate *in situ* data (together with Argo profiling floats, tropical moorings, air-sea flux measurements, sea level etc.) for testing ocean and ocean-atmosphere models.
- Determine the synergy between HR-XBT transects, satellite altimetry, Argo, and models of the general circulation. What are the minimal sampling requirements for *in situ* data?
- Identify permanent boundary currents and fronts, describe their persistence and recurrence and their relation to large-scale transports.
- Estimate the significance of baroclinic eddy heat fluxes.

In the context of NOAA's *Program Plan for Building a Sustained Ocean Observing System for Climate,* the HR-XBT Network is a part of the Ship-of-Opportunity Networks. It directly addresses objective 3 of the Plan: *Document the ocean's storage and global transport of heat and fresh water.*

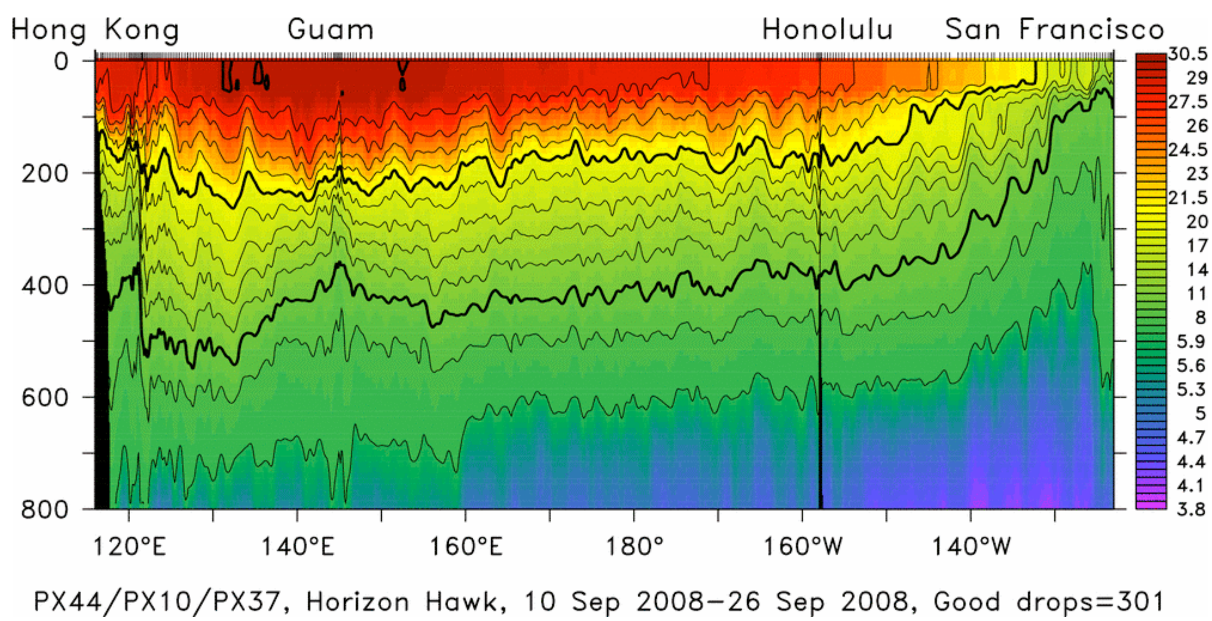

Figure 2. Example of a recent temperature transect with 301 XBT profiles along PX37/10/44.

The configuration of the HR-XBT Network is in accordance with the recommendations of the Upper Ocean Thermal Review (Melbourne, 1999, see http://www.brest.ird.fr/soopip/). The Scripps HR-XBT network is managed for compatibility with the NOAA/SEAS system, and all XBT casts are transmitted (Global Telecommunications System) in near real-time for operational users as well as sent to NODC for archiving. The HRX Network is managed in accordance with the Global Climate Observing System (GCOS) Ten Climate Monitoring Principles.

2. ACCOMPLISHMENTS

2.1.Observations

HRX transects were collected by ship riders along the routes illustrated in Figure 1, and as described in the previous section, in the following months, including yearly sums for total XBT drops and good (or partially good) XBT drops:

PX37/10/44 (North Pacific - San Francisco to Hawaii to Guam to Hong Kong)
4 transects: Oct 2007, Feb 2008, May 2008, July 2008 (1221 good/1243 total drops)

PX38 (North Pacific – Hawaii to Alaska)
4 transects: Dec 2007, Feb 2008, April 2008, August 2008 (354 good/356 total drops)

PX08 (South Pacific – New Zealand to Panama)
3 transects: Oct 2007, Feb 2008, August 2008 (701 good/708 total drops)
+ 2 transects on PX50 NZ to Chile Dec 2007, March 2008 (499 good/502 total drops)

PX06/31 (Central Pacific – New Zealand to Fiji to California)
4 transects: Nov 2007, Feb 2008, May 2008, August 2008 (1076 good/1151 total drops)

PX30 (South Pacific – Brisbane to Fiji, collaborative with Australia)
4 transects: Nov 2007, Feb 2008, May 2008, August 2008 (450 good/480 total drops)

IX21/6 (South Indian – Durban to Mauritius to Strait of Malacca)
4 transects: Oct 2007, Feb 2008, May 2008, June 2008 (826 good/835 total drops)

IX15/31 (South Indian – Mauritius to Fremantle to Bass Strait)
4 transects: Oct 2007, Jan 2008, April 2008, July 2008 (865 good/882 total drops)

The sampling objectives, which are 4 transects per year, have been met on all lines. The probe total for all lines is 5992 good/6157 total (97% yield). The preferred South Pacific line is PX50 (New Zealand to Chile). Due to a lack of shipping, this is done as PX08 (New Zealand to Panama), with occasional research vessel transits on PX50. The South Indian line, IX21/15 (Durban to Mauritius to Fremantle) is done using two ships, and with a ship-rider already on board we've sampled IX-6, Mauritius-Strait of Malacca, as well.

In addition, logistical assistance and/or some XBT probes are provided collaboratively (480 probes per year are as part of our collaboration with CSIRO) for:

PX34 (South Pacific – Wellington to Sydney)
IX28 (Southern Ocean – Hobart to Antarctica)
AX22 (Southern Ocean - Drake Passage, occasionally providing a ship rider)

2.2. Logistics

The commercial shipping industry has undergone enormous change since the beginnings of the HR-XBT network 20 years ago. With respect to HR-XBT sampling, there are two main changes. First, consolidation in the industry has resulted in the elimination of many shipping routes and an increasing reliance on feeder vessels. Second, ships remain on a given line for a much shorter period of time, necessitating frequent recruitment/changeover to new vessels. Specific impacts on HRX sampling include:

1. Elimination of the preferred South Pacific route (PX50) in 2003. The best alternate is PX08, with occasional PX50 transits by research vessels.
2. Occasional disappearance of IX15/21. We re-initiated sampling in September 2005 using two vessels (including a feeder vessel on IX21), and enlisted collaborative support from the University of Capetown. This line appears stable for the time, though is going to Bass Strait rather than Fremantle. It is logistically very difficult due to its remote location.
3. Serious reduction in tanker traffic along PX38.

All of these logistical issues result in increasing demands on the HR-XBT program's operations manager and the staff of trained ship riders, for recruitment and setup of new vessels. The transient nature of remote commercial shipping routes will continue. Our strategy is to continue sampling at our full capacity, but to shift to alternate routes with high scientific value in case shipping is unavailable along primary routes.

2.3. Development and technical issues

The most substantial XBT technical issue of the past year has been the identification of a (warm) temperature bias due to variations over time of XBT fall-rate. Work is ongoing to estimate the time history of fall-rate corrections and to apply this correction to historical data:

Wijffels, S. and 7 co-authors: Changing eXpendable Bathythermograph Fall-rates and their Impact on Estimates of Thermosteric Sea Level Rise, Journal of Climate, in press.

Our role in this work is through providing datasets, suggestions, and ancillary calculations.

The SIO Automatic XBT launcher system and its software are fully integrated with the NOAA/SEAS XBT data acquisition system. This allows HRX data to be transmitted in near real-time, and permits SIO HRX hardware to be used for broadscale XBT sampling.

2.4. Analysis and research highlights

HR-XBT data are being incorporated in regional, basin-wide, and global analyses.

- HRX line PX37/10/44, San Francisco-to-Hong Kong (Figures 1 et 2), has proven especially valuable, with 17 years of data comprising 66 transects along the repeating route, and the dataset having been used in many publications.
- E. M. Douglass completed her PhD thesis in which HRX data were analyzed in combination with other datasets and results from the ECCO Ocean Data Assimilation

model (Douglass, 2007, Douglass et. al., 2008a, 2008b). North Pacific HRX transects, especially PX37/10/44, were a key dataset in this work.

- D. Roemmich, J. Gilson and L. Lehmann are analyzing HRX data from the eastern North Pacific together with Argo and CalCOFI data to study the offshore extent of the California Current and the current's variability in relation to the North Pacific circulation.
- X. Zhang, B. Cornuelle, and D. Roemmich are using HRX and Argo datasets in a tropical Pacific regional version of the ECCO ocean data assimilation model to study recent ENSO variability.
- J. Gilson is pursuing accuracy and consistency issues for both HRX and Argo datasets (e.g. Willis et al., 2008). This is a community-wide effort, whose objectives are to identify and remove systematic errors in the global datasets to enable the XBT and Argo records to be combined with one another as well as with other historical and ongoing data collections.

2.5. Refereed publications

Uehara, H., S. Kizu, K. Hanawa, Y. Yoshikawa, and D. Roemmich, 2008. Estimation of heat and freshwater transports in the North Pacific using high-resolution expendable bathythermograph data. *Journal of Geophysical Research, 113,* C02014, doi:10.1029/2007JC004165.

Douglass, E. M., D. Roemmich, and D. Stammer, 2008a. Data-sensitivity of the ECCO state estimate in a regional setting. Submitted to the *Journal of Atmospheric and Oceanic Technology.*

Douglass, E.M., D. Roemmich and D. Stammer, 2008b. Interannual variability in North Pacific heat and freshwater budgets. Submitted to Deep-Sea Research.

Willis, J., J. Lyman, G. Johnson, and J. Gilson, 2008. In situ data biases and recent ocean heat content variability. Journal of Atmospheric and Oceanic Technology, in press.

2.6. PhD Thesis

Douglass, E.M., 2007. *Interannual Variability in North Pacific Ocean Circulation and Heat Transport: Results from Data Analysis and Ocean Data Assimilation Modeling.* PhD Thesis, Scripps Institution of Oceanography, University of California San Diego.

2.7. *Community service*

D. Roemmich is active in design, coordination, and implementation of global ocean observations. He serves as co-chairman of international CLIVAR's Global Synthesis and Observations Panel, and as co-chairman of the Argo Science/Steering Team. He is also a member of the Steering Team for Pacific Islands - Global Ocean Observing System (PI-GOOS) and for the SEREAD education initiative, which develops teaching units and educational materials relevant to climate and ocean observations for primary and secondary curricula in South Pacific island nations.

Ship of Opportunity Program (SOOP), Volunteer Observing Ships, Expendable Bathythermograph (XBT) and Environmental Data Acquisition Program

Gustavo J. Goni, Molly O. Baringer, and Silvia L. Garzoli
NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami FL

1. PROJECT SUMMARY

This project includes data acquisition, transmission and quality control, related to the Ship of Opportunity Program (SOOP) using volunteer merchant ships for observations of ocean and atmospheric properties. The project includes three main components:

- A system for the merchant fleet to acquire ocean and meteorological information and transmitted in real-time to users worldwide called SEAS (Shipboard Environmental Acquisition System).
- Upper ocean temperature observations using expendable bathythermographs (XBTs) deployed broadly across large ocean regions along repeated transect: the frequently repeated/low-density XBT program.
- Upper ocean temperature observations using XBTs deployed closely spaced in order to measure the mesoscale field: the high-density XBT program

This project is necessary and essential to the Department of Commerce's mission as evidenced by two of the three strategic themes that comprise the Department's mission statement:

- Keep America competitive with cutting-edge science and technology and an unrivaled information base; and,
- Provide effective management and stewardship of our nation's resources and assets to ensure sustainable economic opportunities.

1.1. SEAS System

SEAS 2K is a Windows based real–time ship and environmental data acquisition and transmission system. The SEAS 2K software acquires atmospheric and oceanographic data. This software is employed on ships of the Ship of Opportunity Program (SOOP) Volunteer Observing Ships (VOS), and on NOAA, University-National Oceanographic Laboratory System (UNOLS), and Coast Guard vessels.

SEAS 2K is a user-friendly software that can be operated by a wide variety of users, including users with limited computer competence. The operators are members of the crew of the vessels, who are extremely busy and have little time for computer malfunctions. Thus, SEAS 2K was designed to be easy to use and thoroughly reliable. As new features are added and current features are improved upon, there is a consistent effort to follow this design philosophy.

SEAS 2K is installed on more than 400 ships of the SOOP and of the Voluntary Observing System (VOS). Over three million SEAS meteorological messages are transmitted per year constituting the largest source of marine meteorological observations, which are used in weather forecast prediction models and analysis, such as the National Hurricane Center. Approximately twenty ships of the SOOP participate with NOAA/AOML in deploying about 13,000 XBTs per year using SEAS 2K software. NOAA/AOML and Scripps Institution of Oceanography are the principal users of the software. National Marine Fisheries Service also runs an Antarctic line (AX22) using this software.

These data are transmitted in real-time to the Gateway Telecommunication System (GTS) and to operational databases to be used by scientists. These data are used for ENSO monitoring and prediction and the initialization of climate models at centers for environmental prediction and in delayed mode for research related to seasonal to decadal climate studies of the upper ocean thermal layer. There are no restrictions on sharing this information as it is distributed in real time on the GTS.

Additionally, SEAS 2K software creates a series of reports, which describe point of departure, route and arrival of a ship. These reports are transmitted using Standard-C and include ships in a real-time search and rescue database.

1.2. Frequently Repeated/Low-Density XBT Operations

There are three main modes of deployment of XBT probes: Low Density (LD), Frequently Repeated (FR) and High Density (HD) (Table 1). Most of the probes used in this work are Sippican Deep Blue, which reach depths between 750 and 800m.

Frequently repeated (FR) XBT transects are mostly located in tropical regions. These lines typically run north/south, and cross the equator or intersect the low latitude eastern boundary. These transects are geared to monitor strong seasonal to interannual variability in the presence of intra-seasonal oscillations and other small-scale geophysical noise. They are intended to capture the large-scale thermal response to changes in equatorial and extra-equatorial winds. Sampling is ideally on an exactly repeating track to allow separation of temporal and spatial variability, although some spread is possible and always expected. These lines are preferably covered 18 times per year with an XBT drop every approximately 150 km (or 6 deployments per day). This mode of sampling intends to draw a balance between the spatial undersampling, with good temporal sampling inherent in LD deployments and the good spatial sampling, marginal temporal sampling of HD deployments. Increasing both the temporal and spatial sampling in frequently repeated transects relative to low-density sampling greatly decreases the risk of aliasing in equatorial regions.

The LD or broadly spaced XBT mode is used to investigate the large-scale, low-frequency modes of climate variability, while making no attempt to resolve the energetic, mesoscale eddies that are prevalent in much of the ocean, features that are investigated by XBT transects in HD mode. Sampling in LD mode has been the dominant mode in the early days of the SOOP network. The current LD network is comprised of data usually from SOOP XBT lines around the globe, where sampling is done on a monthly basis, with four XBT deployments per day along the track of the ship. Occasionally these lines are also sampled through basic research and operational experiments in which XBTs are deployed to observe various oceanographic processes.

Table 1. Spacing and frequency sampling of the three different modes of XBT deployment.

MODE	Spacing	Frequency
Low Density (LD)	~ 250 km	12 times per year
Frequently Repeated (FR)	~ 150 km	18 times per year
High Density (HD)	~25 km	4 times per year

AOML maintains several of the recommended FR and LD transects (Figure 1), with some of them operated in cooperation with international partners from France, Australia, and Noumea. All FR and LD transects lead by the U. S. utilizes SEAS 2K software.

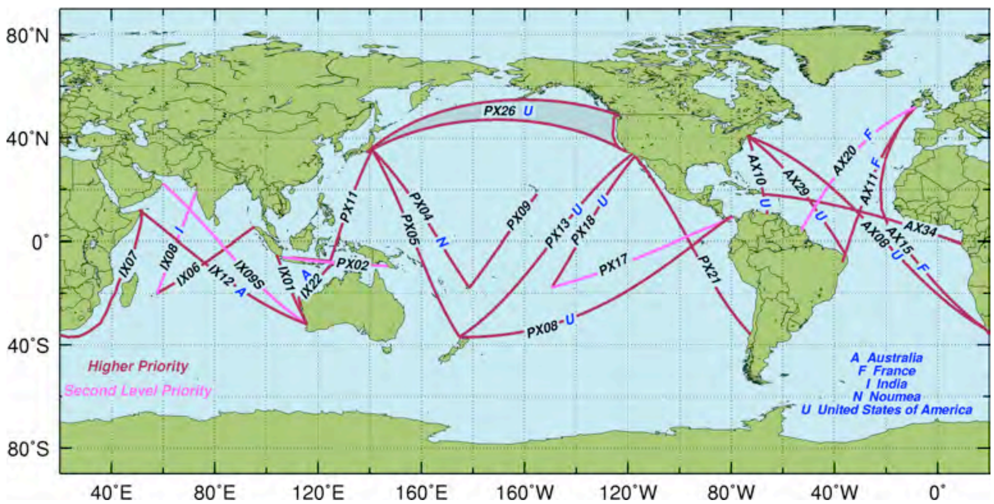

Figure 1. Location of Frequently Repeated and Low Density XBT network recommended by the 1999 Upper Ocean Thermal Review Panel. The blue letters indicate the country that leads the effort of each transect.

1.3. High Density XBT Operations

This program is designed to measure the upper ocean thermal structure in key regions of the Atlantic Ocean (Figure 2). XBTs in HD mode are deployed approximately every three months and are deployed approximately 25 km apart (Table 1) in order to measure the mesoscale structure of the ocean to diagnose the ocean circulation responsible for redistributing heat and other water properties globally. This transects are carried globally (Figure 2), with AOML taking the lead in the operations in the Atlantic Ocean (except for AX03 and AX22).

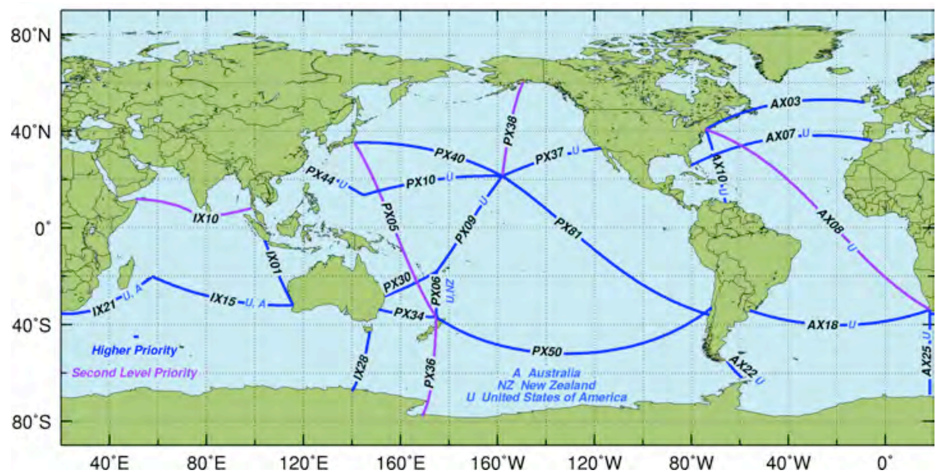

Figure 2. Location of the High Density Repeated XBT transects recommended by the 1999 Upper Ocean Thermal Review Panel. The blue letters indicate the country that leads the effort of each transect.

1.4. Scientific and Operational Goals

This project addresses both operational and scientific goals of the NOAA program for building a sustained ocean observing system for climate. Specifically, AOML manages a global XBT network that provides subsurface temperature data.

a) Scientific Goals

The seasonal to interannual variability in upper ocean heat content and transport is monitored to understand how the ocean responds to changes in atmospheric and oceanic conditions and how the ocean response may feedback to the important climate fluctuations such as the North Atlantic Oscillation (NAO). Additional objectives of this project are to provide the resulting data to increase our understanding of the dynamics of the seasonal to interannual and decadal time scale variability and to provide data for model validation studies.

b) Operational Goals

The data resulting from this project helps to document the ocean heat storage and global transport of heat and fresh water, which is crucial to improving climate prediction models that are initialized with temperature profiles. One primary objective of the AOML XBT component of the internationally coordinated Ship of Opportunity Program (SOOP) is to provide oceanographic data needed to initialize the operational climate forecasts prepared by NCEP. Global coverage is now required as the forecast models not only simulate Pacific conditions but global conditions to improve prediction skill.

1.5. Rationale

Data from these transects have been used extensively (Meyers et al, 1991; Taft and Kessler, 1991; Goni and Baringer, 2002). For example, the scales of mode water and the distribution and circulation of associated water properties can be readily captured by LD/FRX sampling (Hanawa and Yoritaka, 1999). XBT data are also used in ocean analysis and in climate model initialization. For instance, for El Nino prediction XBT data complement that from the TAO array and from satellite-derived sea surface temperature and sea height observations. The use of XBT data serves to measure the seasonal and interannual fluctuations in the upper layer heat storage, now being complemented by profiling float measurements. Heat transport and geostrophic ocean circulation can be measured using the high-density XBT data that measures the meso-scale field.

Within this context, AOML monitors six XBT transects in HD mode to determine properties in the upper layers of the Atlantic Ocean (Figure 2 and Figure 3). The continuation of AX07 and AX10 and the implementation of AX08 and AX18 were recommended by the Upper Ocean Thermal Review Panel in St. Raphael in 1999. The location of the transects recommended at the St. Raphael meeting and the GCOS *Implementation Plan* (GCOS-92) are based on specific advantages of each lines location. HD transects AX07 and AX10 have been maintained since 1994 and 1996, respectively, providing a homogeneous data set for more than a decade. Sustained observations from these and the other three HD transects are required to have observations with adequate spatial and temporal resolution for climate studies. High-density observations in AX08, AX18, AX25, and AX97 provide observations in poorly surveyed regions. A summary of the justification for each of the HD transect is provided below.

- The HD XBT transect AX07 is located nominally along 30°N extending from the Straits of Gibraltar in the eastern Atlantic to the east coast of the United States at Miami, Florida. This latitude is ideal for monitoring heat flux variability in the Atlantic because it lies near the center of the subtropical gyre, which has been shown to be the latitude of the maximum poleward heat flux in the Atlantic Ocean.

- The HD XBT transect AX10 is located between New York City and Puerto Rico. This line closes off the United States eastern seaboard, where subtropical temperature anomalies could have the greatest interaction with the atmosphere. This transect was chosen to monitor the location of the Gulf Stream and its link to the NAO.

- The HD XBT transect AX08, a component of the Tropical Atlantic Observing System, crosses the tropical Atlantic in a NW-SE direction between North America and South Africa. Historical data along AX08 and other historical temperature observations in the tropics exhibit decadal and multi-decadal signals. It has been hypothesized that this large time scale signal may cause atmospheric variability. Given the importance of the tropical Atlantic in climate variability, and the scarcity of observations in this region, data obtained from the measurements along this transect are key to improving our understanding of the ocean and our ability to forecast climate. Temperature profiles obtained from this transect will help to monitor the main zonal currents, countercurrents and undercurrents in the tropical Atlantic and to investigate their spatial and temporal variability.

- The HD XBT transect AX18, which runs between Cape Town and South America (Montevideo, Uruguay, or Buenos Aires, Argentina) is geared towards improving the current climate observing system in the South Atlantic, a region of poor data coverage. Similarly to the AX07 transect in the North Atlantic, the goal of AX18 is to monitor the meridional mass and heat transport in the upper 800 m across 30°S. Given the importance of the South Atlantic and the scarcity of observations in this region, data obtained from the measurements along this transect will be used to investigate the role of the South Atlantic in improving climate forecasts.

- The HD XBT transect AX25 was implemented to monitor the variability in the upper layer interocean exchanges between South Africa and Antarctica on seasonal and interannual time scales. In addition, by exploiting the relationship between upper ocean temperature and dynamic height, XBTs are used to infer velocities and to monitor the various frontal locations in the region.

- The HD XBT transect AX97 supports the MOVAR Project (from Portuguese: Monitoring the upper ocean transport variability in the western South Atlantic) and evolved out of international collaboration efforts of the low-density program. The fluctuations of the zonally integrated baroclinic transport across this transect will be studied and linked to the variability of the Brazil-Malvinas frontal region. This region is critical since Brazil Current rings are the main mechanism to carry subtropical waters to high latitudes.

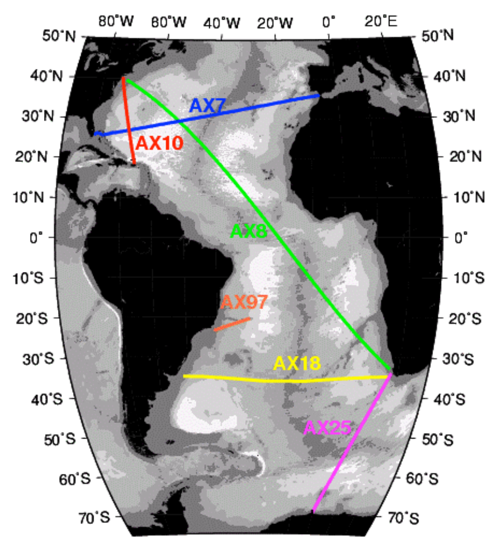

Figure 3. Location of the four High Density transects (AX07, AX08, AX10, and AX18) maintained solely by NOAA/AOML, and the two transects (AX25 and AX97) maintained in collaboration with the University of Cape Town and the Federal University of Rio Grande, respectively.

1.6. Partnerships

AOML maintains several XBT transects and other components of the SEAS operations with the collaboration of domestic and international partners, in order to lower costs and increase efficiency. This collaboration includes:

- Providing probes to oceanographic institutions that have demonstrated reliability in logistics and operations,
- Provide software maintenance,
- Contracting riders (HD transects only) to deploy the probes,

- Providing equipment (computers, antennas, etc) and software, and
- Carrying joint analysis of the data.

The SOOP program and the HD program also partner with other NOAA funded programs and national partners including

- The global drifter program (drifters deployed on HD lines)
- The global ARGO program (ARGO floats deployed on HD lines)
- The United State Coast Guard (AMVER vessel emergency response system is integral to SEAS)
- The National Weather Service (through SEAS transmissions of weather observations and from NWS port meterological officer collaborations for loading and greeting ships).
- For more complete partnerships see the international and domestic collaborations sections below.

1.7. Data Availability and Project Web Sites

Details of this project, such as logistics, equipment, software, and data distribution, are provided through links that can be accessed through the main NOAA/AOML Global Ocean Observing System (GOOS) web page www.aoml.noaa.gov/phod/goos.

- **SEAS:** http://www.aoml.noaa.gov/phod/trinanes/SEAS/
- **HD:** http://www.aoml.noaa.gov/phod/hdenxbt
- **FR/LD:** http://www.aoml.noaa.gov/phod/goos/ldenxbt

Data from the LD, FRX and most HD deployments are transmitted to the GTS and made available in real-time for operational climate forecast and analyses. Data from the international collaboration are not always available in real-time. HD data is also made available on the project web site listed above.

2. ACCOMPLISHMENTS AND HIGHLIGHTS

2.1. SEAS System

The main accomplishment during FY 2008 was to include Iridium transmission for XBT deployments and TSG observations in SEAS 2K.

Every year the focus of our work is to improve, update and support the SEAS 2K program. This includes ongoing development of the following software modules: meteorological (bulletins), automated meteorological, XBT, and Thermosalinograph (TSG) observations. Figure 4 provides the locations of the approximately 13,200 SEAS 2K XBT and 194,000 TSG data transmissions into the GTS during FY2008, respectively.

In addition, time and effort was spent in support of SEAS 2K, by providing training and operational support to users in system operations, data tracking during cruises, and trouble shooting problems at sea in real-time. The specific accomplishments for each component within this system are outlined in this report.

2.2. Meteorological System (VOS ships) and SEAS software

The SEAS 2K meteorological (MET) software is constantly being upgraded with corrections as recommended by the National Weather Service.

The automated MET system is complete for integration with the Woods Hole Oceanographic Institute automated meteorological station. Automated MET continues being developed for the NOAA fleet to integrate SEAS2K with the Scientific Computing System (SCS). The software module is being constantly updated to collect data from the SCS system using socket transfer. Transferring these data into the Automated MET capability of SEAS 2K continue being tested. Once finalized, the data will be transmitted off the ship using ship email.

Approximately 700 merchant ships currently have SEAS software installed, and supported through the NWS/NDBC (Robert Luke) VOS Program. These ships transmitted about 200,000 meteorological bulletins using SEAS software during FY 2008 (Figure 5). This contribution constitutes 10% of non-satellite global marine weather obervations.

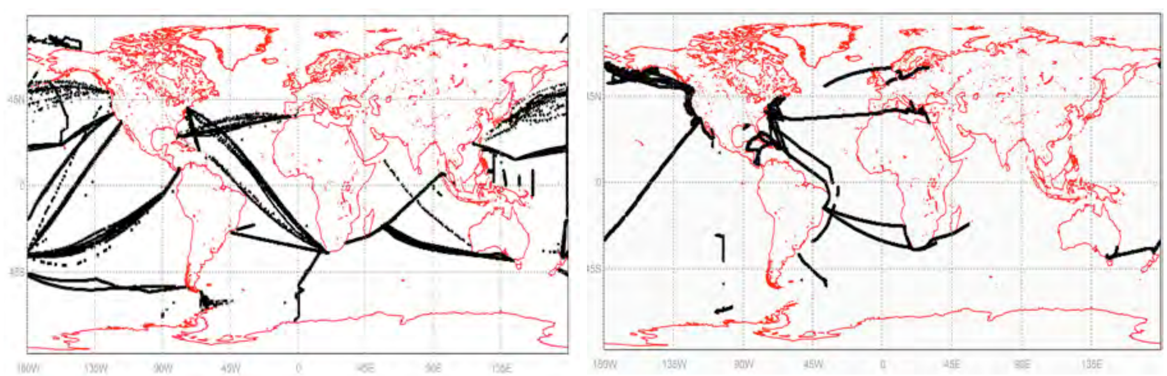

Figure 4. SEAS 2K transmissions of (top) XBTs and (bottom) TSGs into the GTS during FY2008.

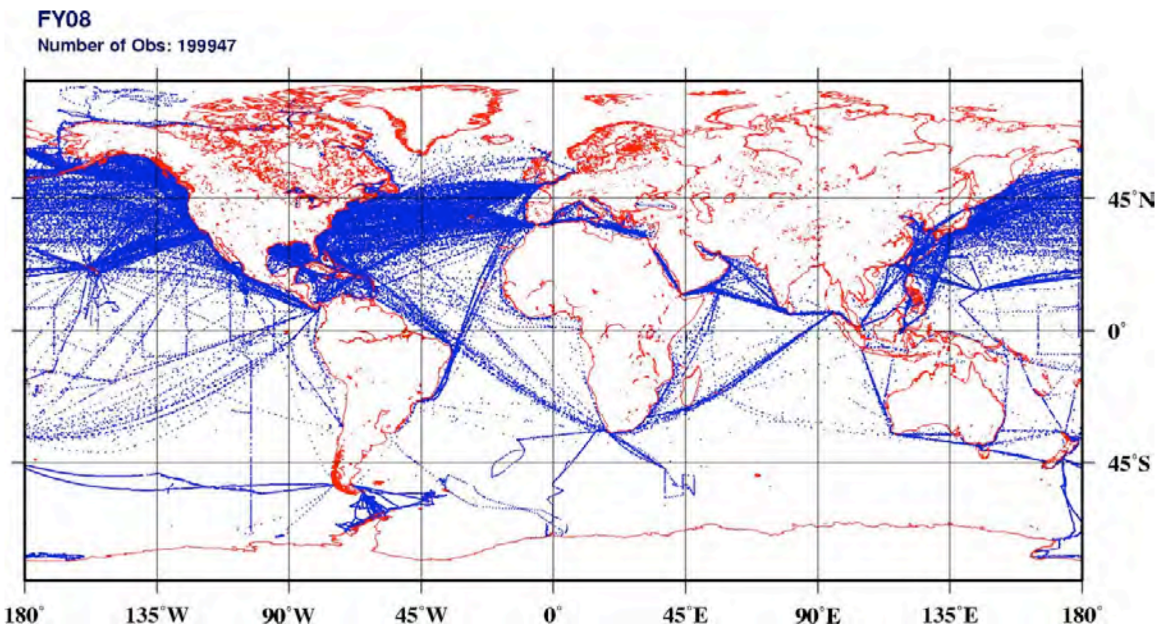

Figure 5. SEAS 2K transmissions of meteorological bulletins into the GTS during FY2008.

2.3. Frequently Repeated/Low-Density XBT Operations

In view of the implementation of the Argo Program and the availability of satellite altimetry data, the international SOOP community decided in 1999 to gradually phase out LD transects while maintaining sections operated in FRX and HD modes. However, the ability of other observing systems, such as of profiling floats, to continue the important records initiated by mechanical BTs and by XBTs is still unknown. Some LD transects contain time series as long as 30 years with much higher horizontal resolution than is available from a fully implemented ARGO program. This time series is longer than 50 years if mechanical BTs are included. A full report of the XBT deployments by transect is shown at: http://www.aoml.noaa.gov/phod/goos/ldenxbt/index.php.

This year LD sampling maintained the reduced levels of the previous year, FRX lines already begun were continued. In view of the seasonal to interannual emphasis for the use of the XBT data, most transects that cross the equator and are located in the subtropics were maintained. Some of these transects were maintained exclusively by AOML and others were maintained as a partnership between AOML and international collaborators with probes provided by AOML.

AOML currently maintains the following transects in LD/FRX mode (Figure 1): AX07, AX08 and AX10 in the Atlantic Ocean, and PX08, PX10, PX13, PX26, PX37 and PX44 in the Pacific Ocean.

The current goal of this project is to have these transects occupied at least 12 (16) times per year in LD (FRX). Some of these transects are also occupied in HD mode, which are carried four times a year, and need to be occupied a lesser number of times per year. The number of XBT deployed in each line is shown in the AOML XBT report that can be obtained from the GOOS web page at: http://www.aoml.noaa.gov/phod/VOS/REPORTS/ (username: tchp, password: uohcval).

2.4. High Density Mode Operations

Figure 6 shows all XBT deployments to date for each of the five HD transects. XBT deployments along HD transects preceded as planned in previous years. Note that AX25 is scheduled for only twice each year due to ice coverage. Several ships were recruited (see Recruitment). Transects AX10 and AX07 are now conducted with new ships. We continue experiencing difficulties with the AX18 route from Cape Town, South Africa to Buenos Aires, Argentina. The shipping company we used has discontinued this transect and there are currently no shipping companies sailing between these ports. We continue to actively search for a new ship with the help of colleagues in Argentina and South Africa. We have identified a slightly shifted route that enters into Santos, Brazil, slightly further north than AX18. Because this section is largely justified based on the ability to provide transoceanic heat transport estimates across the subtropical gyre in the South Atlantic, the exact port locations is less important because the heat transport will not change dramatically between these latitudes in this region. However, ideally since we prefer repeated routes we will continue to search for a replacement vessel for AX18.

The exact locations of XBT deployments along each line during FY2008 are shown on the AOML SOOP web page. A summary of all the cruises conducted in fiscal year 2008 can be found in Table 1. A total of sixteen High Density XBT cruises were conducted, 3146 XBTs deployed, 26 ARGO profilers, 47 SVP Drifting buoys.

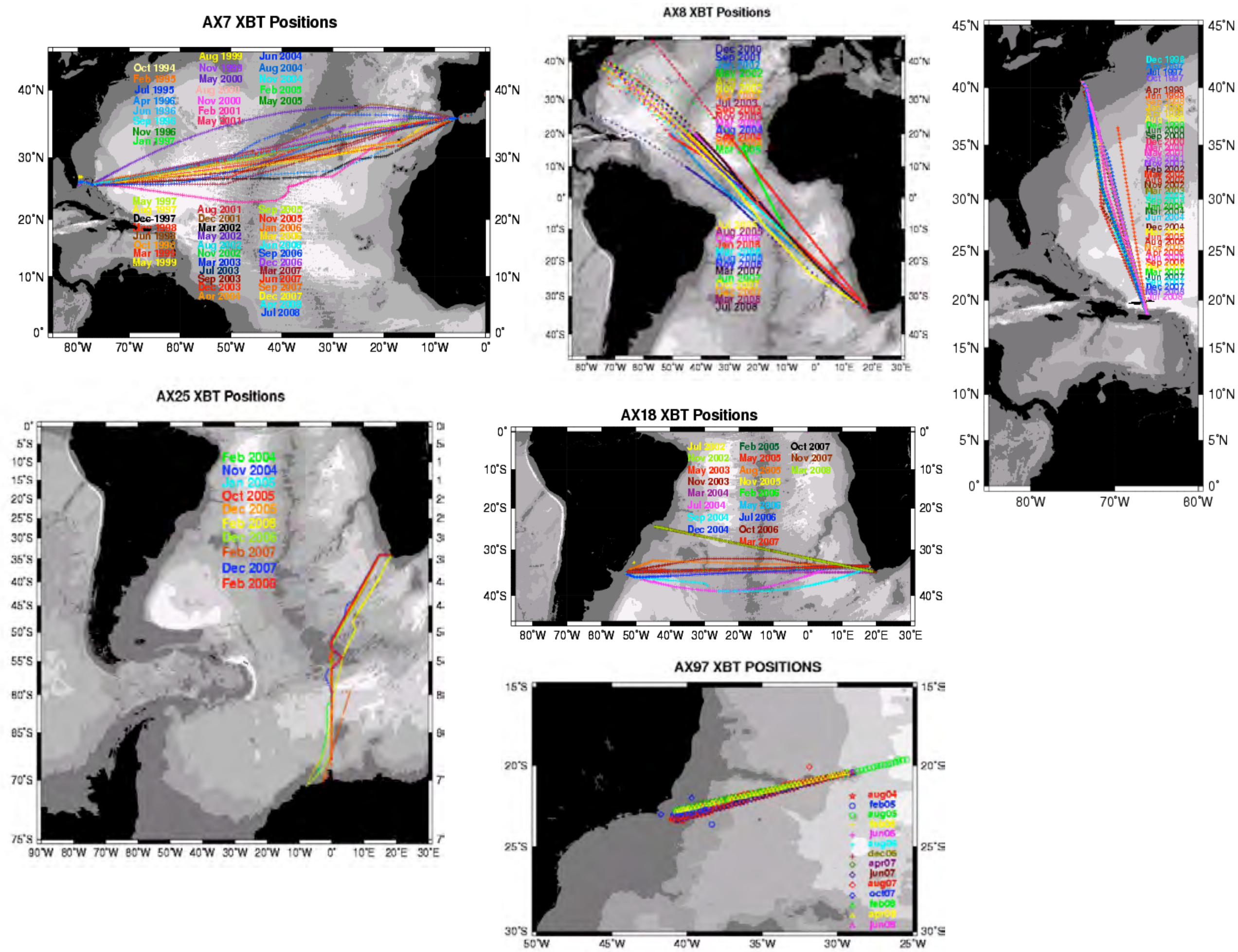

Figure 6. Location of all AOML XBT deployments in HD mode.

Table 2. Table summarizing the XBTs deployed on the five main high-density XBT lines operated by AOML during FY 2008.

Transect Designation	# Sections FY08	# XBTs	Avg # XBTs	Percentage Good	ARGO deployed	Drifters deployed
AX7	3	603	201.0	96.1	0	0
AX10	3	311	103.7	96.8	0	0
AX8	5	1381	276.2	93.6	16	39
AX18	3	523	174.3	97.9	4	4
AX25	2	328	164.0	91.5	6	4
Total	16	3146		94.9	26	47

Note that for Table 2 we use the start date of the cruise for fiscal year reporting, despite the fact that cruises typically take 5 to 25 days to complete. In this past fiscal year only three transects were performed on AX7 and AX10, while five transects were carried out on AX8. This is largely due to slight scheduling shifts in the cruise scheduled for September. The last cruise for AX10 was completed October 11 – 14, 2008 designed to approximately coincide with the last cruise for AX7 which was completed October 2 – 11, 2008. For AX8, the first cruise of the fiscal year was a delayed cruise from FY2007 that was completed in October 2007. Next year AX7 and AX10 will officially report 5 cruises in the fiscal year. This is a caution to note that we do not feel that we have either undersampled or oversampled any of the HD lines. All the lines except AX18 are now operating normally and offer no concerns.

This past fiscal year, increased communications between our LD/FRX international partners has led us to discover one XBT line that could potentially be incorporated into the set of HD lines that AOML maintains. In particular the AX97 line grew out of our international cooperation with Brazilian scientists who have been studying the intensity and variability of the Brazil Current between Rio de Janeiro and the Island of Trinidade, a small island off the coast of Brazil. In fiscal year 2008 four cruises of data were received from our collaborators and processed by AOML: October 2007 (20 XBTs), February 2008 (35 XBTs), April 2008 (49 XBTs), June 2008 (45 XBTs). We already shipped a SEAS 2000 system to allow real-time transmission of their data directly.

2.5. International Collaboration

AOML Provides probes to oceanographic institutions that have demonstrated reliability in logistics and operations. These probes are used to carry out recommended transects in FR and HD modes. By providing probes to international partners, AOML saves the cost of ship greeting for transects that would be difficult and expensive to maintain from the U.S. The probes provided to Noumea are being deployed along lines that cross the equator in the western Pacific to complement PX13 and PX08 in the central and eastern Pacific. The probes provided to Australia are used to a basin wide transect in the Indian Ocean that crosses the equator and to partly support a high density transect between Tasmania and Antarctica. The XBTs provided to Brest are used along lines that cross the equator in the Atlantic Ocean and those provided to Brazil along a line in the subtropical South Atlantic that monitors the Brazil Current.

AOML provides probes to the following international collaborators:
- **IRD, Noumea,** 1 pallet, collaborator: Mr. David Varillon
- **FURG, Brazil,** 1 pallet, collaborator: Dr. Mauricio Mata
- **IRD, France,** 1.75 pallets, collaborator: Mr. Denis Diverres
- **CSIRO and Bureau of Meteorology, Australia,** 2 pallets, collaborator: Ms. Lisa Cowen
- **South African Institute for Aquatic Biodiversity,** 0.3 pallets

AOML provided a total of 5.75 pallets (1863 XBTs) to these partners. Most of the data obtained from these XBTs were placed into the GTS in real-time. For those ships that are not currently transmitting the data in real-time, we are exploring the possibility of installing computers and transmitting antennas for real-time data distribution. Most of the data collected from these deployments were submitted to NODC.

These XBTs were deployed in the following transects:
- **Noumea:** PX09, PX30, PX51

- **Brazil:** Sao Paulo-Isla de Trinidade (AX97)
- **France :** AX05, AX20, AX11
- **Australia :** IX12, IX28
- **South Africa:** Mozambique Channel

Additionally, several agencies are currently collaborating with this project. The Argentine Hydrographic Naval Office (SHN) provides the personnel to deploy the XBTs on AX18; the University of Cape Town provides for the deployments along AX08 and AX25. The South African Weather Service is our contact in Cape Town and Durban to store the equipment in between transects and to provide ship riders. Deployments along AX97 are done in collaboration with the Federal University of Rio Grande, Brazil.

Drs. Gustavo Goni and Molly Baringer are involve in data analysis and scientific collaboration activities with scientists from University of Cape Town, South Africa, and University of Rio Grande, Brazil (see publications).

2.6. Domestic Collaboration

The following is a summary of the domestic collaboration that involves AOML SOOP operations:

- In support of the NOAA-funded "Surface pCO_2 Measurements from Ships" (Drs. Rik Wanninkhof, Richard Feely, and G. Goni, PIs), AOML provided 1.5 pallets (486 XBTs) to NOAA/NMFS in Rhode Island to be deployed along the pCO_2 transects AX32 and AX02.

- NOAA/AOML also provided 3 cases of XBTs in support of the NOAA-funded MASTER (Meso-American System Transport and Ecology Research), off the Mexican and Belizean Yucatan, between 16°-22°N, 90°-80°W. These cruises are performed twice a year.

- NOAA/AOML collaborates with the National Weather Service to provide maintenance of SEAS 2K software to transmit marine meteorological observations.

- Through an agreement with the U.S. Coast Guard, NOAA/AOML maintains the SEAS software, which is used for search and rescue operations.

- Additional collaboration with the Global Drifter and Argo Programs are detailed below.

2.7. Transmissions and data flow

XBT profiles are sent through the Thrane Standard C units. AOML is now continuously using Iridium transmission in the XBT and TSG operations in the Oleander (AX29) using a direct Internet connection and SMTP e-mail. Iridium transmissions are also done continuously from the TSG installed in the M/V Explorer of Semester at Sea. The ratio of XBTs deployed to real time data transmitted is essentially 100%.

For XBT profiles, an operator reviews those profiles that fail the automatic quality control procedures and decides whether or not to send the data to the GTS. Probe failure (as measured by the auto QC procedure) remains consistently between 2 % and 5 % with greater higher failure rates in the higher latitudes during the hemispheric winters.

2.8. Data Tracking

The data tracking operation is currently being transitioned from NOAA HQ to AOML. This operation is aimed to the verification of data flows from the source (observation platform) to the processing centers, where the data is analyzed, quality controlled, and sent to the Telecommunication Gateway at NWS from where the data is inserted into the GTS. Since this is a very complex process, the tracking of these data ensure that the information obtained by different observation platforms are received and that they are generated with the correct codification so that it can be successfully inserted into the GTS. Otherwise the data cannot be used or, if communication problems are not detected, lost. We verify the flow of different kinds of oceanographic data, including XBT, TSG, buoys, drifters and TAO/PIRATA arrays.

Among the several problems that may occur, the most common are:

- Specified platform type not expected from a specific group of headers,
- Data is received from ships with unknown Call Sign,
- Observations are transmitted with wrong date/time,
- Duplicate data is being sent, and
- Data drops: the data is transmitted but it is not reaching its destination.

When an encoding or transmission problem is found, the type of data and the source is determined and the person responsible is contacted. This process is performed daily. Software is currently under development at AOML to automate this task. The software is based on the comparison of several data sources from AOML, the SEAS team, the NWS Communication Gateway and the GTS. The code allows the detection of several ofisthe previously cited most frequent problems, creating a daily report of the oceanographic data flow state. This represents a great improvement for the data-tracking task since many issues can be detected quickly reducing the operator effort. Nevertheless new types of errors occur all the time, requiring the intervention of the operator to ensure the success of the operation.

On a visit to Silver Spring, Dr. Francis Bringas was introduced to Mr. Allan Darling, Chief of NWS Telecommunications Software Branch. Mr. Darling gave Dr. Bringas a detailed description of the data flow through the NOAA Telecommunications Gateway (TG). Dr. Bringas was also given several points of contact with TG data managers. During this visit, Dr. Bringas was invited to CLS North America in Largo, MD, to discuss CLS operations. Consequently, Dr. Bringas is interacting routinely with CLS personnel to resolve data delivery issues, such as duplicate processing between CLS in Largo and CLS in Toulouse, France. CLS is responsible for the decoding of NOAA polar orbiting satellite data and delivering it to the TG for GTS distribution. This data includes drifting buoy, TAO/Pirata moored platform, and profiling float data, which are monitored at AOML.

2.9. Data Base

The SEAS XBT Auto-QC System (XBTRT) and the automatic transfer of *ndc* files from SEAS to AOML were operational except for downtime due to hardware/software maintenance. The tasks being performed are: maintain the XBTRT system, management of the XBTRT operational database residing in a commercial Database Management System, review the daily electronic mail sent by the XBTRT system to detect and report possible problems, assist in identifying data tracking problems, and provide advice regarding software issues.

2.10. New Visual Quality Control (VQC)

The Visual Quality Control (VQC, Figure 7) is a Graphical User Interface (GUI) developed at AOML Miami that allows a user to approve or reject XBT profiles that have not met the minimum specified standards of the Automatic Quality Control System. Accepted profiles are automatically sent to the GTS. When the operator rejects a profile, the data-flow process automatically receives a message to not place that profile in the GTS. AOML does a VQC for an average of 2 profiles every day, which can vary dramatically if there are high-density cruises being done or communication problems. A useful advantage of the VQC is the real-time ability to recognize systemic and random problems with the XBT operations, such as electrical faults in the XBT hand-launchers, or bad weather carrying the XBT wires to contact the hull of the ship.

The AOML VQC system is an upgrade to the previous VQC Matlab script used in Silver Spring, with additions of incorporating geographical position, proximity to other profiles in time or position, and an easy to use GUI. The VQC GUI allows the user to evaluate the profile based on seeing error envelopes for both 5 and 10 standard deviations. Additionally, all flagged profiles in the queue are shown in a secondary graph to easily visually compare physical features. The GUI also has user-friendly mouse enabled features such as zoom and profile selection.

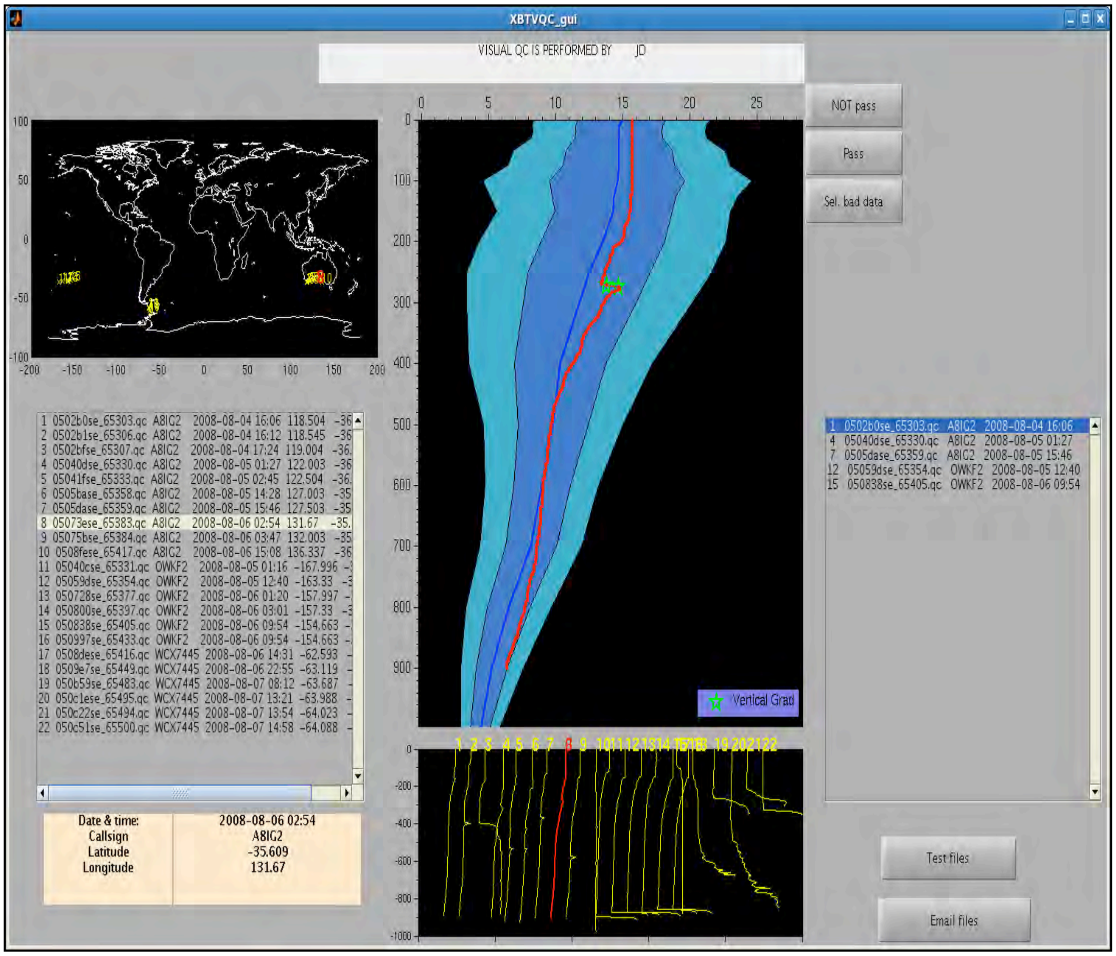

Figure 7. Screen shot of the new AOML Visual Quality Control (VQC) for XBT profiles. The main graph displays an envelope of 5 and 10 standard deviations, the climatology (blue line) and the XBT profile (red line).

2.11. SEAS Updates

The following are updates were performed as part of the SEAS operations:

- Finish conversion of AMVER/SEAS server software to new system and DBMS,
- Install Backup server in Miami and establish appropriate VPN's between AOML and Vizada,
- Replace machines at Gateway with new servers once converted, and
- Write software to allow SMTP e-mail communication from vessels by the ship riders.

2.12. Metadata and BUFR

XBT data are being tested coded in BUFR format, using templates that have been specifically designed to serve operational needs. We are using both BUFR Edition 3 and Edition 4 specifications. A similar approach is underway to migrate TSG data to BUFR. This effort seeks to improve the future migration from the Traditional Alphanumeric

Codes (TACs) to Table-Driven Code Forms (TDCFs), as required by WMO. The testing will provide the feedback necessary to detect, identify and correct problems that can arise in the migration process, providing a robust framework for near-real-time collection, quality control and distribution of SOOP data.

2.13. XBT Reports

Monthly reports are generated showing the temporal and spatial distribution of the SEAS XBT transects, identifying and tracking the FR and HD XBT lines managed by NOAA/AOML. In addition to a web interface, this project provides CSV files with data and metadata information about individual measurements as well as PDF bulletins comprising information about the last 12 months of data, including line coverage and mode, both in text and graphical formats. Future work will focus on improving the quality of metadata presented, advance on the automatic generation of the reports, enhance the input dataset with profiles not sent for QC, and reduce the error rate. These reports can be obtained from the GOOS web page.

2.14. Thermosalinograph (TSG) System

During this fiscal year the TSG Iridium transmission system was successfully tested in the M/V Explorer and on the Oleander. The SEAS 2000 software was implemented for easy setup and to require no user input once started. The TSG computer resides in the engine room and collects data from the TSG junction box and time/position stamps the TSG data. The TSG Server can read GPS data in two possible ways either from the Time Server or from the TSG junction box. If the TSG module collects GPS data from the junction box it can pass on this GPS data to the Time Server for use by SEAS 2K if necessary. The TSG data is transferred to the bridge over the ship intranet and can then be transmitted. TSG collection and transmission was added as a standalone component interfacing to the SEAS 2K Time/Position Server.

NOAA/AOML in collaboration with NOAA/AMAO started real-time transmission of TSG observations into the GTS in the following ships: Ronald Brown, David Starr Jordan, Miller Freeman, Gordon Gunter, Oscar Dyson, Nancy Foster, Oregon II, Fairweather, Rainier, Ka'imimoana, and Hi'ialakai. The location of theses transmissions are included in Figure 4, bottom. The collaboration with AMAO is particularly important since the R/V Gordon Gunter, Ron Brown and Ka'imimoana have pCO_2 systems installed.

2.15. Full Water Column calibration cruises

Two-day cruises on RV Walton Smith are generally scheduled four times per year to coincide with the AX7 high density XBT line in order to obtain boundary current transport information for the heat transport calculations. Sufficient ship-time funds for only three of the cruises were provided in FY07 (the final cruise of FY07 was postponed into early FY08 due to ship availability). All cruises include nine stations with full water column CTD, lowered ADCP, and continuous shipboard ADCP. The station locations are shown in Figure 8. Table 3 below includes the cruise dates and number of water samples taken for oxygen concentration and salinity.

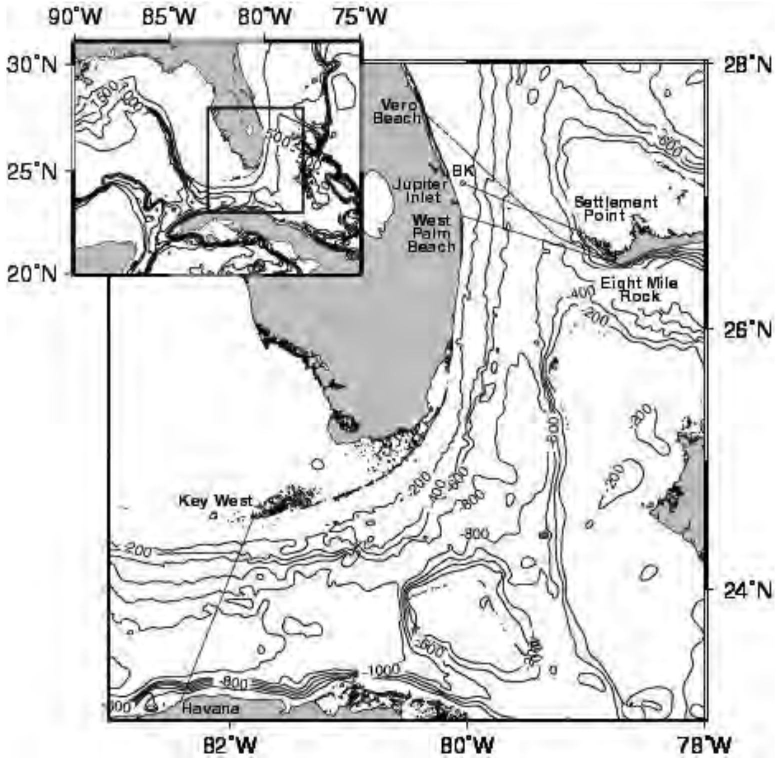

Figure 8. Location of submarine telephone cables (solid black) and nine stations (red) occupied during calibration cruises.

Table 3. Cruise dates for 2-day calibration cruises on the R/V Walton Smith. Note FY2005: The last cruise planned for in FY 2005 was postponed for early FY 2006. Note FY 2007: Only three cruises were completed due to lack of ship-time charter funds. Note FY 2008: Only two cruises carried FY2008 due to lack of ship-time funds.

FY2008		FY2007		FY2006		FY 2005		FY 2004	
Date	Samples	Date	Samples	Date	Samples	Date	Samples	Date	Samples
Dec 2007	19-20, 60 O2, 48 S	Dec 2006	13-14, 60 O2, 48 S	Dec 2005	14-16, 60 O2, 48 S	Dec 3-4, 2004	58 O2, 44 S	Jan 2003	8-9, 55 O2, 46 S
Jul 2007	7-9, 60 O2, 48 S	Jun 2007	28-29, 60 O2, 48 S	Jan 2006	29-31, 60 O2, 48 S	Jun 2005	3-4, 58 O2, 45 S	May 2004	6-7, 47 O2,
		Oct 2007	4-5, 60 O2, 48 S	Jun 2006	25-27, 60 O2, 48 S	Jul 2005	11-12, 58 O2, 45 S	Jul 4-5, 2004	56 O2,
				Sep 2006	18-19, 68 O2, 48 S	Nov 2005	20-23, 60 O2, 48 S	Aug 2004	27-28, 55 O2, 42 S
50% of planned cruises		75% of planned cruises		100% of planned cruises		100% of planned cruises		100% of planned cruises	

2.16. Web Pages

An extensive update of the AOML GOOS center and the Frequently Repeated XBT Lines websites has been completed during FY2008 (Figure 9). Data are available online at: www.aoml.noaa.gov/phod/goos and www.aoml.noaa.gov/phod/goos/ldenxbt, respectively. The Frequently Repeated XBT Lines websites features the latest information on operational XBT lines in both FR and HD modes along with specific webpages showing the latest XBT, Meteorological, and TSG observations, available online at: http://www.aoml.noaa.gov/phod/goos/seas/latest/.

The GOOS center website now features a Google Earth layer displaying Global Marine and Meteorological Observations available online at:
http://www.aoml.noaa.gov/phod/VOS/GE/GE_AOML_DT.kmz.

This application is a potent tool to visualize the global extent of ocean and meteorological observations interactively.

2.17. SEAS and High Density Installation Manuals

An extensive effort documenting the operations of the SOOP was carried out during FY08. This documentation is available online at: www.aoml.noaa.gov/phod/goos/docs in support of our global operations with collaborators from the US and countries around the world. For instance, a handbooks including hardware setup and software operation of the semi-automatic equipment developed in-house and used in high density lines is now available to all ship-riders though this website. This handbook has substantially simplified the training of new ship riders. A handbook for operation and troubleshooting of the TSG installations is also available.

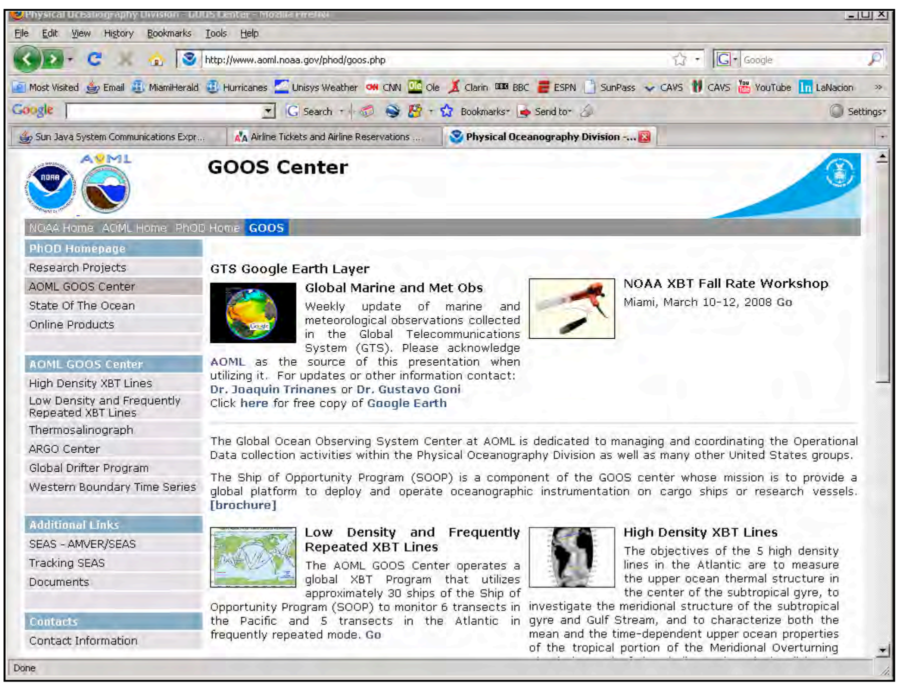

Figure 9. Global Ocean Observing System web page maintained by the SOOP at NOAA/AOML: www.aoml.noaa.gov/phod/goos.php.

2.18. Portable Integrated Data and Transmission Platform

The HD briefcase prototype (Figure 10) is an attempt to consolidate many of the components needed for a high density cruise in a lightweight portable briefcase reducing setup time and user setup error. Included in the briefcase is a laptop, a MK-21, an auto-launcher power supply, MK-21 power supply, and a power supply that will power both the TL-3026 (Mini-C) transceiver and the Iridium modem. These components are powered via a single power connector that accepts both 120 and 240 volts AC eliminating the need for a power converter that is typically needed on foreign vessels. The briefcase is compatible with the older T&T transceivers and was designed with the newer Mini-C transceiver and Iridium modem in mind.

2.19. XBT and TSG Test Bench

The TSG\XBT test bench (Figure 11) includes all of the components for a low density installation and most of the components needed for a TSG installation and a high density installation. Cabling to the roof allows us to test real-time transmissions with our different transmitters and modems without having to leave the bench. The components of this test bench are:

- Two shuttle computers,
- A shared monitor\keyboard\mouse,
- MK-21,
- Hand launcher,

Figure 10. Main components of the recently developed Portable Integrated Data and Transmission Platform.

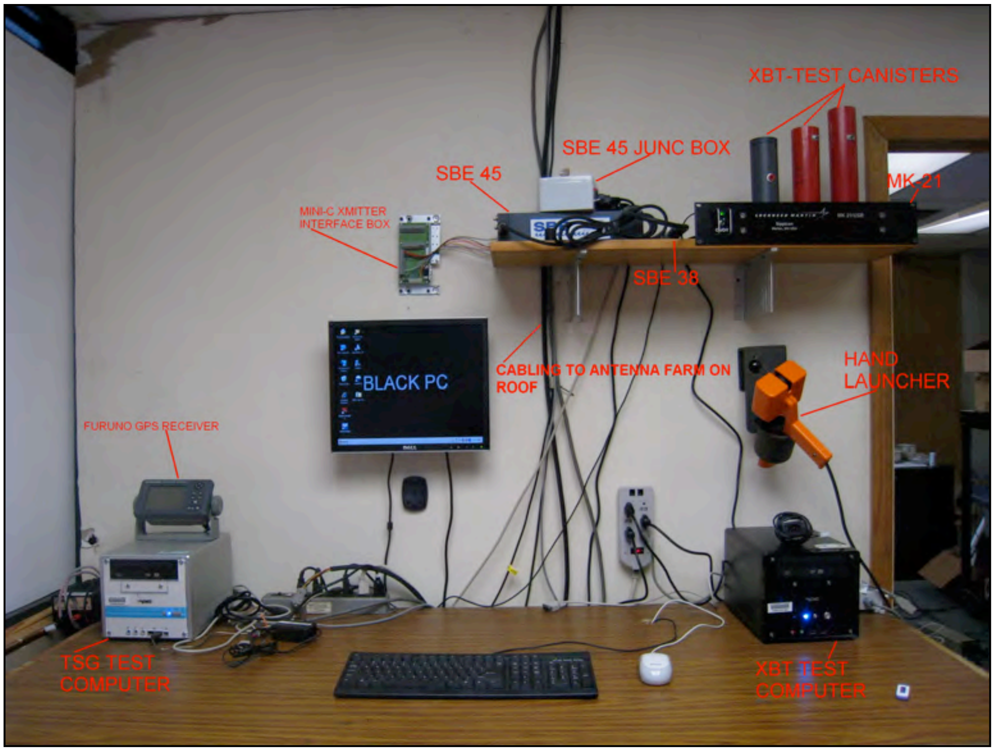

Figure 11. Components of the recently developed XBT and TSG test bench.

- Test canisters,
- TSG SBE-45,
- SBE-45 Junction box,
- External temperature sensor SBE-38,
- Furuno GPS receiver, and
- Cabling to antenna farm on the roof.

2.20. Fast Deep XBT Autolauncher

A total of 33 boxes (396 probes) of Fast Deep XBTs were purchased to use the new autolauncher in applications where increased depth is desired, particularly on the heat transport lines AX7 and AX18. One XBT was tested using a hand launcher and it was quickly determined that a redesigned autolauncher would be required for use of these new probes. AOML undertook a base-funded operation to redeign and build this new autolauncher system. The newly redesigned AOML 8-shooter autolauncher (Figure 12) is currently being assembled and tested. The main improvement in the new 8-shooter is that it is capable of launching not only the Deep Blue probes but also the Fast Deep probes. Structurally, this new autolauncher is 5 inches longer than the current AOML autolauncher and they will all be built to carry 8 probes. The anodizing of the redesigned autolauncher is done outside AOML. For the Deep Blue XBT the maximum rated depth is 760 meters. For the Fast Deep XBT the maximum rated depth is 1000 meters.

Figure 12. New Fast Deep XBT autolauncher being constructed at AOML is placed to the left of the Deep Blue XBT autolauncher at NOAA/AOML.

2.21. Collaboration with Global Drifter Program

The Surface Drifter Program would not be able to maintain the drifter array without contributions from national and international partners who deploy the drifters worldwide. Many drifters are deployed from vessels cooperating with the NOAA Ship Of Opportunity Program (see Table 2 for HD deployed drifters). SOOP personnel (J. Trinanes) also support AOML's efforts to collect the hurricane drifter data for subsequent quality control and redistribution.

2.22. Collaboration with the Argo Program

Ships recruited through SOOP to deploy XBTs are also used as a platform to deploy Argo profiling floats. Betweeen October 2007 and September 2008, a total of 26 floats were deployed from ships of the SOOP (see Table 2).

XBT temperature profiles have also been used to identify problems in Argo floats (Willis *et al.*, 2008) highlighting the importance of maintaining independent observing systems for ocean subsurface temperature.

2.23. Google Earth Application

A Google Earth-based application was implemented to display the status of the ocean observing system network, including SOOP platforms. Through this interface, users can easily monitor the different data streams received operationally through the GTS, identifying possible data gaps affecting data distribution, tracking specific platforms and generating animations including field measurements overlaid on top of the daily global SST fields. This application is freely available to the public at: http://www.aoml.noaa.gov/phod/goos.php.

2.24. SOOPIP

The NOAA/AOML SOOP Program is a participating member of JCOMM and JCOMMOPS. The AOML SOOP XBT program is represented annually at the WMO/IOC Ship Observations Team (SOT) meeting. Participation on these international panels provides an important mechanism for integrating and coordinating with other national or regional programs which, in the long run, improves our national climate mission by making more efficient and effective use of available resources.

Dr. Gustavo Goni continues being the Chairman of the WMO/IOC Ship Of Opportunity Program Implementation Plan (SOOPIP) and Dr. Joaquin Trinanes is a member of the Meta-T panel.

2.25. Recruiting

AX-7, AX-8, AX-10, and AX-18 are on container ships, and optimally run 4 times per year, and AX-25 is staffed by University of Cape Town personnel on their research vessel, and it is carried out twice a year.

Typically, we can keep with a particular ship company on a specific transect for approximately 2 to 3 years. When they discontinue their service on a given route, a new recruitment process begins. The following ships were recruited during this last fiscal year:
AX-08: Safmarine Ngami, 1st cruise: Jul 08.
AX-10: Horizon Navigator, 1st cruise: Apr 08.
AX-18: CMA CGM Santos.

2.26. Collaboration with SeaKeepers

Seakeepers TRACKOB data (with international location indicator KWUM) was not accomplishing the objective of full, global and public distribution. NOAA/AOML and Environment Canada were two of the intended destinations not having access to these bulletins. Two action items were established during a meeting with SeaKeepers management: modify the distribution designator (ii) for testing the dissemination scheme of a limited set of bulletins, and contact the NWSTG in order to update the distribution tables and reach the same global distribution scheme as the SOVX01 KWBC header, being used with NOAA TRACKOB datasets. Finally, and with the essential intervention of NDBC (Robert Luke), NWSTG modified the route of SeaKeepers TSG measurements and KWUM bulletins started being globally distributed, solving the problem.

2.27. AOML contribution to the Oleander Project

AOML provided hardware equipment (computer for data acquisition and transmission antenna) for the Oleander. Approximately 350 XBTs are deployed by this ship between New York and Bermuda.

2.28. Fall Rate Equation Studies

There is evidence that there is a systematic depth dependant error in XBT temperature profiles, which is likely due to an error in the XBT fall-rate equation. This error has introduced a warm bias in the global XBT data base. A workshop was organized by G. Goni and M. Baringer to discuss the findings related to this issue by different groups. As a consequence, a new fall rate equation may need to be developed and applied to both past and future XBT data. Information on this workshop is at: http://www.aoml.noaa.gov/phod/goos/meetings/2008/XBT

A workshop report is currently being written. AOML is currently involved in two research efforts to identify systematic biases in XBT temperature profiles: a) Comparison between simultaneous XBT and CTD deployments, and b) Comparison between simultaneous XBT and Argo float observations using sea height anomaly fields derived from altimetry to quantify the biases.

Two manuscripts are currently being written:

- Snowden, D., G. Goni and M. Baringer, A comparison of six expandable bathythermograph data acquisition systems: Temperature and fall rate errors, to be submitted to *J. Geophys. Res.*, 2008.
- DiNezio, P., and G. Goni, Identifying and estimating biases between XBT and Argo observations using satellite altimetry, to be submitted to *J. of Clim.*, 2008.

2.29. Contribution to Heat Storage quarterly reports

XBT observations provide approximately 25% of all global temperature profile data and are used to create quarterly reports of heat storage: http://www.aoml.noaa.gov/phod/soto/ghs/reports.php.
This work is funded by NOAA/CPO under the project: Evaluating the Ocean Observing System: Performance Measurement for Heat Storage, by C. Schmid and G. Goni.

2.30. SOOP Brochure

A new brochure was created for recruiting and general information purposes. They can be obtained from the SOOP web site at: http://www.aoml.noaa.gov/phod/goos/docs/.

2.31. Peer-reviewed Publications

Swart, S., S. Speich, I. Ansorge, G. Goni, S. Gladyshev, J. Lutjeharms, 2007: Transport and variability of the Antarctic Circumpolar Current south of Africa, *J. Geophys. Res.*, in press.

Mainelli, M., M. DeMaria, L. Shay, G. Goni, 2007: Application of oceanic heat content estimation to operational forecasting of recent Atlantic category 5 hurricanes. *Weather and Forecasting*, in press.

2.32. Presentations

Goni, G., M. Baringer, R. Molinari, D. Snowden, and S. Garzoli. The status of the XBT network, 2008 Ocean Sciences Meeting, March 2-7, Orlando, Florida.

Baringer, M. Heat transport changes from High-Density XBT lines in the North Atlantic, 2008 Ocean Sciences Meeting, March 2-7, Orlando, Florida.

Johns, W. E., H. L. Bryden, M. O. Baringer, L. M. Beal, S. A. Cunningham, T. Kanzow, J. Hirschi, J. Marotzke, Z. Garraffo, C. S. Meinen, Observations of Atlantic Meridional Heat Transport Variability at 26.5°N from the RAPID-MOC Array, 2008, 2008 Ocean Sciences Meeting, March 2-7, Orlando, Florida.

Baringer, M. and S. L. Garzoli, 2007. The Meridional Heat Transport in the South Atlantic Ocean AGU Joint Assembly, Acapulco (Mexico), 22-25 May 2007.

Baringer, M. O., 2006. Heat transport variations in the subtropical North Atlantic, Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.

Johns, W; S. Cunningham, T. Kanzow, H. Bryden, J Marotzke, M. Baringer, L. Beal; C. Meinen, J. Hirschi, D. Rayner, 2007. Variability of the Atlantic meridional overturning circulation during 2004-2005 as observed from the 26° N RAPID- MOC Array. AGU Joint Assembly, Acapulco (Mexico), 22-25 May 2007.

Observations of the Brazil Current baroclinic transport variability near 22S, M. Mata, M. Cirano, M. Caspel, G. Goni and M. Baringer, EGU 2008 General Assembly, Austria, April 2008.

2.33. Worshops

Two SEAS/XBT workshops were held at NOAA/AOML during FY 2008:

- NOAA/AOML SEAS, XBT, and TSG Operations. Miami, Florida, June, 2008.
- XBT Fall Rate Equation Workshop, Miami, March 10-12, 2008.

2.34. Publications that use NOAA XBT observations

1. Aoki, Shigeru; Akitomo, Kazunori. Observations of small-scale disturbances of the Subantarctic Front south of Australia. Deep Sea Research (Part I, Oceanographic Research Papers) [Deep Sea Res. (I Oceanogr. Res. Pap.)]. Vol. 54, no. 3, pp. 320-339. Mar 2007.

2. Baringer, MO; Garzoli, SL. The Meridional Heat Transport in the South Atlantic Ocean. Proceedings of the American Geophysical Union 2007 Joint Assembly. [np]. 2007.

3. Baringer, MO; Garzoli, SL. Meridional heat transport determined with expendable bathythermographs-Part I: Error estimates from model and hydrographicdata. Deep Sea Research (Part I, Oceanographic Research Papers) [Deep Sea Res. (I Oceanogr. Res. Pap.)]. Vol. 54, no. 8, pp. 1390-1401. Aug 2007.

4. Cornuelle, B; Hoteit, I; Koehl, A; Stammer, D. Strong Adjoint Sensitivities in Tropical Eddy-Permitting Variational Data Assimilation. Proceedings of the American Geophysical Union 2007 Joint Assembly. [np]. 2007.

5. Douglass, E M; Roemmich, D; Stammer, D. North Pacific Variability From a Data-Assimilating Model. Proceedings of the American Geophysical Union 2007 Joint Assembly. [np]. 2007.

6. Garzoli, SL; Baringer, MO. Meridional heat transport determined with expandable bathythermographs-Part II: South Atlantic transport. Deep Sea Research (Part I, Oceanographic Research Papers) [Deep Sea Res. (I Oceanogr. Res. Pap.)]. Vol. 54, no. 8, pp. 1402-1420. Aug 2007.

7. Gopalakrishna, VV; Rao, RR; Nisha, K; Girishkumar, MS; Pankajakshan, T; Ravichandran, M; Johnson, Z; Girish, K; Aneeshkumar, N; Srinath, M; Rajesh, S; Rajan, CK. Observed anomalous upwelling in the Lakshadweep Sea during the summer monsoon season of 2005. Journal of Geophysical Research. C. Oceans [J. Geophys. Res. (C Oceans)]. Vol. 113, no. C5, [np]. Jul 2008.

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10. Korotenko, KA. A regression method for estimating salinity in the Ocean. Oceanology, Volume 47, Number 4, Aug 2007.

11. Kovach, R; Keppenne, C; Rienecker, M; Marshak, J; Jacob, J. Assimilation of Temperature, Salinity, and Sea Surface Height Data into the GMAO Ensemble Kalman

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13. Maximenko, Nikolai A; Melnichenko, Oleg V; Niiler, Pearn P; Sasaki, Hideharu. Stationary mesoscale jet-like features in the ocean. Geophysical Research Letters [Geophys. Res. Lett.]. Vol. 35, no. 8, [np]. May 2008.

14. Mainelli, M; DeMaria, M; Shay, L; Goni, G. Application of Oceanic Heat Content Estimation to Operational Forecasting of Recent Atlantic Category 5 Hurricanes. American Meteorological Society. Vol. 23, pp. 3-16. Feb 2008.

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Ship of Opportunity (VOS)

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1. PROJECT SUMMARY

Ships of Opportunity, also known as Volunteer Observing Ships or VOS, are merchant marine ships that make repeated ocean passages. In this project we focused on developing instrumentation for fast container ships that make regular crossings of broad areas of the ocean basins and, if possible, those that pass close to our Ocean Reference Stations (ORS), which are surface moorings at fixed locations (Figure 1). This provided broad spatial sampling of the regimes found across ocean basins that is an excellent complement to the high time resolution sampling at our fixed time series sites (ORS). When possible we also selected ships that were used by other groups for deployment of XBTs (expendable bathythermographs) and profiling floats, as sharing of logistic support facilitates the work. Our goal was to obtain from the selected VOS time series of surface meteorology and ships position that are complete and accurate and thus allow us to compute, using the bulk formulae, time series of air-sea heat (sensible, latent, shortwave, longwave, and net), freshwater, and momentum flux. These time series are used to quantify the spatial variability in the in-situ surface meteorology and air-sea fluxes, to identify spatial biases and other others in gridded meteorological and flux products (such as those from the National Centers for Environmental Prediction (NCEP) or those developed from remote sensing methods), to develop improved fields of air-sea fluxes over the oceans, and to support climate research.

The instrumentation used on the VOS is the Air-Sea Interaction Meteorology (ASIMET) system developed at WHOI and available commercially through Star Engineering. An ASIMET system collects one minute averaged values of wind speed and direction, air and sea surface temperature, relative humidity, barometric pressure, incoming shortwave radiation, incoming longwave radiation, and precipitation. Although the packaging is different, the sensors and electronics used for the VOS project are the same as those used on the surface buoys in the ORS project. Thus, there is significant synergy between VOS and ORS instrument development activities. The implementation of the ASIMET hardware on the VOS is the AutoIMET. AutoIMET is a distributed, wireless, system developed at WHOI for making systematic, climate quality measurements of surface meteorology from ships of opportunity. The AutoIMET system interfaces to the NOAA SEAS 2000 (Shipboard Environmental (Data) Acquisition System) that automatically receives the meteorological data and sends in hourly reports via Inmarsat.

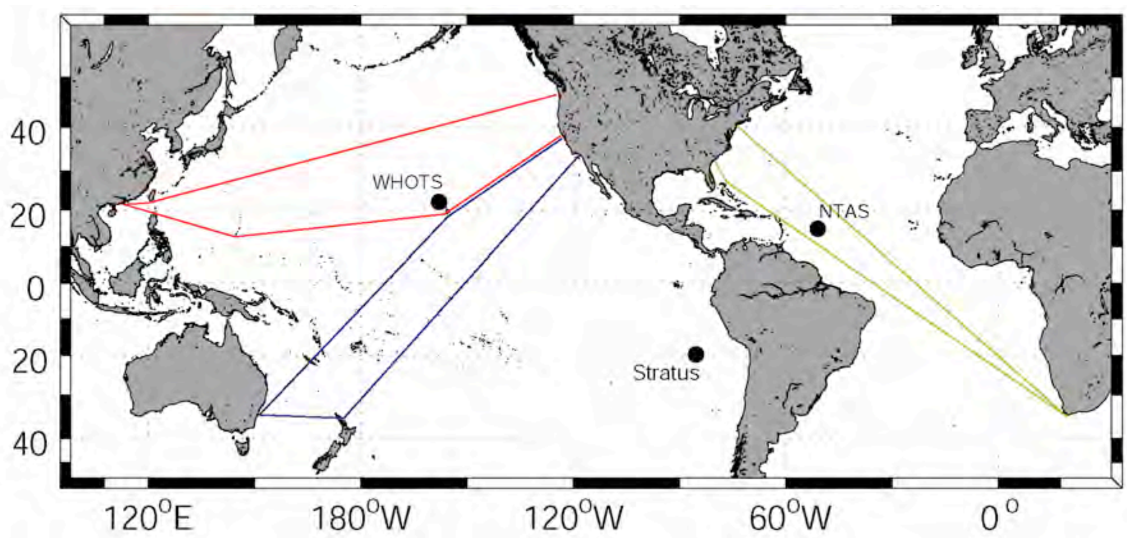

Figure 1. Schematic of routes occupied by the WHOI VOS program along with location of the WHOI ORS sites. Ships occupying the different routes were: Horzon Enterprise, northern Pacific route (red); Columbus Florida and Direct Tui, southern Pacific route (blue); SeaLand Express, trans-Atlantic route (green), Merkur, north Atlantic route (not shown).

The ASIMET sensors produce high-quality data, accurate enough to support calculation of monthly air-sea heat exchanges to better than 10 W m^{-2}. The data from the VOS are used to: 1) identify errors in existing climatological, model-based, and remotely-sensed surface meteorological and air-sea flux fields, 2) motivate improvements to existing parameterizations and algorithms used in models and in preparing products from satellite data, 3) provide the data needed to correct existing climatologies, and 4) validate new model codes and remote sensing methods. The VOS data, due to the cross-basin, repeat sampling, are an important resource for work to improve the accuracy of global fields of the air-sea fluxes of heat, freshwater, and momentum and to document variability and change in the coupling of the atmosphere and the ocean.

The VOS provide a challenging operating environment in which to make high quality surface meteorological observations. Acceleration and vibration, radio frequency interference, freezing temperatures, and power surges are among the issues we have faced. Examination of performance and failure rates of ASIMET sensor modules revealed where the present set of modules introduce reliability problems and negatively impact data return rates. This led to a variety of analysis and development activities which provided improved sensors for both VOS and ORS programs. As newly developed ASIMET modules become commercially available, these benefits will be passed on to the oceanographic community. These activities are described in more detail below under Instrument Development.

A subcontract to colleagues at the National Oceanographic Centre (NOC, formerly Southampton Oceanography Centre) in the U.K. has addressed another aspect of the challenge of working from VOS – flow distortion by the structure of the ship and its cargo – in order to predict the likely biases in wind speed measurements. Given the range of shapes and sizes of ships in the merchant fleet, simple generic ship shapes were developed and used to represent different types or classes of ships. The generic results have some limitations for bow-on flows, but in general wind observations were shown to be most sensitive to the ratio of the height above the bridge z to the "step height" H (the bridge-to-deck distance for bow-on flows and bridge-to-waterline for beam-on flows). A normalized height z/H of 0.4 or greater is desirable to keep speed distortion to about 10%. The case of bow-on flows over container ships is complicated because the ship's geometry changes with the number of containers loaded and their distribution. It was suggested that wind bias estimates could be made using the VOS data by comparing beam-on winds speeds (corrected for flow distortion) with un-corrected bow-on speeds.

2. PROGRAM STATUS

The Ships of Opportunity Program has been managed as three tasks: A) VOS Field Operations, B) Instrumentation Upgrades, and C) Data Processing. When submitting our work plans for 2008 last year, we presented a plan to refocus this effort that met with agreement. We took the position that we now had in hand a sufficient body of data from VOS, were facing continuing challenges in identifying suitable ships on desirable routes, and were finding increasing challenges in upgrading the instrumentation common to our VOS and Ocean Reference Station (ORS) moorings. As a result, we proposed ramping down for now VOS Field Operations, while maintaining support for the Instrumentation Upgrades and Data Processing components. This proposal was agreed upon and we reduced our request in this project from $680,699 to $489,735.

Moving forward, the VOS program will no longer be identified or reported on separate from the Ocean Reference Station (ORS) project. Instead, in preparing the work statement and budget for 2009 we have brought our entire effort under the ORS project. The VOS Instrumentation Upgrades effort is now included within a new element of the ORS project, Sustaining Engineering. The instrumentation development and upgrades that in the past supported both VOS and ORS efforts now targets just ORS. Continued work on VOS data processing will be supported at a modest level within the existing NTAS Analysis budget.

3. ACCOMPLISHMENTS

3.1. VOS Field Operations

This is the final year of field operations while we ramp down the data collection effort. We have typically supported ASIMET installations on two ships, and this was the case during the reporting period. A first-order challenge is the short lifetime of a given ship on a given route. Our longest running vessel has been the Horizon Enterprise, doing the Oakland -Hawaii-Guam-Taiwan-Tacoma run (Figure 1). The second VOS was an Atlantic ship (originally the SeaLand Express and then the Merkur during 2004-2005). In February 2006, the Atlantic ship was sold and our Atlantic VOS operations were discontinued. At present we are maintaining two Pacific installations, the Horizon Enterprise and the Horizon Hawk. This includes the preparation and calibration of the systems, and recovery of the raw data as well as the ancillary time series of ships' position and velocity. The Enterprise stopped going all the way across the Pacific, and now runs between the West Coast and Hawaii (Figure 2a). Recognizing the value of the complete trans-pacific route, an AutoIMET system was installed on the Horizon Hawk, which runs from the west coast to Hawaii, Guam, Taiwan, Hong Kong, and back to the west coast (Figure 2b).

Figure 2. Recent routes for the Horizon Enterprise (left) and Horizon Hawk (right).

Specific activities relating to supporting the VOS Horizon Enterprise and Horizon Hawk during the reporting period are listed below:

- September/October 07, Tacoma, WA and Oakland, CA: Meet the Hawk in Tacoma for a new AutoIMET installation, sail with the Hawk to Oakland to complete the installation. Return to Tacoma to meet the Enterprise for an AutoIMET calibration turn-around.

- November/December 07, Oakland CA: Meet the Enterprise and the Hawk to repair their AutoIMET humidity and wind sensors, respectively.

- January 08 Tacoma, WA and Oakland, CA: Meet the Hawk in Tacoma for AutoIMET repairs, sail with the ship to Oakland for evaluation.

- March 08, Honolulu, HI: Meet the R/V Kilo Moana to install an AutoIMET system for the WHOTS ORS mooring recovery cruise in June; prepare the AutoIMET installation on the Enterprise for her upcoming shipyard period (take down most sensors).

- April 08, Oakland CA: Meet the Hawk for a standard AutoIMET calibration turn-around.

- June 08, Oakland CA: Meet the Enterprise following her return from the shipyard to re-install AutoIMET wind component only. This represented the termination of full AutoIMET data acquisition and SEAS data distribution on the Enterprise.

- July/August 08, Tacoma, WA: Meet Horizon Enterprise and Horizon Hawk for wind sensor repairs. A decommissioning trip planned for early 2009 will represent the termination of AutoIMET data acquisition and SEAS data distribution on the Hawk.

3.2. Instrumentation Upgrades

The VOS are a challenging operating environment in which to make high quality surface meteorological observations. Performance evaluation and sensor failures have shown the need to upgrade some sensor modules to address problems. Prototype new sensor modules are built and tested at WHOI and in the field and are then phased into use on the VOS and ORS moorings. Two examples of note relate to wind and longwave radiation. Early wind deployments showed the need for a dedicated GPS system coupled to the wind measurement, and development work was done to provide GPS as part of the VOS installations. Experience over multiple deployments showed the vulnerability of the mechanical propeller and vane wind sensor on VOS installations, and led to the development of a new ASIMET wind module based on a Gill sonic anemometer (Figure 3) that is under test now as a replacement for the current mechanical sensor.

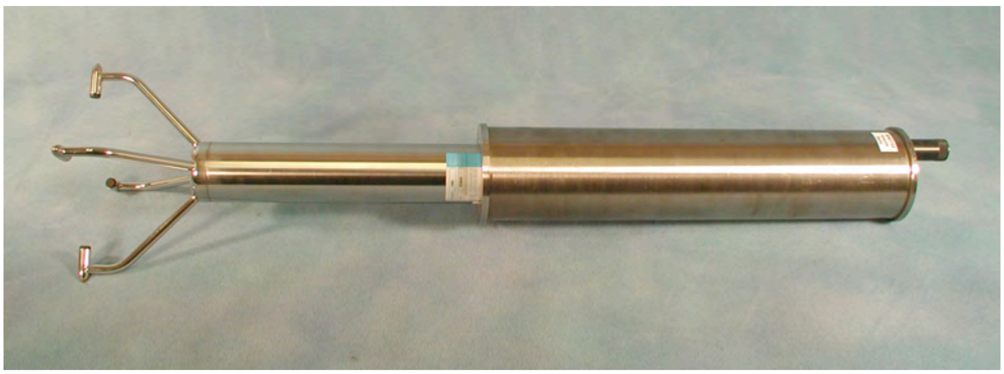

Figure 3. ASIMET sonic anemometer module based on a Gill OceanObserver II.

Examination of repeated pre- and post-deployment calibrations, and efforts to get close agreement (to roughly 2 W m^{-2}) in calibrated sensor modules identified the incoming longwave radiation module as introducing the largest uncertainty in our heat flux estimates. Effort was focused on modifying module electronics, improving calibration procedures, and evaluating alternate sensors. Specifically, a new “front end” circuit board (preamplifer for the thermopile voltage from the longwave sensor) has been developed and implemented in an upgraded longwave module using the Eppley sensor. In addition, a longwave module based on a Kipp and Zonen CP-4 sensor has been developed and tested. Intercomparison with longwave sensors from Chris Fairall’s group during cruises on the NOAA Ship *Ronald H. Brown* showed we were successful in improving ASIMET longwave performance.

Within the last few years we have found that some of the components in our ASIMET circuit boards are no longer available or soon to be obsolete, including the digital memory cards used to log the data and specific circuit board components. As a result, upgrades are being made to the ASIMET electronics. The PCMCIA-type flash memory (which is getting hard to obtain and is difficult to use) is being replaced by digital flash memory. Obsolete parts and cold sensitivities are being identified in conjunction with design of a new processor board.

At the same time, under this effort, we have gone forward with an effort to develop the capabilities within the ORS/ASIMET instrumentation to collect subsurface ocean data on ORS moorings, bring it up to the surface by inductive and acoustic telemetry methods, and integrate this averaged (and thus decimated to a reasonable volume) subsurface data into the telemetered data stream coming from ORS. In support of this we also worked at implementing Iridium-based data telemetry. Full implementation of this pathway for the ORS must, however, await NOAA arranging a tariff agreement that would reduce to cost to us of using Iridium.

3.3. Data Analysis

The basic deliverable of the VOS program is the data, supported by the appropriate metadata. Descriptions, technical information and raw data from the several VOS being serviced can be accessed through on our VOS website: http://uop.whoi.edu/projects/VOS/vos.html. Data (plots) are presented for all ship sets. Quality controlled data files are available for the VOS Enterprise for April 2002 through May 2006. Data from other cruises are available by request from Frank Bahr (fbahr@whoi.edu).

In addition to data processing to produce quality controlled files for each VOS, effort under this task includes the use of VOS data to develop information about the accuracy of flux fields on basin scales and the spatial variability and coherence of surface meteorological fields. Our initial focus was on results from VOS tracks passing near the NTAS buoy at 15 N, 51 W. Tracks from the VOS Merkur in 2004 resulted in six “encounters” where the ship passed within a 500 km radius of the buoy (Figure 4). The duration of a typical encounter was about one day. Auto- and cross-correlation analyses, showed that auto-correlation times for both buoy and ship meteorological variables are from 3-6 h, barometric pressure and shortwave radiation show correlation between buoy and ship (due to the atmospheric tide and diurnal solar cycle, respectively), and other variables have weak or no correlation. This work can be extended using time series records from nearby NDBC buoys (Figure 4) as well as shipboard meteorological data from the NTAS mooring service cruises.

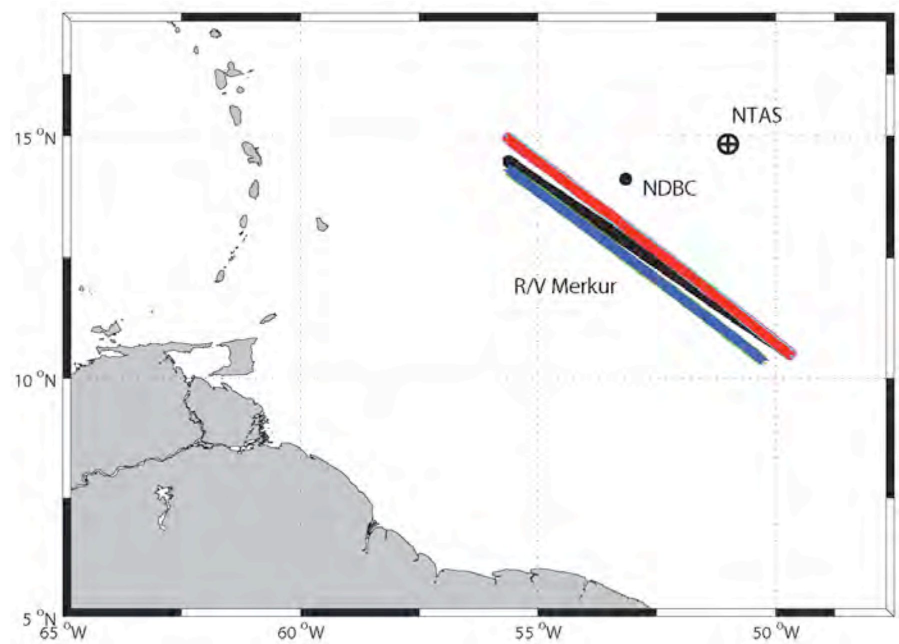

Figure 4. Ship tracks for 6 passes of the VOS Merkur within 500 km of the NTAS ORS.

Data from the Horizon Enterprise, which crosses the North Pacific on an approximately 5-week schedule, are the most complete and provide the most extensive spatial coverage. These data were used in two studies comparing in-situ meteorology with that from the ECMWF numerical weather prediction model. The first study focused on the ~2400 mile segment between Oakland, California, and Honolulu, Hawaii. Surface meteorology from the VOS was compared with that from the ECMWF model for 29 transects during 2003 – 2006 (Figure 5). Most variables showed good agreement in the mean, but large standard deviations indicated shortcomings in of the ECMWF model on short spatial scales. Some variables did have notable mean differences, for example ECMWF wind speed was ~2 m/s less than the VOS on average. The second study focused on downwelling longwave irradiance (LWR) observed from 10 round-trips along the full north Pacific route during calendar 2004. The VOS observations were compared to LWR from two global model products – the NCEP-2 reanalysis and the International Satellite Cloud Climatology Project (ISCCP) longwave product. Annual mean values along the VOS tracks and the seasonal cycle at several fixed locations were compared.

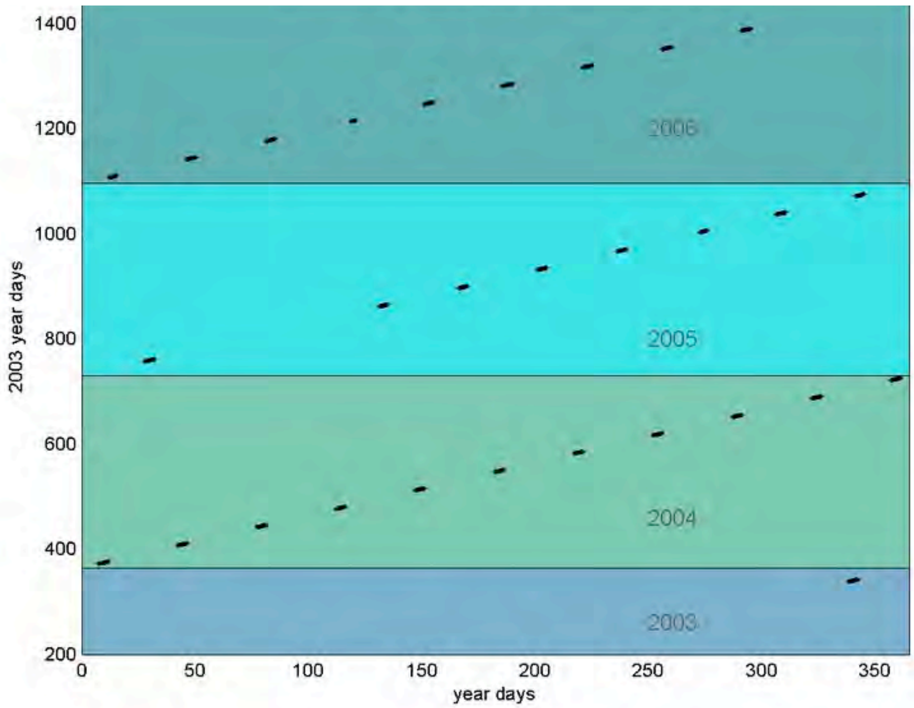

Figure 5. Season vs. year breakdown of twenty nine VOS Horizon Enterprise transects between Oakland CA and Honolulu for the period 2003 – 2006.

Comparisons of annual mean LWR along the northern VOS route showed ISCCP to be consistently more accurate than NCEP, whereas NCEP was more accurate along the southern route (Figure 6). This behavior is consistent with the annual mean difference (NCEP – ISCCP), which indicates a change in the relative amplitudes along 40 N. Applying meridional corrections of opposite slope, increasing NCEP by about 20 W/m to the N and ISCCP by 20 W/m to the S, would improve the comparison with VOS observations. Comparison of the seasonal cycle in selected regions showed relatively good agreement among VOS, NCEP and ISCCP where the cycle amplitude was strongest. The VOS data indicate that the 'tongue' of strong seasonal variability extends further to the east than shown by NCEP and that there is a weak seasonal cycle to the south that is not captured by NCEP or ISCCP. Further work will include extending the analysis period from one to three years, improving the space and time registration of the comparison (e.g. by using daily NCEP and ISCCP data along the individual VOS tracks rather than monthly data along the average track), and including ORS moorings at the WHOTS and KEO sites as tie-down points.

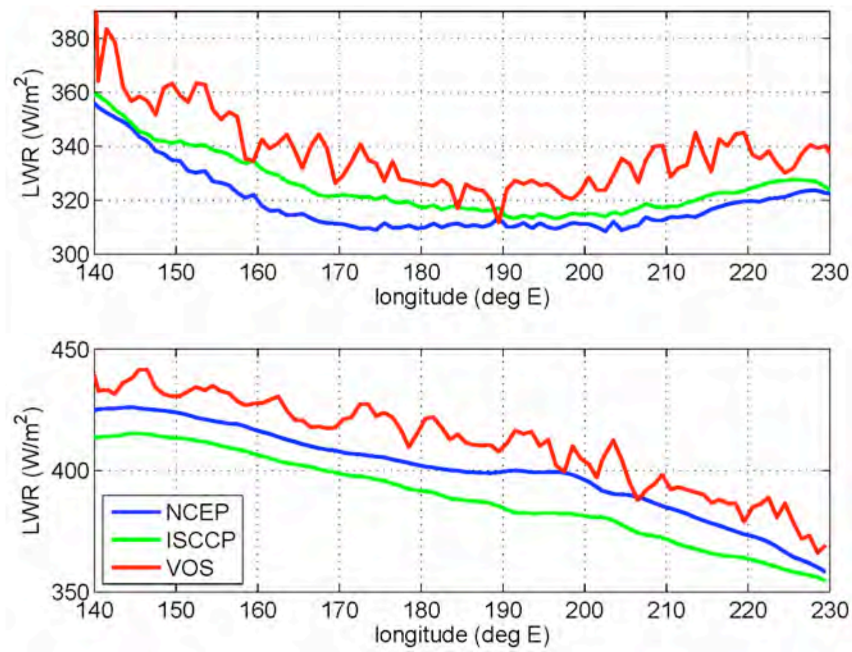

Figure 6. Comparison of longwave radiation (LWR) form the VOS Horizon Enterprise (red), the NCEP-2 reanalysis (blue) and the ISCCP flux product (green). The upper panel is along the northern leg of the north Pacific route (Figure 1) and the lower panel is along the southern leg.

4. PUBLICATIONS AND REPORTS

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6. Argo Profiling Floats

a. The Argo Project: Global Observations for Understanding and Prediction of Climate Variability

The Argo Project: Global Observations for Understanding and Prediction of Climate Variability

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1. PROJECT SUMMARY

The U.S. component of the international Argo Project (http://www.argo.ucsd.edu), a global array of autonomous profiling floats, is implemented through this award. The present report covers Year 1 of the 5-year "sustained phase" of the project, which builds on progress made under previous awards (Phases 1,2 and 3) for pilot float arrays, data system development, and global implementation.

As of November 1, 2007, the international Argo Project, including the US contribution, has met its goal of building a global array of 3000 active profiling CTD floats (Roemmich and Owens, 2000, Roemmich et al, 2001, 2002, Gould et al., 2004), and established a data system to meet the needs of both operational and scientific users for data delivery in real time and delayed mode. In order to maintain the Argo array, it is necessary to replace over 25% (800) instruments every year. Argo is a major initiative in oceanography, with research and operational objectives, providing a global dataset for climate science and other applications. It is a pilot project of the Global Ocean Observing System (GOOS).

Phase 1 (9/99 – 9/02) and Phase 2 (7/00 – 6/02) of US Argo provided regional arrays of CTD profiling floats to demonstrate technological capabilities for fabrication and for deployment of float arrays in remote ocean locations (Phase 1) and to demonstrate the capability for manufacture and deployment of large float arrays (Phase 2). Development of the U.S. Argo Data System was carried out to make Argo data publicly available within a day of collection, to apply automated quality control procedures consistent with international Argo practices, and to provide research-quality data in delayed-mode.

Phase 3 of US Argo was a 5-year project (8/01 – 6/06) aimed at full implementation of the US component of Argo. Float deployment rates were increased to more than 400 per year beginning in CY 2004 (Figure 1). Objectives were to achieve 1500 active US Argo floats (50% of the global array), to improve the spatial distribution of floats toward the target of uniform 3^{o} spacing, to increase the mean lifetime of floats to 4 years, to operate the near-real time and delayed-mode data systems consistent with international agreements, and to provide substantial leadership and coordination roles for international Argo.

Phase 4 of US Argo is a follow-on 5-year project (7/06 – 6/11) aimed at improving and sustaining the US component of Argo. Float deployment rates should continue at about 400 per year. Objectives are to complete and sustain the array of 1500 active US Argo floats, to further improve the spatial distribution of floats through targeted deployments, to further increase the mean lifetime of floats beyond 4 years, to continue to improve and operate the near-real time and delayed-mode data systems

consistent with international agreements, and to provide substantial leadership and coordination roles for international Argo.

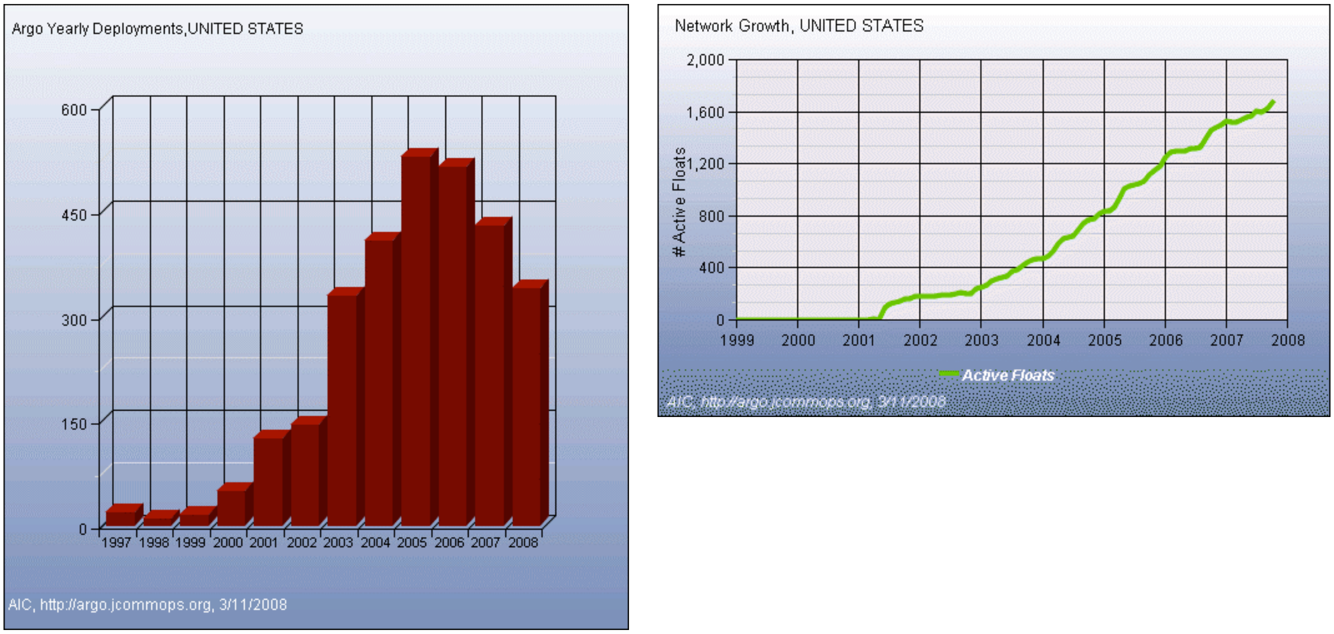

Figure 1. Yearly deployments of United States Argo floats through 11 November 2008 (including Argo-equivalent), and growth in the number of active US floats. (Source:AIC).

Float production and deployment are accomplished by four facilities – SIO (production and deployment), WHOI (production)/AOML (deployment), UW (assembly and deployment), and PMEL (thorough testing and deployment of commercially manufactured floats). This distributed effort has been designed to safeguard the US contribution to the Argo project from unforeseen problems at any one of the partner institutions. It also makes Argo success independent of the participation of any individual PI and institution or of any single float design. It allows the large amount of effort to be shared. It encourages individual, technical innovation and enhancement. While the initial focus has been on improving float technical performance, attention of the PIs will increasingly focus on demonstrating the scientific value of Argo.

The data system is also distributed. AOML is the US Argo Data Assembly Center (DAC), responsible for acquiring the float data received by satellite communications, for carrying out real-time quality control, and for distribution of data via the GTS and to the Global Argo Data Assembly Centers. The second step in data management is a semi-automated drift-adjustment of the salinity sensor carried out by each float-providing PI, using nearby high quality CTD data for comparison with float temperature/salinity data (Wong et al, 2003). The final step is individual examination of all profiles by the float-providing PIs, in order to provide high-quality data suitable for research applications.

All Argo data are freely available within about 24 hours of collection, and can be accessed from the GTS or internet (http://www.usgodae.org/, or http://www.ifremer.fr/coriolis/cdc/argo.htm).

2. ACCOMPLISHMENTS

The goal of 1500 active US Argo floats has been achieved (Figure 2). As of 30 September 2008 there are 1750 active US Argo floats, plus 75 US Argo-equivalent instruments that also feed data to the US Argo DAC. Float deployments have continued at an average of approximately 400 per year through the third year of Phase 4. 1155 of the 1825 active US Argo floats are in the Southern Hemisphere, reflecting the US commitment to eliminate the northern bias of the international Argo array and achieve uniform global coverage. A notable effort has been the collaboration between US Argo and NIWA (Argo-New Zealand), resulting in approximately 600 deployments since 2004 in remote ocean locations by NIWA's R/V Kaharoa. Funding shortfalls may decrease the level of this work in future.

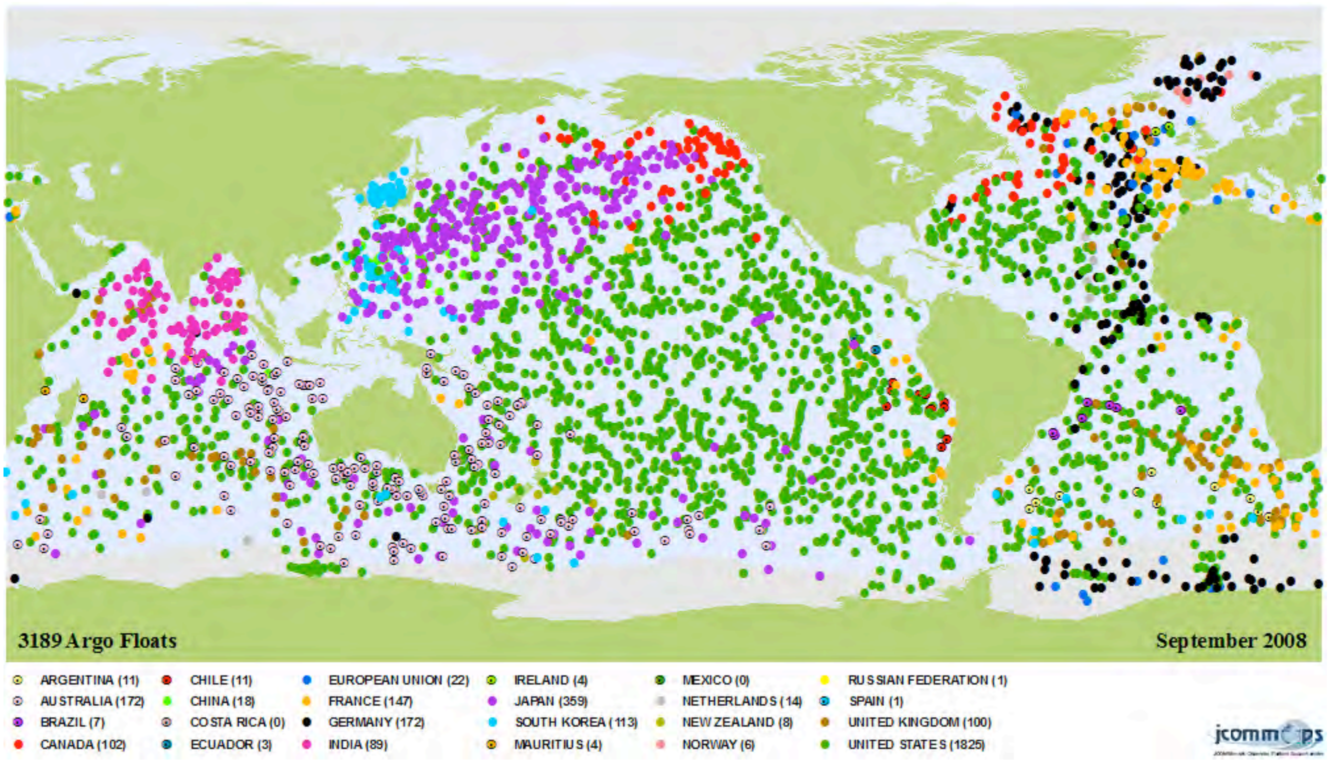

Figure 2. The Argo Array as of 30 September 2008. The 1825 active US floats (Green), included 1750 floats funded via US Argo, and 75 other US (Argo-equivalent) floats whose data are released by the PIs via the US Argo Data Assembly Center.

Good progress has been made in increasing float lifetimes (Figure 3). For floats deployed in 2004, about 70% remain active after 130 cycles. Nearly 85% of 2005 deployments remain active after 100 cycles. It is likely that the goal of a 4-year mean lifetime has been met for both APEX and SOLO designs. The re-design of the SOLO float (SIO) is nearly complete for increased lifetime and capabilities. Prototypes will be deployed in the coming year. The US is the technology leader in profiling floats and about 90% of floats in the international array are made in the US.

The Argo data system continues to operate well, with the AOML DAC providing near-real time data to the GDACs in NetCDF format consistent with international specifications. Improvements in procedures continue to be implemented as required by the International Argo Data Management Team. A backlog in processing of research-quality delayed-mode data has been substantially reduced and will continue to be reduced in the coming year. A pressure-offset error was detected in some WHOI floats this year and corrective steps have been taken (http://www-argo.ucsd.edu/Acpres_offset2.html). Procedures are being considered for more effective detection of systematic data errors.

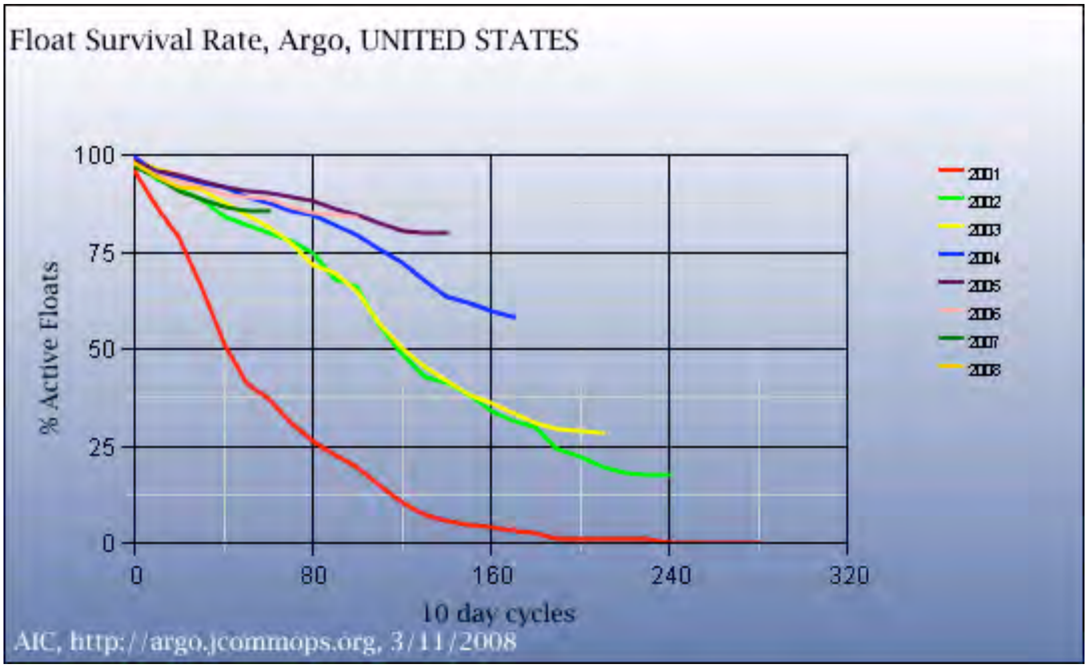

Figure 3. Float reliability. Note that the percentage of floats surviving for at least 100 cycles increased from about 65% for 2002/03 deployments to about 85% for 2005 deployments.

The US Argo consortium plays strong leadership roles in the international Argo project. This includes the international Argo Steering Team Co-Chairman (Dean Roemmich, SIO) and the international Argo Data Management Team Co-Chairman (Mark Ignaszewski, FNMOC) as well as many international panel memberships. US partners provide international leadership in float technology and data management techniques through workshops and training of international colleagues. US partners provide coordination for deployment planning activities in the Pacific, Atlantic, and Southern Oceans. The US is also a leader in utilization of Argo data, organizing international symposia such as the Argo-relevant sessions at the 2008 GODAE Final Sympostium, and through sharing of research results and operational capabilities.

The Argo array is providing unprecedented views of the evolving physical state of the ocean. It reveals the physical processes that balance the large-scale heat and freshwater budgets of the ocean and provides a crucial dataset for initialization of and assimilation in seasonal-to-decadal forecast models.

About 400 research publications have resulted so far from Argo data, including 156 in 2007-2008 (to date). These publications span a wide variety of research topics from small spatial-scale/short time-scale phenomena such tropical cyclone intensification, to studies of mesoscale eddies, to large-scale phenomena such as water mass variability and basin-scale ocean circulation. Almost none of this work would have been possible without the contributions of US Argo to building, sustaining, and utilizing the array.

A sparse global Argo array was achieved in 2004, and so there are now nearly 4 years of continuous global coverage. The 4-year global dataset provides a baseline of the present climate-state of the oceans (Figure 4), against which future variability can be observed by a sustained Argo array. It also provides a comparison point for past datasets to describe decadal change in the oceans. With 4-years of data we have, for the first time, a stable estimate of the mean and annual cycle of the global ocean over a fixed period of time (Figure 5).

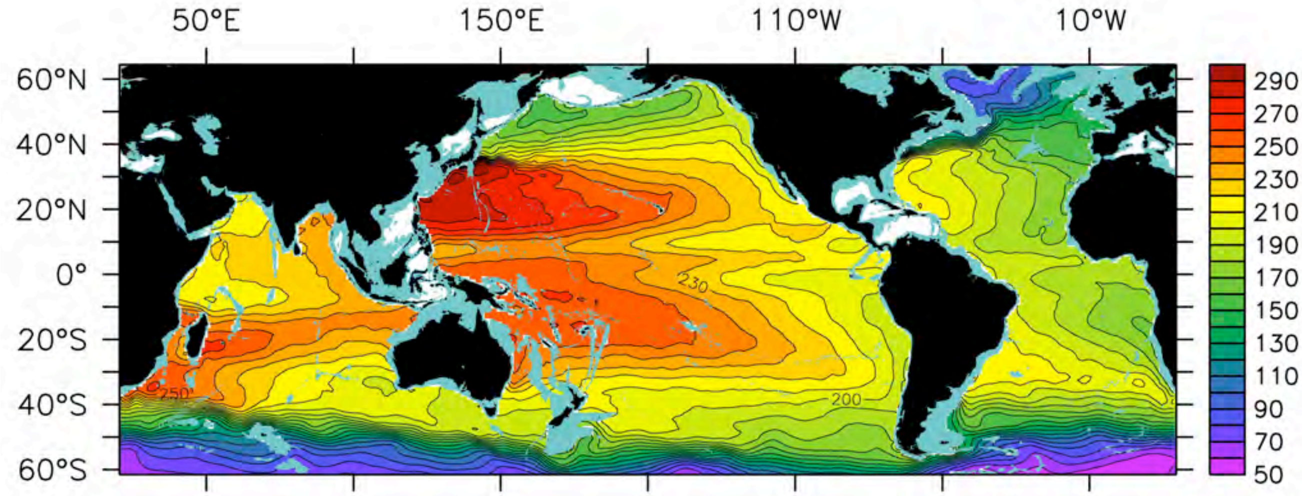

Figure 4. Argo observes the mean state of the oceans, 2004 – 2006: mean dynamic height of the sea surface relative to 2000 dbar (dyn-cm).

At least 13 operational centers around the world are using Argo data on a routine basis (http://www.argo.ucsd.edu/FrUse_by_Operational.html). Operational applications include ocean state estimation, short-term ocean forecasting, atmosphere/ocean seasonal-to-interannual prediction, and coupled climate modeling. Ocean state estimation has an increasing number of valuable uses including climate monitoring, forecast initialization, fisheries and ecosystem modeling, provision of boundary conditions for regional and coastal modeling, and others.

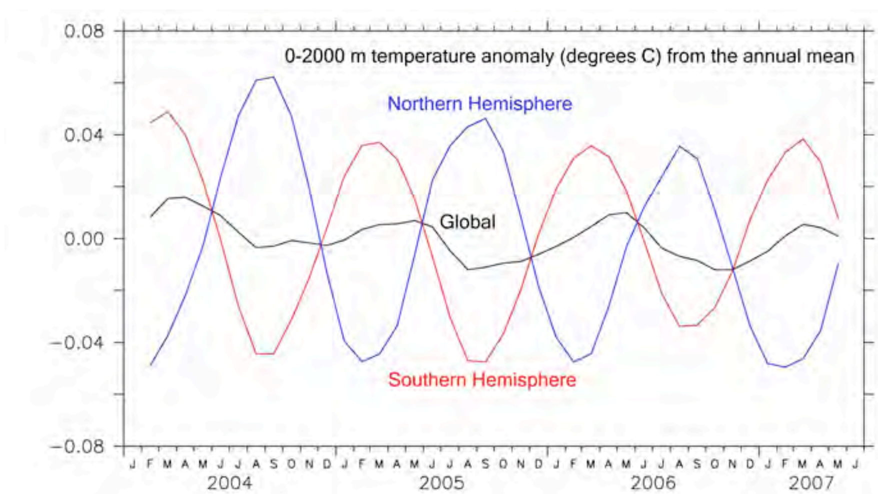

Figure 5. Argo takes the ocean's "pulse": Time-series of global (black), Southern Hemisphere (red) and Northern Hemisphere (blue) averaged ocean temperature (anomaly from the annual mean), 0-2000 m, from Argo data.

US Argo Consortium relevant web sites:

Argo Steering Team home page http://www-argo.ucsd.edu
Argo Information Center http://argo.jcommops.org

Scripps Institution of Oceanography http://sio-argo.ucsd.edu
Woods Hole Oceanographic Institution http://ursa.whoi.edu/~argo/
University of Washington http://flux.ocean.washington.edu/argo/
NOAA PMEL http://floats.pmel.noaa.gov
NOAA AOML (US DAC and South Atlantic Argo Regional Center)
http://www.aoml.noaa.gov/phod/argo/index.php
US GDAC http://www.usgodae.org

3. PUBLICATIONS AND REPORTS

See http://www.argo.ucsd.edu/FrBibliography.html.

About 400 research publications have resulted so far from Argo data (see above link), including 156 publications in 2007-2008, to date. These publications span a wide variety of research topics from small spatial-scale/short time-scale phenomena such tropical cyclone intensification, to studies of mesoscale eddies, to large-scale phenomena such as water mass variability, basin-scale ocean circulation, and climate change. Almost none of this work would have been possible without the contributions of US Argo to building, sustaining, and utilizing the global Argo array.

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7. Ocean Carbon Networks

a. Global Repeat Hydrographic/CO_2/Tracer Surveys in Support of CLIVAR and Global Carbon Cycle Objectives: Carbon Inventories and Fluxes

b. Surface Water pCO_2 Measurements from Ships

- Appendix: Underway CO_2 Measurements aboard the RVIB Palmer and Data Management of the Global VOS Program

c. High-Resolution Ocean and Atmosphere pCO_2 Time-Series Measurements

Global Repeat Hydrographic/CO_2/Tracer Surveys in Support of CLIVAR and Global Carbon Cycle Objectives: Carbon Inventories and Fluxes

Richard A. Feely[1], Rik Wanninkhof[2], Christopher Sabine[1], Gregory C. Johnson[1], Molly Baringer[2], John Bullister[1], Calvin W. Mordy[3] and Jia-Zhong Zhang[2]
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[2]NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami FL
[3]Genwest Systems, Inc., Edmonds WA

1.PROJECT SUMMARY

The Repeat Hydrography CO_2/tracer Program is a systematic and global re-occupation of select hydrographic sections to quantify changes in storage and transport of heat, fresh water, carbon dioxide (CO_2), chlorofluorocarbon tracers and related parameters. It builds upon earlier programs (e.g., World Ocean Circulation Experiment (WOCE)/Joint Global Ocean Flux Survey (JGOFS) during the 1990s) that have provided full depth data sets against which to measure future changes, and have shown where atmospheric constituents are getting into the oceans. The Repeat Hydrography CO_2/tracer Program (Figure 1; Table 1) reveals much about internal pathways and changing patterns that will impact the carbon sinks on decadal time scales.

The program is designed to assess changes in the ocean's biogeochemical cycle in response to natural and/or man-induced activity. Global warming-induced changes in the ocean's transport of heat and freshwater, which could affect the circulation by decreasing or shutting down the thermohaline overturning, can also be followed through long-term measurements. Below the 2000-m depth of Argo, Repeat Hydrography provides the only global measurements for observing long-term trends in the ocean. The program also provides data for the Argo sensor calibration (e.g., www.argo.ucsd.edu), and support for continuing model development that will lead to improved forecasting skill for oceans and global climate. By integrating the scientific needs of the carbon and hydrography/tracer communities, major synergies and cost savings have been achieved. The philosophy is that in addition to efficiency, a coordinated approach will produce scientific advances that exceed those of having individual carbon and hydrographic/tracer programs. These advances will contribute to the following overlapping scientific objectives: 1) data for model calibration and validation; 2) carbon inventory and transport estimates; 3) heat and freshwater storage and flux studies; 4) deep and shallow water mass and ventilation studies; and 5) calibration of autonomous sensors.

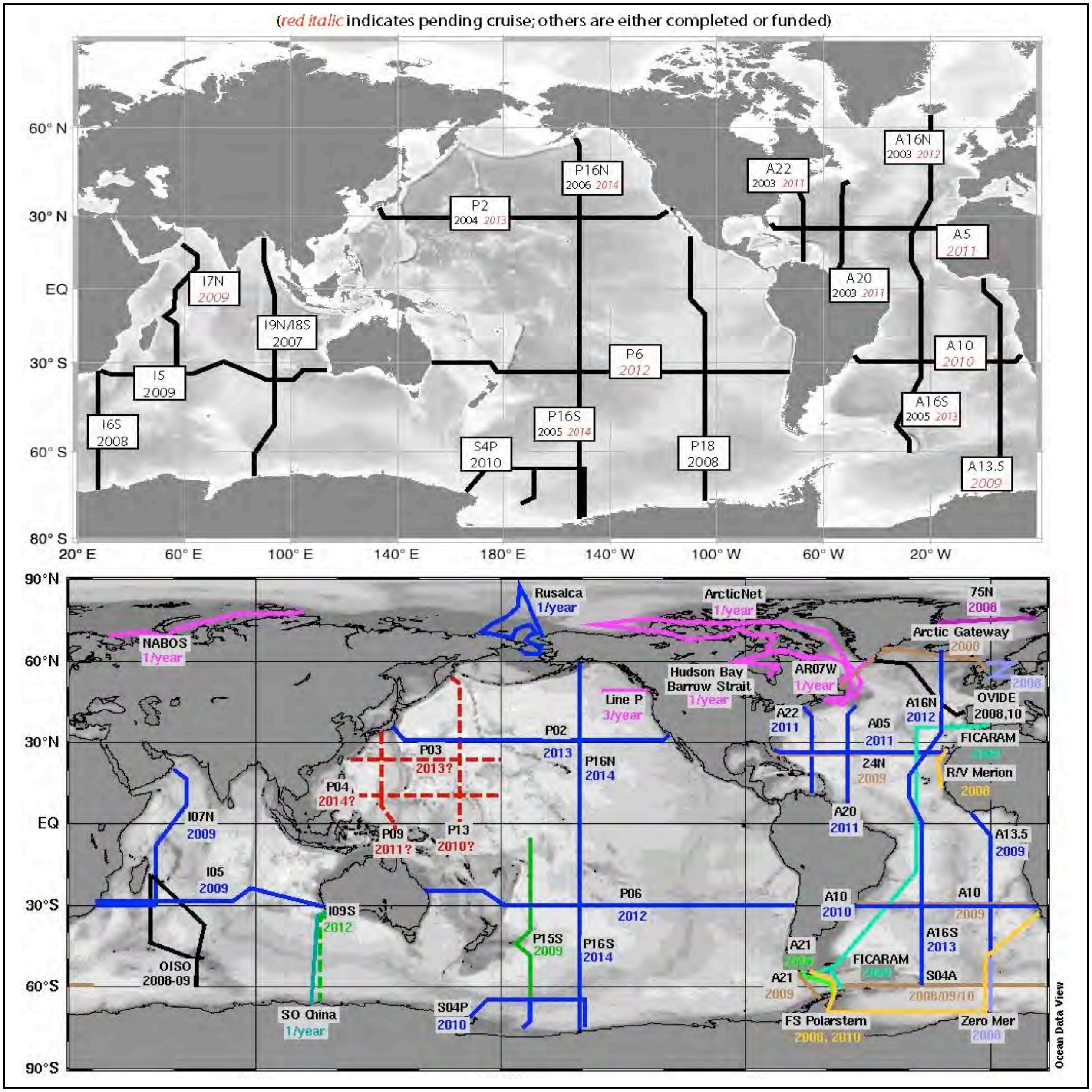

Figure 1. Global map of U.S (Top) and international (Bottom) Repeat Hydrography CO_2/tracer Program hydrographic sections with carbon system measurements. In the bottom plan solid lines indicate funded lines. Dashed lines indicate planned lines that are not fully funded at this time. The U.S. cruises are designated with blue lines.

Table 1. Sequence of Repeat Hydrography CO_2/tracer completed and planned cruises in the oceans - from 2003 to 2014.

Schedule of US CO2/CLIVAR Hydrography Lines (as of 8/31/07)						
Dates	**Cruise**	**Days**	**Ports**	**Year**	**Contact/Chief Scientist**	**Ship**
					overall coordinator: Jim Swift, SIO	
06/19/03-7/10/2003	A16N, leg 1 Planning Cruise results	22	Reykjavik-Madeira	1	Bullister, PMEL	Ron Brown
07/15/03-8/11/2003	A16N, leg 2 Planning Cruise results	28	Madeira - Natal, Brazil	1	Bullister, PMEL	Ron Brown
09/15/03-10/13/2003	A20 Cruise results	29	WHOI - Port Of Spain	1	Toole, WHOI	Knorr
10/16/03-11/7/2003	A22 Cruise results	21	Port Of Spain - WHOI	1	Joyce, WHOI	Knorr
06/15/04-7/25/2004	P2, leg 1 Cruise results	41	Yokohama-Honolulu	2	Robbins, SIO	Melville
07/28/04-8/27/2004	P2, leg 2 Cruise results	32	Honolulu - San Diego	2	Swift, SIO	Melville
01/09/05-2/22/2005	P16S Cruise results	45	Wellington-Tahiti	3	Sloyan/Swift, WHOI/SIO	Revelle
01/11/05-2/26/2005	A16S Planning Cruise results	48	Punta Arenas - Fortaleza	3	Wanninkhof,Doney; NOAA/AOML,WHOI	Ron Brown
02/13/06-3/3/2006	P16N, leg 1 Planning	18	Tahiti-Honolulu	4	Sabine; NOAA/PMEL	Thompson Schedule
03/10/06-3/30/2006	P16N, leg 2 Planning	21	Honolulu-Kodiak	4	Feely; NOAA/PMEL	Thompson Schedule
02/04/07-3/17/2007	I8S	38	Dunedin, NZ-Perth	5	Swift, SIO	Revelle
03/22/07-5/2/2007	I9N	38	Perth-Colombo, Sri Lanka	5	Sprintall, SIO	Revelle
02/04/08-3/17/2008	I6S	43	Cape Town	6	Speer, FSU	Revelle
12/06/07-1/16/2008	P18, Leg 1	32	San Diego-Easter Island	6	Bullister PMEL	Ron Brown
01/19/08-2/23/2008	P18, Leg 2	35	Easter Island- Punta Arenas	6	Johnson PMEL	Ron Brown
2009	I5	57	Capetown - Perth	7	scheduled	UNOLS
2009	I7N	51	Mutrah – Port Louis	7	scheduled	UNOLS
2010	A13.5	62	Abidjan-Cape Town	8	future planning	NOAA
2010	S4P	60	Lyttelton – Punta Arenas	8	future planning	NSF
2011	A10/A5	30	Tenerife - Miami	9	future planning	NOAA
2012	A20/A22	59	Woods Hole-Port of Spain-Woods Hole	10	future planning	UNOLS
2012	A16N	29		10	future planning	NOAA
2013	P06	95		11	future planning	UNOLS

2013	A16S		11	future planning	NOAA
2014	P16N		12	future planning	NOAA
2014	P16S or P2	42	12	future planning	UNOLS

The Repeat Hydrography CO_2/tracer Program is being implemented to maintain decadal time-scale sampling of ocean transports and inventories of climatically significant parameters in support of the Ocean Carbon Monitoring Network (Objective 7) of the Program Plan for Building a Sustained Observing Network for Climate. The sequence and timing for the sections (Figure 1; Table 1) takes into consideration the program objectives, providing global coverage, and anticipated resources. Also considered is the timing of national and international programs, including the focus of CLIVAR in the Pacific in the 2005-2008 timeframe; the Ocean Carbon and Climate Change Program (OCCC) that emphasizes constraining the carbon uptake in the Northern Hemisphere oceans, in part, in support of the North American Carbon Program (NACP); and the international Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) program. Emphasis in 2008-2010 is on the Southern Hemisphere. In addition, the proposed sections are selected so that there is roughly a decade between them and the WOCE/JGOFS occupations.

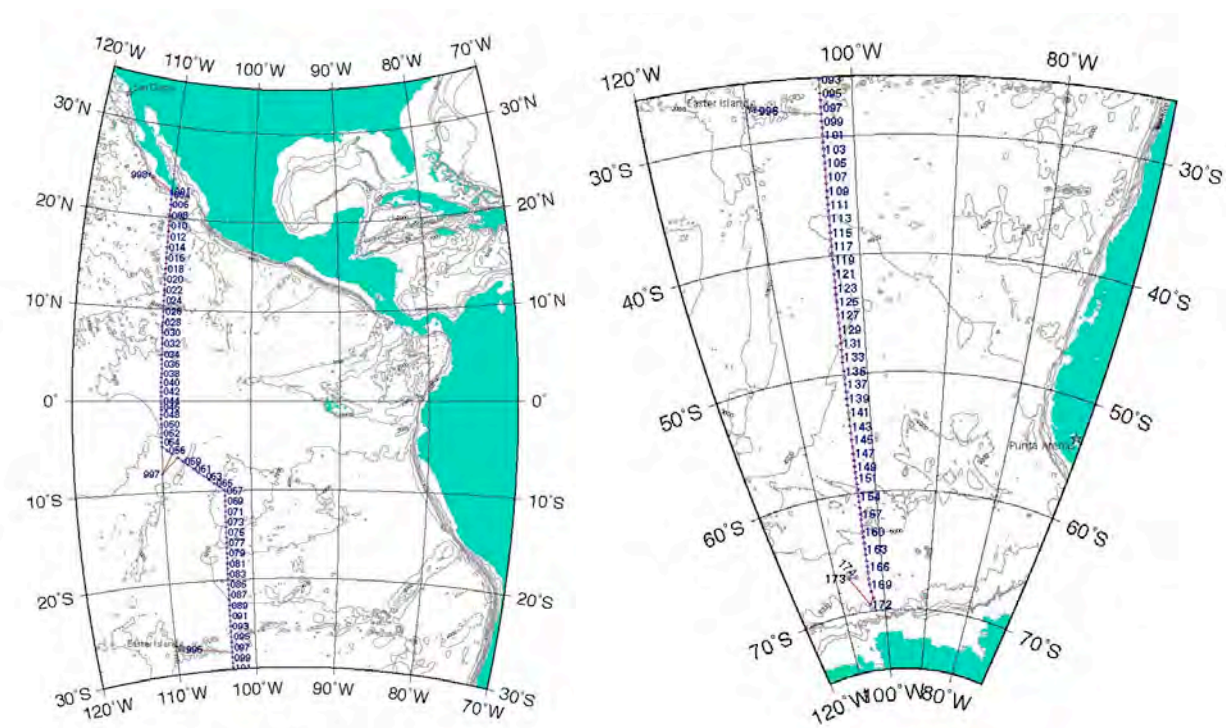

Figure 2. Cruise Tracks of Repeat Hydrography PI8 Legs 1 & 2 during Dec 2007 – Feb 2008 in the Pacific Ocean.

The scientific objectives are important both for the CLIVAR and the OCCC programs, and for operational activities such as Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). In mid-2001 the US scientific steering committees of CLIVAR (www.clivar.org) and the Carbon Cycle Science Program, (CCSP; www.carboncyclescience.gov) proposed the creation of a joint working group to make recommendations on a national program of observations to be integrated with international plans. Several community outreach efforts have been implemented to provide information about the program, such as a web site with interactive forum (http://ushydro.ucsd.edu/index.html), articles in EOS (Sabine and Hood, 2003) and the JGOFS newsletter, as well as AGU and Ocean Science meeting forums. The Repeat HydrographyCO_2/tracer Program addresses the need, as discussed by the First International Conference on Global Observations for Climate (St. Raphael, France; October 1999), that one component of a global observing system for the physical climate/CO_2 system should include periodic observations of hydrographic variables, CO_2 system parameters and other tracers throughout the water column (Smith and Koblinsky, 2000); (Fine et al., 2001). The large-scale observation component of the OCCC has also defined a need for systematic observations of the invasion of anthropogenic carbon in the ocean superimposed on a variable natural background (Doney et al., 2004). The CCSP has identified the critical need for the federal government to begin delivering regular reports documenting the present state of the climate system components. Through this plan NOAA has developed the infrastructure necessary to build, with national and international partners, the ocean component of a global climate observing system and to deliver regular reports on the ocean's contribution to the state of the climate and on the state of the observing system.

Recognizing the need to develop an international framework for carbon research, various working groups of programs like the International Geosphere-Biosphere Programme (IGBP), the World Climate Research Programme (WCRP), the International Human Dimensions Programme (IHDP), the Intergovernmental Oceanographic Commission (IOC), and the Scientific Committee on Oceanic Research (SCOR) have worked together to develop research strategies for global carbon cycle studies. Based on the recommendations coming from these programs, NOAA and NSF have co-sponsored the Repeat Hydrography CO_2/tracers Program, with program direction coming from the Repeat Hydrography Oversight Committee (Richard Feely and Lynne Talley, co-chairs; http://ushydro.ucsd.edu/index.html). Many other nations are also sponsoring similar carbon studies that are comparable in focus and have been designed to be complimentary to our program (http://www.clivar.org/carbon_hydro/index.htm). Consequently, there is an immediate need for global-scale coordination of these carbon observations and research efforts to achieve the goal of a global synthesis. There is also an urgent need to critically assess the overall network of planned observations to ensure that the results, when combined, will meet the requirements of the research community. Because of these issues, the Global Carbon Project (GCP; http://www.globalcarbonproject.org/) has initiated the International Ocean Carbon Coordination Project (IOCCP; http://www.ioc.unesco.org/ioccp/) to: (1) gather information about on-going and planned ocean carbon research and observation activities, (2) identify gaps and duplications in ocean carbon observations, (3) produce recommendations that optimize resources for international ocean carbon research and the potential scientific benefits of a coordinated observation strategy, and (4) promote the integration of ocean carbon research with appropriate atmospheric and terrestrial carbon activities. It is through the workings of the IOCCP and international CLIVAR that international coordination of data management, data synthesis and scientific interpretation of the global repeat sections results will be implemented. In addition, the Repeat Hydrography CO_2/tracer Program is being managed in accordance with the COSP Ten Climate Monitoring Principals.

2. PROGRESS REPORT AND ACCOMPLISHMENTS

2.1. PI8 Cruise Results

A hydrographic survey (CLIVAR/Carbon P18) was carried out on the NOAA Ship *Ronald H. Brown* from December 2007 through February 2008 in the eastern Pacific. John Bullister served as Chief Scientist on Leg 1 and Greg Johnson served as Chief Scientist on Leg 2. Most of the survey work was a repeat of a 1994 occupation of a meridional section nominally along 110 – 103°W (WOCE P18). Two stations along a 1992 section along 67°S west of 103 deg. W (WOCE S4P) were also taken towards the end of the cruise. Operations included CTD/LADCP/Rosette casts and radiometer casts. Underway data collected included upper-ocean currents from the shipboard ADCP, surface oceanographic and meteorological parameters from the ship's underway systems, and bathymetry data. Ancillary operations included surface drifter deployments, Argo float deployments, and XBT drops. NDBC TAO buoy servicing was also performed during the first leg of the cruise.

After an 8-day delay, NOAA Ship Ronald H. Brown departed San Diego, CA on 15 December 2007 at 0215 UTC. The ship anchored off Easter Island, Chile from 18-21 January 2008 for a personnel change and short break between leg 1 and leg 2. CLIVAR/Carbon P18 ended in Punta Arenas, Chile on 23 February 2008.

A total of 174 stations and 7 TAO Buoy sites were occupied during P18. 179 CTD/LADCP/Rosette casts (including 2 Test casts, 2 TAO calibration casts and 2 casts at station 8: the first to end leg 1 and the second to start leg 2) plus 54 radiometer casts were made. Twenty-four ARGO floats were deployed, 17 SVP drifters were deployed, and approximately 82 XBTs were dropped. CTD data, LADCP data and water samples (up to 36) were collected on most Rosette casts, in most cases to within 10-20 meters of the bottom.

Salinity, dissolved oxygen and nutrient samples were analyzed for up to 36 water samples from each cast of the principal CTD/LADCP/Rosette program. Water samples were also measured for CFCs, pCO_2, Total CO_2 (DIC), Total Alkalinity, pH, CDOM and Chlorophyll a. Additional samples were collected for ^{3}He, Tritium, $^{13}C/^{14}C$, ^{32}Si, oxygen/Argon (ONAR), DOC, DON, POC, and CDOM2C/CDOM3C.

2.2. CTD/O_2 and Bottle Salinity (Baringer and Johnson)

The central goals of the project are to collect high-quality continuous profiles of Temperature, Salinity, and Dissolved Oxygen (CTD/O_2) as well to make high-quality discrete measurements of salinity on CLIVAR/CO_2 repeat hydrography sections, to calibrate and process these data, and make them available to the research community.

The oceans are the flywheel of the earth's climate system, storing large amounts of heat and water, transporting these quantities around the planet, and exchanging them with the atmosphere. Research goals for this project include:

1. Improve the estimates of variations in heat and freshwater storage and transport of the ocean, especially for the deep ocean below the reach of the Argo array.
2. Provide the physical oceanographic measurements required to support carbon system studies, as well as to perform deep and shallow water mass and ventilation studies.
3. Provide data for model calibration and validation.
4. Provide high quality in situ data to aid in the calibration of autonomous sensors such as the CTDs on Argo floats.

While analyses of repeat hydrographic data are not funded through this proposal, they are vital to the success of the program, so our efforts in this regard in FY2008 are summarized here. This year we worked on analyses of repeat hydrographic section data demonstrating significant Antarctic Bottom Water (AABW) warming in the main deep basins of the Pacific Ocean (Johnson, 2007), warming in the Scotia Sea (Meredith et al., 2008), warming and freshening the southeast Indian Ocean (Johnson et al., 2008a), and even warming and reductions in northward transport the western North Atlantic (Johnson et al., 2008b). Analysis of bottom water variability in the eastern Pacific Ocean by comparing the 2007-2008 repeat of P18 to the 1994 data along the same track is in progress. While there is little warming north of the Chile Rise crossed at about 36°S by this section, there is a statistically significant warming of roughly 0.03°C below about 3500 m, again in the Antarctic Bottom Water (AABW; Figure 3) and also evidence of freshening there (not shown). Together, the results in the S. Indian, Pacific, S. Atlantic, and even the N. Atlantic Oceans suggest the possibility of a global pattern of AABW warming (and freshening near the source) in the past decade, which could constitute an important mode of climate variability, and a significant contribution to the global heat and sea level budgets. Given the potential importance of global AABW variations mentioned above, we have worked to quantify the dominance of AABW in ventilating the deep global oceans (Johnson et al., 2008b). We have also used repeat hydrographic data in a study of continued warming in the deep Caribbean Sea (Johnson and Purkey, 2008), as well as in a study of increasing low-oxygen zones in the tropical oceans (Stramma et al., 2008) that garnered a lot of media attention.

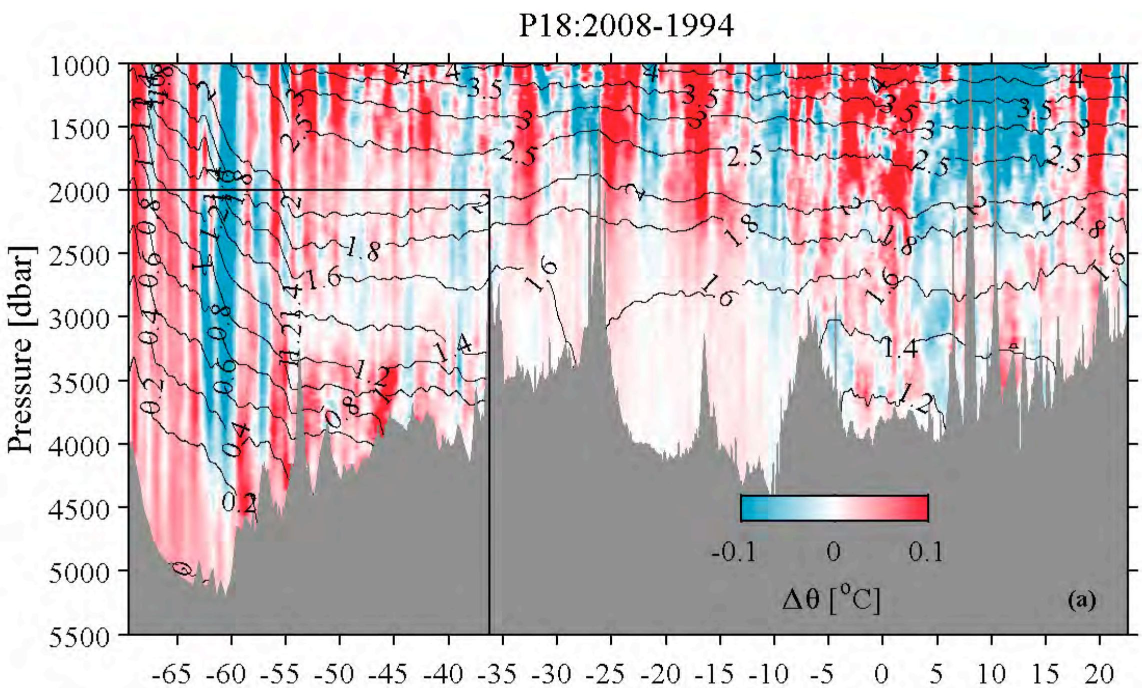

Figure 3. Difference of deep potential temperature, Δθ [°C], along WOCE Section P18 in the eastern Pacific resulting from subtracting the 1994 from the 2007/2008 data. Red areas indicate warming and blue areas cooling with color saturation at ±0.1°C. Mean potential temperatures from all the data are contoured (black lines).

In FY 2008 the PMEL CTD group supported the 2007/2008 reoccupation of WOCE Section P18 from San Diego, CA to Punta Arenas, Chile via Easter Island, Chile. We built, modified, or purchased necessary CTD/O_2 equipment, assembled the necessary gear, and arranged for pre- and post-cruise calibrations of all CTD/O_2 sensors. We shipped cruise gear to the ship for the cruise and back to Seattle after the cruise. Our lead CTD/O_2 data processor K. Mctaggart participated on both legs of the cruise. Dr. G. Johnson served as chief scientist for the second leg, and JISAO employee S. Purkey stood a CTD watch. We have completed the final calibration of the cruise CTD/O_2 data, which are available at http://cchdo.ucsd.edu/data_access?ExpoCode=33RO20071215.

In FY 2008 the AOML CTD group was in charge of bottle salinity analyses, provided hardware support for the CTD/O_2 program, and assisted with the collection of Lowered ADCP data. The group provided two people per cruise leg, for a total of 4 people over the duration of the cruise.

Bottle salinity analyses were performed in the ship's temperature-controlled salinity laboratory using a Guildline Model 8400B inductive autosalinometer, and a dedicated PC. Software allowed the user to standardize the autosalinometer. IAPSO Standard Seawater Batch P147 was used as the standard. The autosal was standardized a few times each day, as needed given stability of the instrument and laboratory temperature. 5708 salinity measurements were taken and approximately 200 vials of standard seawater (SSW) were used. A duplicate sample was drawn for each cast in order to confirm sampling accuracy. Comparisons of salinity measurements to historical data along the cruise suggest that the measurements were within the WOCE accuracy specifications of 0.002 PSS-78.

In addition to performing salinity measurements, the AOML group personnel on the cruise assisted with CTD/O_2 package hardware repair and maintenance, and the operation of the Lowered ADCP during the cruise.

2.3. Total Dissolved Inorganic Carbon (DIC) (Feely, Sabine and Wanninkhof)

The central goals of this project are to make high-quality measurements of dissolved inorganic carbon (DIC) on CLIVAR repeat hydrography sections, to calibrate these data and to make the data available to the research community.

Carbon dioxide concentrations in the atmosphere have increased rapidly over the past several decades, and these increases have been reflected in changing surface water concentrations. Our specific goals include:

1.) Improve estimates of uptake and storage of anthropogenic CO_2 in the ocean.

2.) Estimate the rates of key biogeochemical processes in the ocean.

3.) Provide data to initialize ocean carbon model simulations, evaluate strengths and weaknesses in the models, and suggest ways to improve the models.

a) P18

Samples for DIC measurements were drawn according to procedures outlined in the Guide to Best Practices for Ocean CO_2 Measurements (DOE, 1994) from 10.4-L Niskin bottles (except Niskin 34; 9.6L) into cleaned 300-mL glass bottles. Over 2500 samples were analyzed for discrete DIC; full profiles were completed on odd numbered stations, with replicate samples taken from the surface, oxygen minimum, salinity maximum, and bottom Niskin-type bottles. On the even numbered stations, samples were drawn throughout the water column with focus on the upper 1000 m. The replicate samples were interspersed throughout the station analysis for quality assurance of the integrity of the coulometer cell solutions. The coulometers were calibrated by injecting aliquots of pure CO_2 (99.995%) by means of an 8-port valve outfitted with two sample loops with known gas volumes bracketing the amount of CO_2 extracted from the water samples for the two PMEL systems. The stability of each coulometer cell solution was confirmed three different ways: the Certified Reference Material (CRM), Batch 78, supplied by Dr. A. Dickson of SIO, was measured at the beginning, gas loops in the beginning and at the end, and the duplicate samples at the beginning, middle, and end of each cell solution. The coulometer cell solution was replaced after 25 mg of carbon was titrated, typically after 9-12 hours of continuous use.

Calculation of the amount of CO_2 injected was according to the Guide to Best Practices for Ocean CO_2 Measurements (DOE, 1994). The concentration of CO_2 ($[CO_2]$) in the samples was determined according to:

$$[CO_2] = Cal.factor * \frac{(Counts - Blank * Run\ Time) * K\ \mu mol/count}{Pipette\ volume * density\ of\ sample}$$

Where Cal. Factor is the calibration factor, Counts is the instrument reading at the end of the analysis, Blank is the counts/minute determined from blank runs performed at least once for each cell solution, Run Time is the length of coulometric titration (in minutes), and K is the conversion factor from counts to µmol.

The instrument has a salinity sensor, but all DIC values were recalculated to a molar weight (µmol/kg) using density obtained from the CTD's salinity sensor. The results underwent initial quality control on the ship using property plots: DIC-depth, DIC-potential temperature, DIC-salinity and DIC-LAT-depth contour plots were used to analyze the quality of the data (Figure 4). The difference plot indicates DIC anomalies ranging from 5-55 µmol/kg in the upper 1000 m of the water column. These anomalies are due to uptake of anthropogenic CO_2, changes in mixing and ventilation of the water masses, and changes in biogeochemical processes. Our synthesis project will determine the relative contributions of each process to the total change in DIC over the 12-year interval.

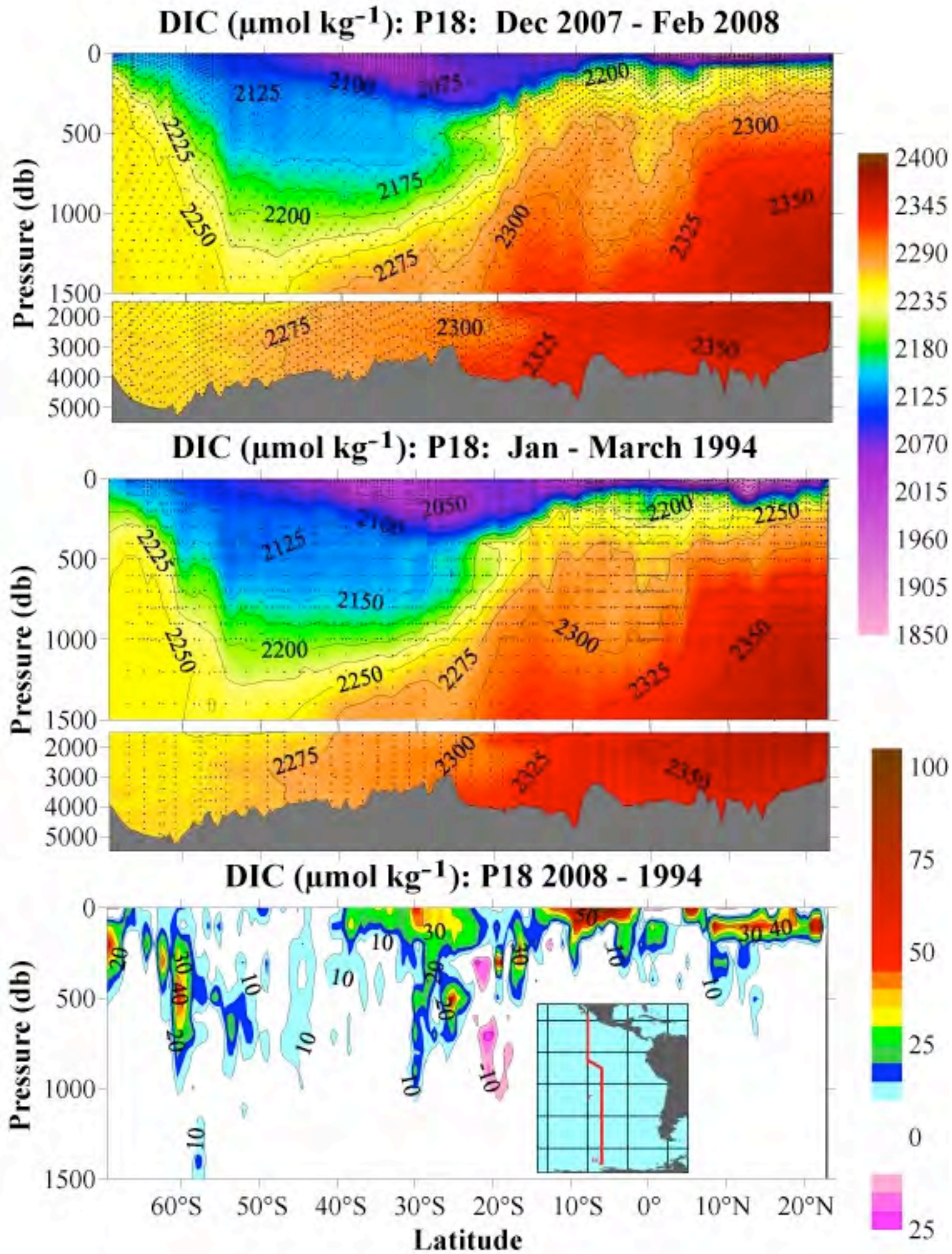

Figure 4. DIC in μmol kg^{-1} along the P18 section in the Pacific Ocean along 110-103 °W. The gridded difference plot is shown on the bottom panel for the fourteen year time difference between the cruises. The increases in DIC are the result of a combination of processes including anthropogenic CO2 invasion and changes in circulation and biogeochemistry.

b) I6S

In addition to the inorganic carbon measurements on the P18 cruise, DIC and underway PCO_2 measurements were performed on the I6S cruise that was run under the auspices of NSF. Cruise I6 S on UNOLS vessel *Roger Revelle* departed Durban, South Africa on February 4, 2008 entered the southward-flowing Agulhas Current and traveled due south along a transect coinciding with Longitude 30 ˚E into the Antarctic Circumpolar Current down to the ice edge at 70 ˚S, and returned to Cape Town, South Africa on March 16, 2008.

Analyses were performed with newly fabricated instruments patterned after the SOMMA but with improved interfaces and software. The DICE (Dissolved Inorganic Carbon Extractors) performed well during the study. A total of 2089 samples were analyzed. There were 177 duplicate samples and 89 underway samples. The average difference of the duplicate samples was 1.4 μmol/kg. The CRM batch was #85 with an assigned DIC value of 2000.44 μmol/kg (as certified by Prof. A. Dickson at SIO) and a salinity of 33.326. The average measured CRM value for the DICE was 1998.2 μmol/kg. All data was corrected to the first CRM run on each coulometer cell on a per cell basis.

A cross section of the DIC data from the cruise is shown in Figure 5. Very high DIC values are observed in the Southern Ocean with a shallow thermocline south of 55 ˚S. The penetration of North Atlantic Deep Water from the North at a depth of 2000-3500 m is manifested by lower DIC values. This is attributed to better ventilation of this water mass compared to the older waters of Antarctic origin.

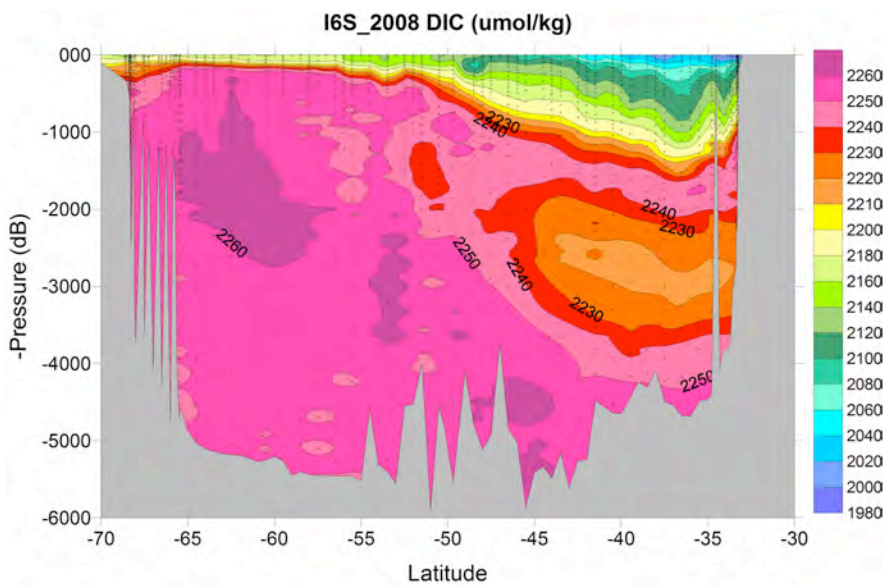

Figure 5. Cross-section of DIC values for the I6S cruise. Note the higher resolution scale for values greater than 2200 μmol/kg to accentuate small changes in deep water values.

2.4 Discrete and Underway fCO_2 on I6S and P18

a) I6S

The cruise went from South Africa to the ice edge and back (Figure 6). A total of 7240 fCO_2 water measurements were made and 2715 air XCO_2 measurements. Several hours of data were lost due to insufficient water and air flows due to blockages and other minor issues were encountered as described in the metadata file accompanying the data. The data is served from the AOML fCO_2 website: http://www.aoml.noaa.gov/ocd/gcc/clivari6s/. A color-coded map indicating surface water CO_2 levels (fCO_{2w}) is shown in Figure 6. A cross section for the southbound leg is given in Figure 7. A distinguishing feature in this cruise is the very sharp gradients in fCO_2, SST and surface salinity corresponding with the Argulhas Current front and the south subtropical front near 43 ˚S. Highly variable values are found near the ice edge due to the interplay of upwelling waters from depth with high CO_2 and patchy biological productivity drawing down the CO_2.

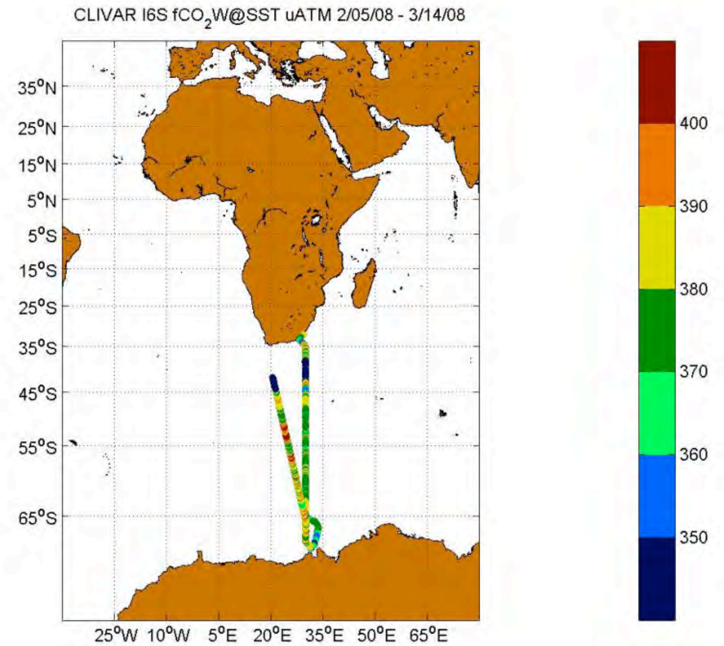

Figure 6. Map of the cruise track with colors indicating the fCO2w levels (see color bar in µatm).

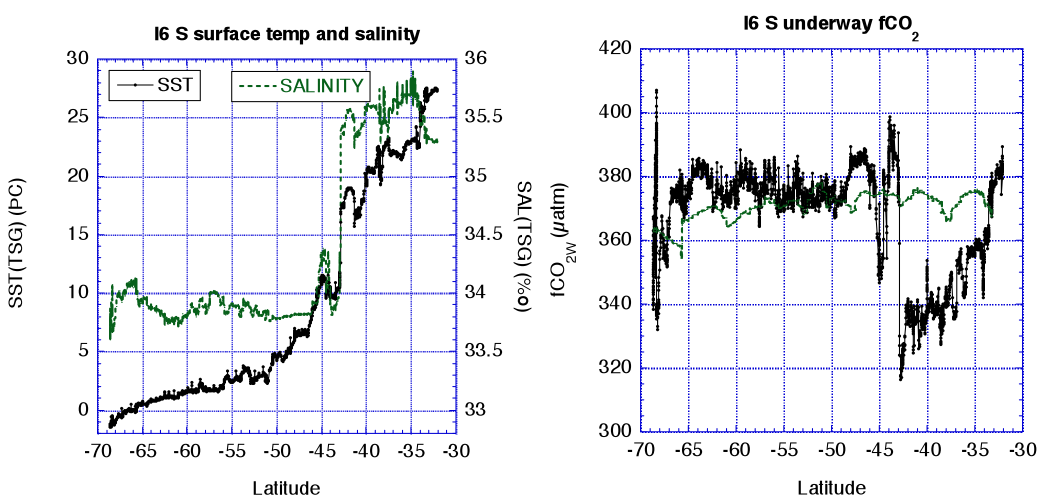

Figure 7. Left panel: Sea surface temperature (left axis) and salinity (right axis). Right panel: surface water fCO2 (black) and air fCO2 (green). The data are for the southbound leg of I6 from Durban to the ice edge.

b) Underway fCO_2 measurements for P18

Underway fCO_2 measurements were made on NOAA ship *Ronald H. Brown* along the entire two-legged cruise track from San Diego, Ca (32 ˚N, 117 ˚W) to Punta Arenas (53 ˚S, 71 ˚W). A total of 12534 surface water samples and 4700 air samples were taken. Sampling and data reduction followed standard protocol as outlined in Pierrot et al., (2007). The only major problem encountered was that the analog/digital converter on the thermistor in the equilibrator failed to register temperature readings below 6˚C. Utilizing the data from the thermosalinograph at the intake and an auxiliary thermosalinograph next to the underway system in the hydrolab, an empirical algorithm was developed to estimate equilibrator temperatures < 6 ˚C. The correction procedure is believed to yield results with an error less than 0.1 ˚C.

The results are shown in Figure 8. During the end of 2007 and beginning of 2008 there was a very strong outgassing of the Equatorial Pacific. The boundaries of the high fCO_2 associated with upwelling are sharp near the equator and at 12˚S. The Southern hemisphere subtropics were a strong source as well associated with seasonal warming. A large sink was observed at high southern latitudes near the ice edge associated with sea-ice melt and a strong algae bloom as indicated by high chlorophyll values. Small CO_2 sinks are observed at the start of the cruise track and just north of the Equator. These are believed to be caused by seasonal cooling and year-round biological productivity at lower latitudes. Air fCO_2 values are relatively constant with most of the variability attributed to changes in barometric pressure. Of note are persistent high air fCO_2 values at the start of the cruise when the ship sailed near the coast of the Baja California. These are attributed to continental air masses and point towards possible biases in estimating air-sea CO_2 fluxes near land using marine air background values.

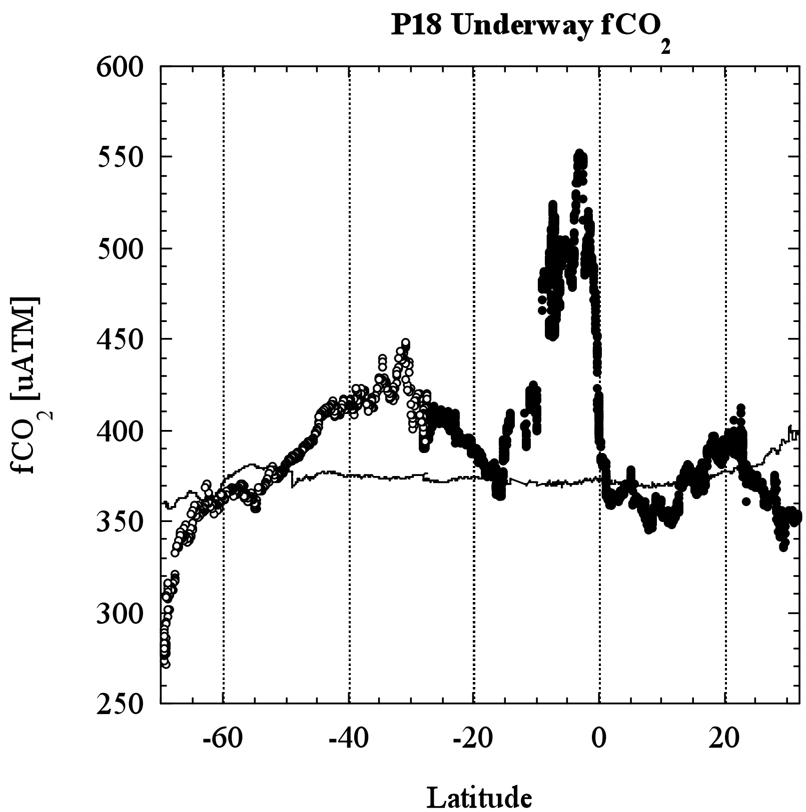

Figure 8. Surface water and air fCO_2 values along the transect of P18. The solid circles are the water values for leg 1 and the open circles those of leg 2. The thin line is the air fCO_2 values.

A comparison with underway fCO_2 data obtained in 1994 along the same transect shows a significant increase in surface water values that corresponds closely with the 26 ppm increase air XCO_2 values over the 14 year time period (Figure 9). Although the 1994 and 2008 cruises were run in different seasons and directions, a significant increase in surface water values along most of the transect is apparent clearly indicating the atmospheric imprint on the surface ocean. The offset in the equatorial fCO_{2w} maximum is attributed to the spatial variation in the core of the upwelling water attributed to tropical instability waves. Data can be found at: http://www.aoml.noaa.gov/ocd/gcc/rvbrown_introduction.php under years 2007 (leg 1) and 2008 (leg 2)

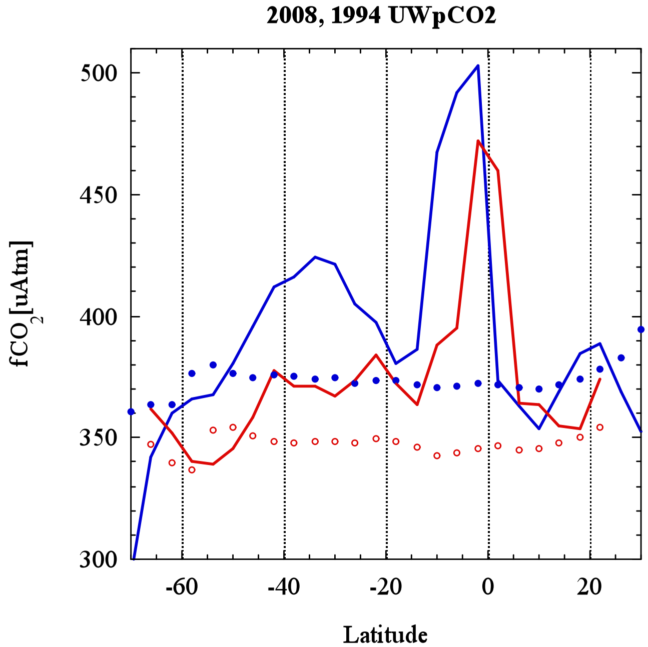

Figure 9. Surface water (solid line) and air (circles) fCO2 values in 1994 (red) and 2008 (blue) along the P18 line. The increases in surface water fCO_2 values due to invasion of anthropogenic CO_2 are apparent. The data are 4-degree averages to smooth out smaller scale variability.

c) Discrete pCO_2 measurements for P18

Rationale

Discrete pCO_2 measurements were made on P18 to ascertain complete understanding of inorganic carbon system dynamics and to have a sensitive carbon system parameter to discern changes over time. Figure 10 shows the difference in pCO_2 measured at 20 ˚C, pCO_2 (20) at 40˚S, 110˚W between this cruise and the initial occupation during WOCE in 1994. [Note, following common but incorrect nomenclature we refer to the measured quantity as pCO_2 while the data has been corrected for non-ideality and should accordingly be listed as fCO_2]. The data shows the increase of pCO_2 (20) in the thermocline indicative of the invasion of anthropogenic CO_2. The pCO_2 calculated from DIC and Total Alkalinity (TA) had a poorer agreement and larger standard deviation and points to the strong need to include a third inorganic carbon system parameter if the data from the CLIVAR/CO_2 cruises are to be used effectively to address the pressing concerns about biota in a high CO_2 /low pH ocean.

Sampling and analyses

Every other station was sampled with samples drawn from at least 15 Niskin-type bottles with one duplicate at each station. Near the equator an effort was made to increase the sampling density across stations. South of Easter Island we increased the number of samples per station due to the increase in ocean depth. We also reduced the station resolution from every other station to alternating every other station with every third station.

The sampling statistics are as follows:

	# bottles sampled	# pCO_2 samples taken	#duplicates
Leg 1	736	782	46
Leg 2	542	589	47
Total	1278	1371	93

The precision of the duplicates was on average 0.5 % (4 µatm).

Samples were drawn into 500 ml volumetric flasks using Tygon© tubing. About 5ml of water was withdrawn to allow for expansion of the water as it warms and to provide space for the stopper, tubing, and frit of the analytical system. Saturated mercuric chloride solution (0.2 ml) was added as a preservative. The sample bottles were sealed with a screwcap containing a polyethylene liner. The samples were stored in coolers at room temperature generally for no more than 5 hours. All analyses were done at 20°C. No flask was analyzed without spending at least two hours in a bath close to the analytical temperature.

The discrete pCO_2 system is patterned after the instrument described in Chipman et al., (1993) and is discussed in detail by Wanninkhof and Thoning (1993) and Chen et al., (1995). Once the samples reach the analytical temperature, a~50-ml headspace is created by displacing the water using a compressed standard gas with a CO_2 mixing ratio close to the anticipated pCO_2 of the water. The headspace is circulated in a closed loop through the infrared analyzer that measures CO_2 and water vapor levels in the sample cell. The samples are equilibrated until the running mean of 20 consecutive 1-second readings from the analyzer differ by less than 0.1 ppm (parts per million by volume). This equilibration takes about 10 minutes. An expandable volume in the circulation loop near the flask consisting of a small, deflated balloon keeps the headspace of the flask at room pressure.

In order to maintain analytical accuracy, a set of six gas standards are run through the analyzer before and after every ten seawater samples. The standards are obtained from Scott-Marin and referenced against primary standards purchased from C.D. Keeling in 1991, which are on the WMO-78 scale. Prior to station 60, many values at depths from 400 to 2000 meters were higher than the highest standard (1533.7 ppm). For this reason, these values have been flagged as "questionable" (3) for the time being, but after further quality control it is likely that many if not most of these values will be flagged as "good" (2). For most of the stations after 155, nearly all of the samples were within the range of only two standards: 792.51 ppm and 1036.95 ppm.

Table 2. Gas standards for the determination of discrete pCO_2.

Cylinder Serial Number	**Value**
CA5998	[205.07 ppm]
CA5989	[378.71 ppm]
CA5988	[593.64 ppm]
CA5980	[792.51 ppm]]
CA5984	[1036.95 ppm]
CA5940	[1533.7 ppm]

The calculation of pCO_2 in water from the headspace measurement involves several steps. The CO_2 concentrations in the headspace are determined via a second-degree polynomial fit using the nearest three standard concentrations. Corrections for the water vapor concentration, the barometric pressure, and the changes induced in the carbonate equilibrium by the headspace-water mass transfer are made. The corrected results are reported at the analytical temperature and at a reference temperature of 20°C.

No instrumental problems occurred during the cruise. The relatively time-consuming analyses and the presence of only one analyst limited the spatial coverage. Sampling and analyses focused on precision and accuracy rather than high throughput.

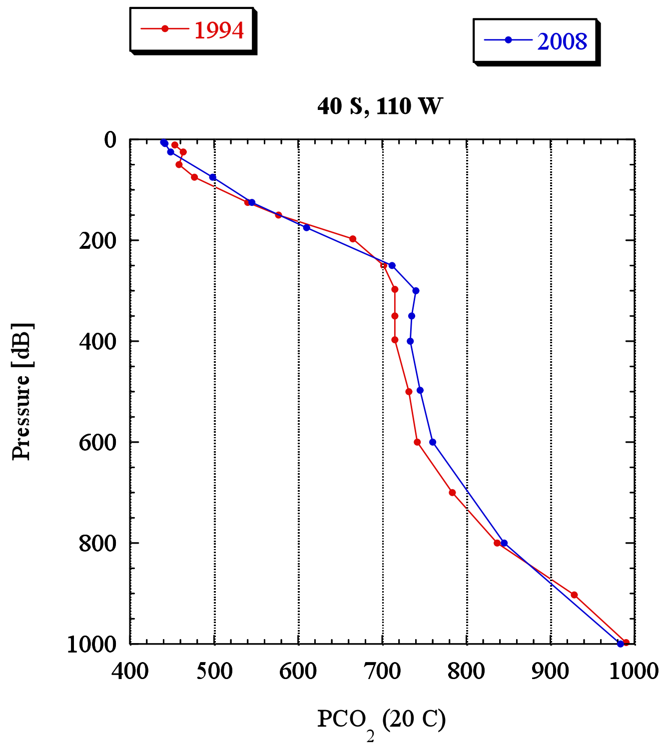

Figure 10. An example of the difference in pCO_2 (20) between the 2008 and 1994 occupation of a station near 40 ˚S and 103 ˚W. The increase of pCO_2 in the thermocline is indicative of the invasion of anthropogenic CO_2.

2.5. Nutrients (Mordy and Zhang)

The objectives of this project are to make high-quality measurements of inorganic nutrient (nitrate, nitrite, phosphate and silicate) concentrations in seawater on CLIVAR/repeat hydrography cruises and to perform data quality control and make it available to the climate and carbon research community.

Nutrient concentrations in seawater are traditionally considered a core hydrographic parameter in any oceanographic program. In combination with other hydrographic parameters (such as salinity, temperature and dissolved oxygen concentration), it has been used as a water mass tracer to identify the change in ocean circulation. Availability of nutrients in surface water controls the primary production of the ocean and thus the flux of carbon sequestration through the biological pump. Change in nutrient concentration over space and time has been used to separate anthropogenic CO_2 from changes in total carbon inventory in the ocean. The scientific goals of our project are:

1. Improve estimates of uptake and storage of anthropogenic CO_2 in the ocean.

2. Estimate the rates of key biogeochemical processes, such as remineralization, in the ocean.

3. Provide essential hydrographic data for testing and improving the numerical ocean model simulations.

The primary task of the nutrient group was to collect and process nutrient data from the P18 repeat hydrographic line in the eastern Pacific. Preparations included re-building much of the autoanalyzer (all new glass coils and tubing, new debubblers), creating new software for data reduction and quality control, and a 4 day visit of Erik Quiroz to PMEL to review the procedures and software required for the cruise. Erik Quiroz was the lead nutrient chemist on Leg 1, and Calvin Mordy was the lead nutrient chemist on Leg 2.

There were 5,596 samples collected for the analysis of phosphate, nitrate, nitrite, and orthosilicic acid. Nutrients were analyzed with a continuous flow analyzer (CFA) using the standard and analysis protocols for the WOCE hydrographic program as set forth in the manual by (Gordon et al., 1994). Working standards were freshly made at each station by diluting the stock solutions in low nutrient seawater. Mixed standards were verified against standards purchased from Ocean Scientific.

There were several problems encountered on the cruise. Temperatures in the ship's bioanalytical laboratory fluctuated greatly with temperatures ranging from 17.2°C to 25.3°C with an average temperature of 20.9±1.9°C; however, temperatures were generally stable during an individual analytical run. On leg one, a 24-channel Ismatec pump failed and was replace with an identical spare pump. On leg 2, an Alpkem sampler using 35 ml polyethelene sample bottles failed and was replaced with a Westco CS9000 sampler that used 20 ml plastic sample bottles.

A typical analytical run included replicates for the 3 deepest Niskin bottles from each cast, plus any samples with questionable peaks. The standard deviation of these replicates was used to estimate the overall precision for nitrate and silicic acid were <0.2% full scale, and within quality standards set forth by the WOCE and CLIVAR programs. The standard deviation of phosphate replicates was higher due to problems with extensive carryover. Preliminary data was available at the end of the cruise, and final data was submitted after quality control procedures.

Table 3. Nutrient Sample Replicates.

	Phosphate	Silicic Acid	Nitrate
Number of Replicates	494	503	511
Mean Standard Deviation	0.02 µM	0.2 µM	0.1 µM
Percent Deviation	0.8%	0.1%	0.2%

Sections of the major nutrients show familiar patterns of high concentrations in the North Pacific, an intense sub-surface nitrate and phosphate maximum in the Equatorial Pacific, and lower nutrients the central South Pacific Subtropical Gyre. The sub-surface nutrient maximum occurs in sub-oxic waters that support vigorous denitrification (the loss of nitrate as nitrogen gas). The loss of nitrate is evident as deviations from linearity in the nitrate-phosphate plot (Figure 12).

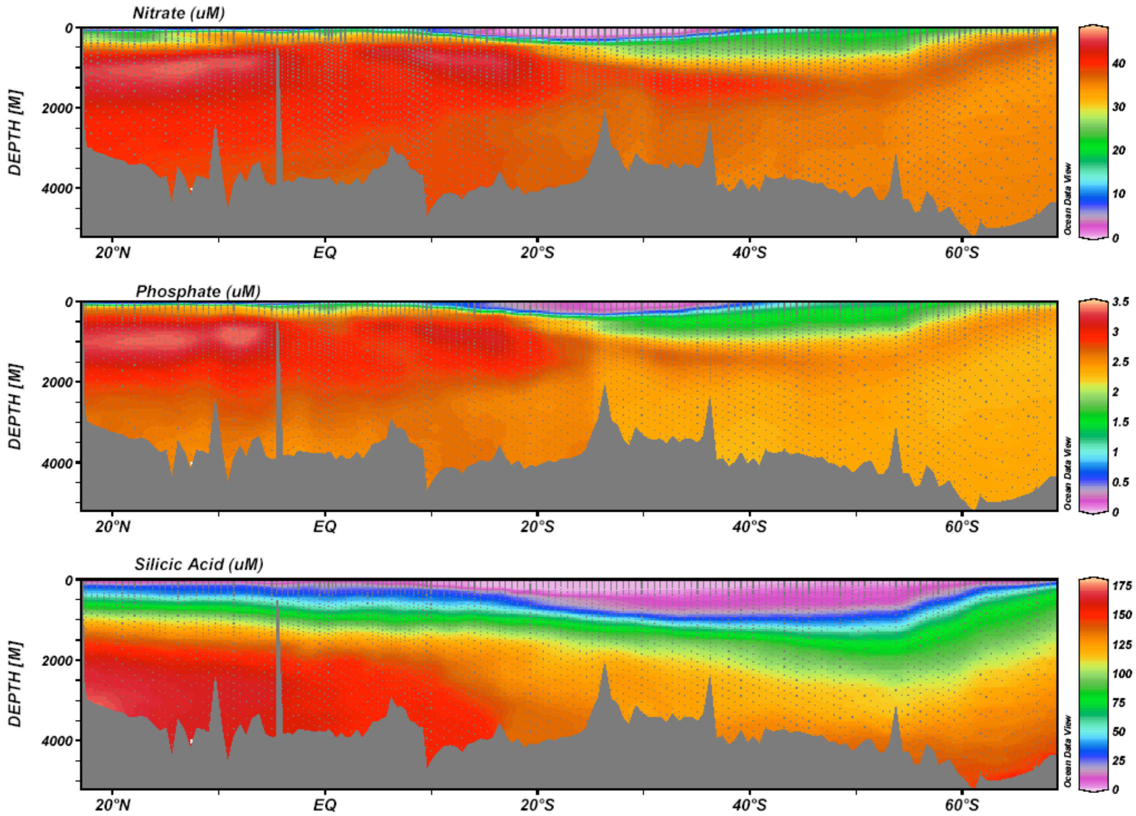

Figure 11. Sections of nitrate, phosphate and silicic acid along the P18 cruise track.

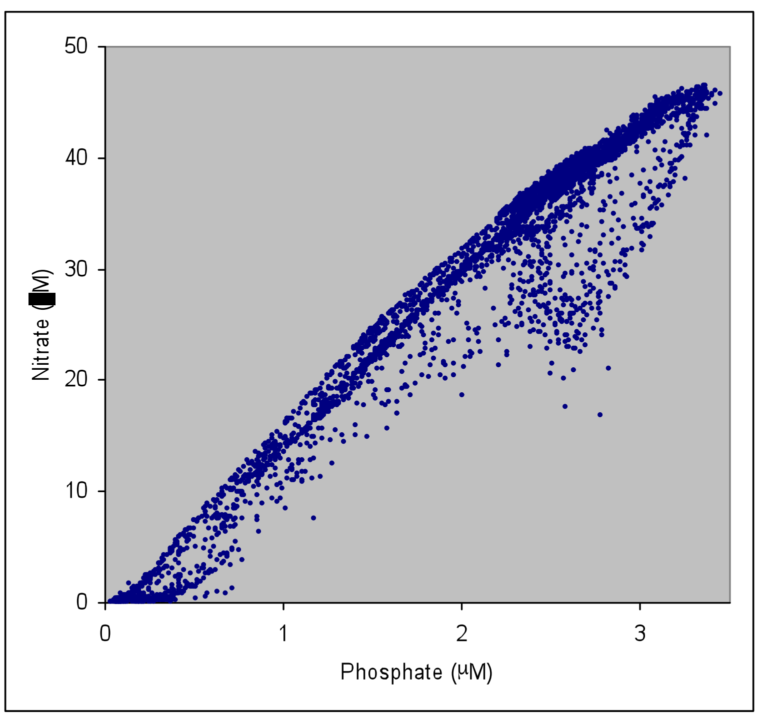

Figure 12. Property-property plot of nitrate and phosphate.

In addition to the P18 cruise, the AOML group participated in an international inter-comparison for nutrient in seawater organized by Dr. Aoyama of the Japanese Meteorological Research Institute who is also responsible for nutrient measurements in the repeat hydrography program sponsored by the Japanese government. A total of 55 laboratories from 15 counties participated in this exercise, including our repeat hydrography program partner, the nutrient lab at Scripps Institution of Oceanography. Our measurements provided high quality data to the inter-comparison.

2.6. Discrete Oxygen (Baringer and Langdon)

Results from P18

Discrete oxygen samples were collected along 110 W from 20N to 69S. Dissolved oxygen samples were drawn from Niskin bottles into calibrated 125-140 ml iodine titration flasks using silicone tubing to avoid contamination of DOC and CDOM samples. Bottles were rinsed three times and filled from the bottom, overflowing three volumes while taking care not to entrain any bubbles. The draw temperature was taken using a digital thermometer with a flexible thermistor probe that was inserted into the flask while the sample was being drawn. These temperatures were used to calculate mmol kg^{-1} concentrations and as a diagnostic test of Niskin bottle integrity. 1-ml of $MnCl_2$ and 1-ml of NaOH/NaI were added immediately after drawing the sample using Repipetor, the flasks were then stoppered and shaken well. DIW was added to the neck of each flask to create a water seal. 24 or 36 samples plus two replicates were drawn from each station, depending on which rosette was used. The total number of samples collected was 5598. The flasks were stored in plastic totes at room temperature for 1.5 hours before analysis.

Oxygen analyses were performed with an automated titrator using an amperometric end-point detection (Culberson and Huang, 1987). The titration of the samples, data logging and graphical display were performed on a PC running a LabView program written by Ulises Rivero of AOML. The titrations were done in a climate-controlled lab at 18.5 - 22.5°C. Thiosulfate was dispensed by a 2-ml Gilmont syringe driven with a stepper motor controlled by the titrator. Tests were conducted pre-cruise to confirm that the precision and accuracy of the volume dispensed was comparable or superior to the Dosimat 665. The whole-bottle titration technique of (Carpenter, 1965), with modifications by (Culberson and Knapp, 1991) was used. Four replicate 10 ml iodate standards were run every 24 hours. The reagent blank was determined from the difference between V1 and V2, the volumes of thiosulfate required to titrate successive 1-ml aliquots of the iodate standard in the same DIW sample. The reagent blank was determined at the beginning and end of the cruise and was found not to have changed significantly. This method was found in pre-cruise testing to produce a more reproducible blank value than the value determined as the intercept of a standard curve. The temperature-corrected molarity of the thiosulfate titrant was determined as given by (Dickson, 1994).

A total of 351 sets of duplicates were run during the cruise. The standard deviation of replicates averaged 0.89 mmol kg^{-1} for stations 1-52. Correcting a problem with the NaOH/NaI dispenser improved reproducibility significantly. The standard deviation for stations 52-89 average 0.14 mmol kg^{-1}. The standard deviation of replicates for stations 99-174 averaged 0.15 mmol kg^{-1}.

The P18 oxygen data revealed a decline in oxygen and an increase in apparent oxygen utilization (AOU) in the main thermocline across the entire section (Figure 13). This is similar to change that was observed in the North Pacific along the P16N line. The current consensus is that these changes reflect physical changes in the circulation of the ocean. Less ventilation of the thermocline as outcrop waters become warmer and fresher is likely part of the story however changes in isopycnal depth, water mass variability and changes in the biological pump are other possible contributors.

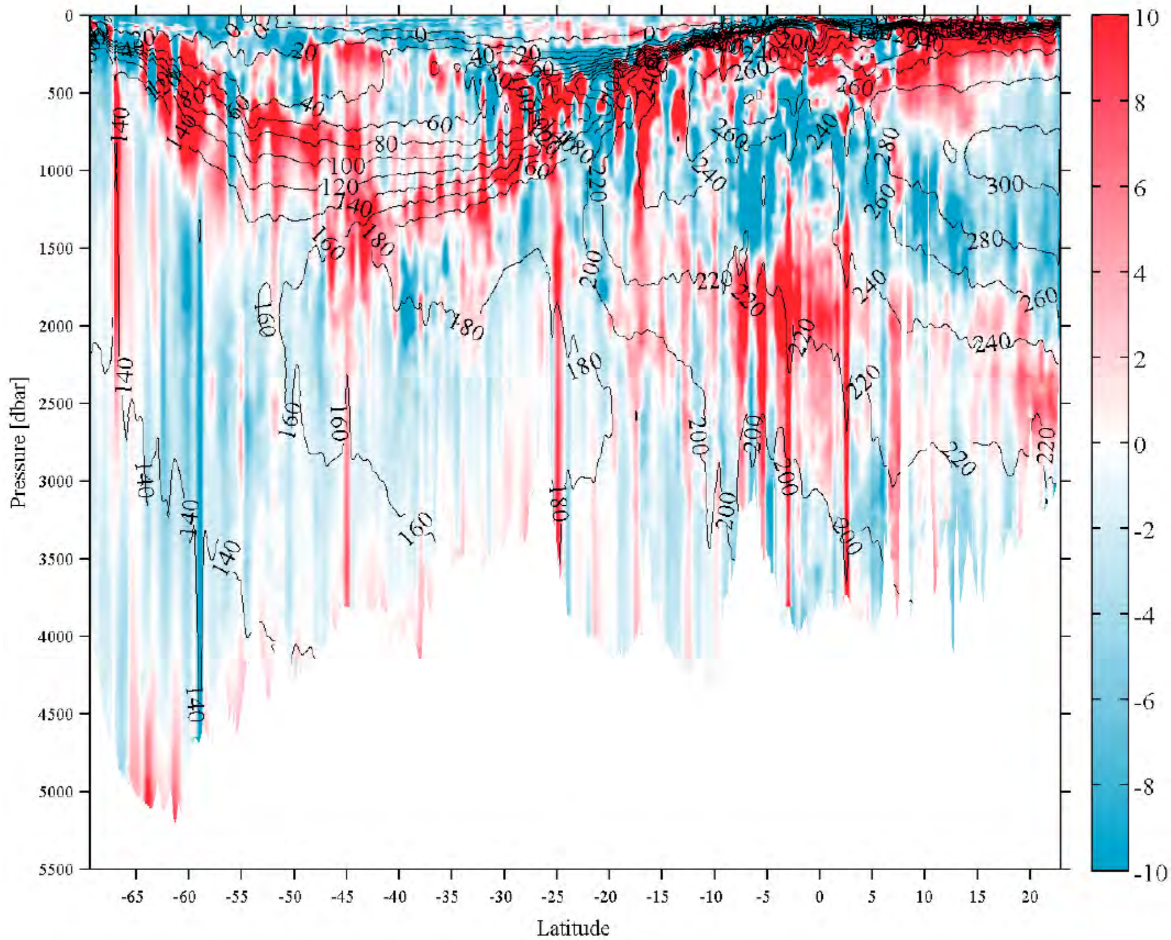

Figure 13. Section of the apparent oxygen utilization change along the P18 line between 1994 and 2008 (14 year difference).

2.7. PMEL CFC Tracer Group Project Summary

The central goals of this project are to make high-quality measurements of dissolved chlorofluorocarbons (CFCs) and sulfur hexafluoride (SF_6) on CLIVAR repeat hydrography sections, to calibrate these data and to make the data available to the research community.

The concentrations of these anthropogenic compounds in the atmosphere have increased rapidly in the past decades, and these increases can be reconstructed as functions of location and time. Atmospheric CFCs and SF_6 dissolve in surface seawater and the equilibrium concentrations can be calculated as a function of seawater temperature and salinity.

The entry of these compounds into the surface layer of the ocean and their subsequent transfer into the ocean interior makes them extremely useful as time-dependent (transient) tracers to:

1.) Determine the rates and pathways of ocean circulation and mixing processes.

2.) Estimate water mass formation rates and decadal changes in ventilation.

3.) Estimate the rates of key biogeochemical processes in the ocean.

4.) Improve estimates of uptake and storage of anthropogenic CO_2 in the ocean.

5.) Provide a unique way to test numerical ocean model simulations, evaluate strengths and weaknesses in the models, and suggest ways to improve the models.

We have developed extraordinarily sensitive analytical techniques for the rapid shipboard analysis of CFC11, CFC12 and SF_6 in seawater, with limits of detection currently: CFC11 and CFC12~1 x 10^{-15} mole kg^{-1}; SF6~2 x 10^{-17} mole kg^{-1}.

We have successfully included measurements of SF_6 simultaneously with the CFCs on several of our recent CLIVAR expeditions and have demonstrated the enhanced value of routinely including SF_6 along with CFC11 and CFC12 measurements on future hydrographic sections. We are continuing to work to improve these techniques.

Coupled with the CFCs, this dual tracer pair approach provides improved CO_2 uptake estimates, and an opportunity to diagnose ventilation rate changes.

Recent work (Johnson et al., 2008a) has revealed significant warming during the past 15 years in the abyssal waters along the southern end of CLIVAR section I8SI9N. This warming is strongly correlated with the region of significant CFC and SF_6 invasion in the abyssal waters along the section. CFCs may prove to be a sensitive indicator of regions of the ocean where climate change signals (e g. warming) propagate into the interior of the ocean on decadal time scales.

2.8. Preparations for the CLIVAR P18 section on NOAA Research Vessel Ronald H. Brown

We prepared, tested and calibrated a CFC/SF_6 analytical system and shipped this in our PMEL CFC laboratory van from Seattle to San Diego, CA and returned it from Punta Arenas, Chile to Seattle at the completion of the expedition. J. Bullister led in the preparation of the P18 Cruise Project Instructions, assisted with the planning and execution of the ~15 major science projects on this expedition, and coordinated the science programs with the ship personnel. J. Bullister participated as Chief Scientist on Leg 1 of this expedition. D. Wisegarver coordinated preparing the CFC/SF_6 equipment for the cruise, assisted by F. Menzia.

Perform CFC measurements on the P18 cruise:

The field measurement program was shared with Dr. M. Warner at the University of Washington. We sent 2 CFC analysts on Leg 1. We matched whenever possible the sampling of CFC/SF_6 with carbon-system measurements collected along this section.

David Wisegarver from PMEL was the lead analyst for the CFC measurements. Because of health issues, F. Menzia was unable to participate on the cruise and the second CFC analyst was hired for this work on a contract negotiated with the University of Miami.

D. Wisegarver processed the data sets, calibrated and maintained the equipment for the P18 Cruise in the Pacific.

Data collected on this cruise are available and archived at:
http://whpo.ucsd.edu/data/co2clivar/pacific/p18/p18_33RO20071215/p18_33RO20071215_hy1.csv

Samples for the analysis of dissolved CFC-11, CFC-12 and SF_6 were drawn from ~3168 of the water samples collected during the P18 expedition. Efforts were made to sample CFCs and SF_6 (CFCs/SF_6) from the same bottles sampled for carbon parameters (DIC, alkalinity, pCO_2 and pH) and other tracers. Special water sampling bottles designed at PMEL were used on the cruise to minimize CFC/SF_6 contamination. When taken, water samples for CFCs/SF_6 analysis were the first samples drawn from the sample bottles. Care was taken to coordinate the sampling of CFCs/SF_6 with other samples to minimize the time between the initial opening of each bottle and the completion of sample drawing. In most cases, CFCs/SF_6, helium-3, dissolved oxygen, DIC, alkalinity and pH samples were collected within several minutes of the initial opening of each bottle.

Concentrations of CFC-11, CFC-12 and SF_6 in air samples, seawater and gas standards were measured by shipboard electron capture gas chromatography (EC-GC) using techniques modified from those described by Bullister and Weiss (1988) and Bullister and Wisegarver

(2008). The analytical system was calibrated frequently using a standard gas of known CFCs/SF_6 composition. Multiple injections of these loop volumes were made to allow the system to be calibrated over a relatively wide range of concentrations. Air samples and system blanks (injections of loops of CFCs/SF_6-free gas) were injected and analyzed in a similar manner.

Concentrations of the CFCs in air, seawater samples and gas standards are reported relative to the SIO98 calibration scale and concentrations of SF_6 are reported relative to the NOAA-GMD calibration scale (Bullister et al., 2006). Concentrations in air and standard gas are reported in units of mole fraction CFC/SF_6 in dry gas, and are typically in the parts per trillion (ppt) range. Dissolved CFC concentrations are given in units of picomoles per kilogram seawater (1 pmol kg^{-1} = 1 x 10^{-12} mol kg^{-1}). Dissolved SF_6 concentrations are given in units of femtomoles per kilogram seawater (1 fmol kg^{-1}= 1 x 10^{-12} mol kg^{-1}). CFC/SF_6 concentrations in air and seawater samples were determined by fitting their chromatographic peak areas to multi-point calibration curves, generated by injecting multiple sample loops of gas from a working standard.

The estimated precisions for the CFC-11 and CFC-12 seawater analyses are shown in the following tables.

Table 4. Summary of number of CFC-11 samples taken and the estimated precision for the CLIVAR P18 cruise.

	CFC-11
Number of samples	3168
Number of replicates	505
Average standard deviation	0.003 pmol kg^{-1} (or 1.0%), whichever is greater

Table 5. Summary of number of CFC-12 samples taken and the estimated precision for the CLIVAR P18 cruise.

	CFC-12
Number of samples	3168
Number of replicates	505
Average standard deviation	0.003 pmol kg^{-1} (or 1%), whichever is greater

Table 6. Summary of number of SF6 samples taken and the estimated precision for the CLIVAR P18 cruise.

	SF6
Number of samples	3168
Number of replicates	505
Average standard deviation	0.02 fmol kg^{-1} (or 2.0%), whichever is greater

A small number of water samples had anomalous CFC/SF_6 concentrations relative to adjacent samples. These samples occurred sporadically during the cruise and were not clearly associated with other features in the water column (e.g. anomalous dissolved oxygen, salinity or temperature features). This suggests that these samples were probably contaminated with CFCs and/or SF_6 during the sampling or analysis processes. Measured concentrations for these anomalous samples are included in the data set, but are given a quality flag value of either 3 (questionable measurement) or 4 (bad measurement). Approximately 68 samples out of 3168 (~1.7%) were assigned quality flags of 3 or 4.

A section of CFC-12 concentrations along P18 in 2007/2008 is shown in Figure 14.

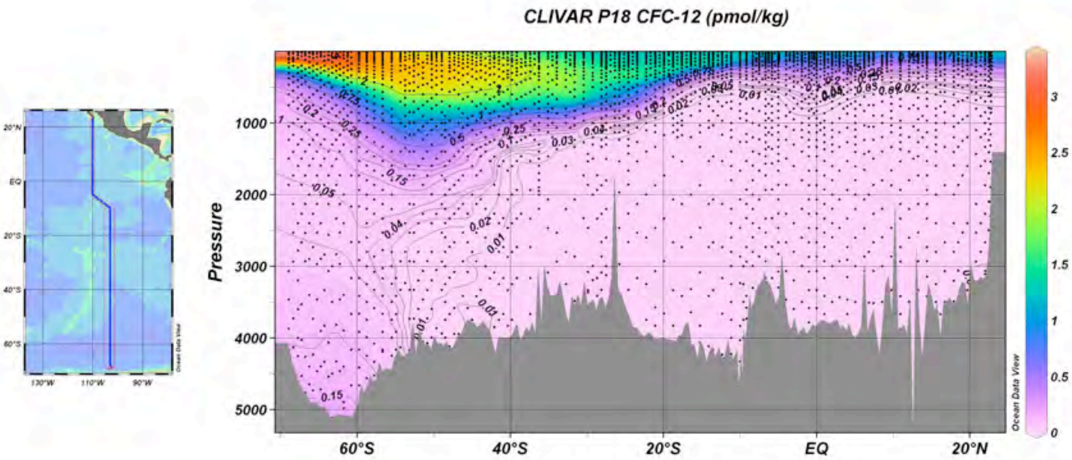

Figure 14. CFC-12 concentration (in picomoles kg^{-1}) along CLIVAR repeat section P18 in the Pacific Ocean in 2007/2008. Dots indicate locations where samples were collected.

The strong latitudinal gradient in surface concentrations primarily reflects the latitudinal gradient in surface temperature, since the solubility of CFCs is greater at cold temperatures. CFC concentrations are highest in surface waters, and in general decrease with depth, reflecting the relative isolation of deeper waters from recent exchange with the atmosphere. There is especially strong penetration of CFC-12 in abyssal, mode and intermediate waters in the southern hemisphere south of 40^oS, reflecting vigorous ventilation of these waters on decadal timescales and indicating the potential of this region to rapidly take up atmospheric gases, including CO_2.

There is a clear CFC signal in the abyssal waters to ~40^oS, reflecting ventilation via Antarctic Bottom Waters from the south. The extremely sensitive analytical techniques for measuring dissolved CFCs allows the ventilation pathways to be detected in regions where the corresponding anthropogenic CO_2 signal is difficult to detect.

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Surface Water pCO_2 Measurements from Ships

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1. PROJECT SUMMARY

The oceans are the largest sustained sink of anthropogenic carbon with a flux into the ocean of about 1.6 10^{15} gram (= 1.6 gigaton) of carbon each year. Changes in this sink are determined by monitoring regional and seasonal patterns of carbon uptake and release. Quantification of regional sources and sinks of carbon dioxide in the ocean are of critical importance to international policy decision making, as well as for forecasting long-term climate trends. In this project NOAA investigators and academic partners have outfitted research and commercial vessels with automated carbon dioxide analyzers as well as thermosalinographs (TSGs) to measure the temperature, salinity and partial pressure of CO_2 (pCO_2) in surface water and air in order to determine the carbon exchange between the ocean and atmosphere. This task is coordinated at national level with the U.S. Carbon Cycle Science Program and its subcommittee on Ocean Carbon and Climate change (OCCC). We work with the International Ocean Carbon Coordination Project (IOCCP) for international coordination. Collaborative efforts are underway to combine datasets in the Atlantic through a Memorandum of Understanding with the European Union project CARBOOCEAN. Pacific collaboration is established through the PICES working group 13. In addition there are one-on-one interactions with investigators in Norway, Iceland, France, the United Kingdom, Australia, New Zealand, and Japan on reciprocal data exchange and logistics support. The overall effort to assemble all surface water pCO_2 data is called the Surface Ocean Carbon Atlas (SOCAT).

Documenting carbon sources and sinks relies critically on other efforts undertaken under sponsorship of the Office of Climate Observation (OCO) including implementation of the ship lines, and moored and drifting buoys. The surface water pCO_2 programs support climate services by providing knowledge and quantification of the radiatively important gas, carbon dioxide. The near-term focus is on completion of the Northern Hemisphere ocean carbon observing system to provide data for quantifying carbon dioxide sources and sinks over the coterminous United States through inverse modeling in collaboration with scientists involved in the atmospheric CO_2 observing system. We are currently expanding our focus on the high-latitude sources and sinks.

The project is a partnership of AOML, AOML/GOOS, PMEL, LDEO of Columbia University, RSMAS of the University of Miami, and the Bermuda Institute of Ocean Sciences (BIOS), formerly known as the Bermuda Biological Station for Research (BBSR). The partners are responsible for operation of the pCO_2 systems on the ships, auxiliary measurements, data reduction, and data management from all ships. The following ships had pCO_2 systems on them during part or all of the performance period: NOAA ship *Ronald H. Brown*, NOAA ship *Ka'imimoana*, container ship *Albert Rickmers*, RVIB *Palmer*, cruise ship *Explorer of the Seas*, container ship *Oleander*, and UNOLS RV *Atlantic Explorer* (ship owned and operated by BIOS), UNOLS RV *Walton Smith* (owned and operated by RSMAS), and UNOLS RV *Knorr* (owned and operated by Woods Hole Oceanographic Institute). Similar to the previous year, several ships were taken off lines and several new ships were outfitted. The final datasets are combined and sent to CDIAC for dissemination and archival. All work follows established principles of monitoring climate forcing gases and biogeochemical cycles.

2. PROGRESS

2.1. Acquisitions, deployments and data return

The main metric for this program is obtaining, reducing, quality controlling and disseminating high quality surface water and marine air pCO_2 data. The number of cruises with pCO_2 observations from research ships and VOS that have been completed during the performance period are listed in Table 1. Details for each ship are provided below.

Table 1.VOS Data Summary FY-2008.

SHIP	# Cruises	# Data Points	% Recovery*
R/V Brown	9	60,148	85.0%
Explorer of the Seas	11	16,466	85.0%
RVIB Palmer	8	76,112	98.0%
R/V Ka'imimoana	7	189782	97.0%
R/V Atlantic Explorer	TBD	TBD	TBD
OOCL Tianjin	1	4480	94.0%
M/V Albert Rickmers	1	5,945	91.0%
M/V Oleander	TBD	TBD	TBD

*The values are to illustrate overall performance of the program. They should be used with caution when making ship to ship comparisons. The number of data points is a function of frequency of measurements, number of cruises and instrument malfunction that differ for each ship. Percent recovery has been determined in different fashion by each investigator ranging from number of data points that could have been obtained if the units had operated whenever the ship was at sea to number of acquired data points that were discarded during quality control.

Four other critical endeavors in support of determining regional fluxes have been completed during the performance period:

1. To assure uniformity in measurements and to expand the effort within NOAA OCO and beyond, a technology transfer has been done in which General Oceanics Inc. of Miami, FL is building the underway pCO_2 systems to our specifications. Substantial time and effort is involved by participants at AOML and RSMAS to assist in building, troubleshooting, improving instrument design and training customers on the operation of the system. Over 24

units have been produced and sold to customers around the world. So far, about 12 of these units have been purchased by participants of the NOAA program.

2. The GOOS/TSG (thermosalinograph) component lead by Gustavo Goni currently operates and maintains TSGs in four ships of the SOOP: *Albert Rickmers, Explorer of the Seas, M/V Explorer and Oleander*. The *Explorer of the Seas* operations are in transition since December 2007, from a staffed operation to a fully autonomous effort. The pCO_2 and TSG components have been transitioned to a fully automatic mode but water intake and general computer control transition is still underway. AOML receives TSG data in real time. These raw data are submitted to an initial quality control check, where several procedures based on the ten GOSUD (Global Ocean Surface Underway Data Pilot Project) real-time control test are applied. Data are flagged and sub sampled using the median to one sample every 3 minutes. The reduced data are then resubmitted to the full automatic quality check and, if approved, immediately submitted to the Global Telecommunication System (GTS). As part of the TSG project, a web site has been created and maintained at AOML containing several products displaying TSG data location and values (http://www.aoml.noaa.gov/phod/tsg/index.php). This web site currently includes information regarding data analysis and quality control procedures for TSG data corresponding to the ships of the NOAA fleet and the SOOP. In particular, several products display the data obtained from *Oleander* and also from other ships that previously had TSG installations, such as M/V *Explorer of the Seas* and M/V *Skogafoss*. Another product shows the location of TSG real-time data that was inserted into the GTS (see Figure 1).

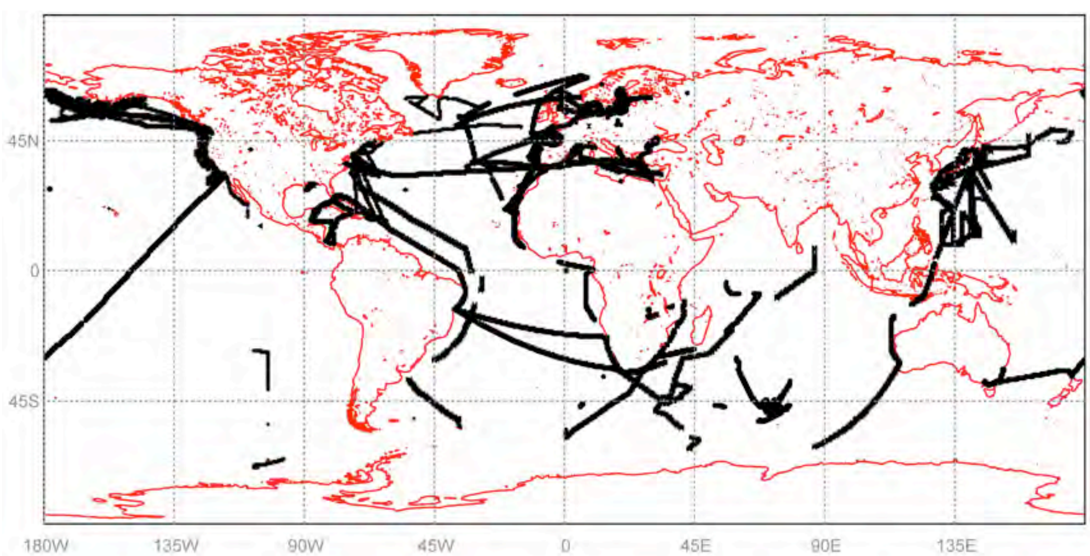

Figure 1. Location of real-time TSG transmissions into the GTS during FY 2008 for ships of the SOOP and the NOAA fleet.

The operations in the *Skogafoss* that transected between Boston and Iceland ended in May 2007, and its data were processed and transmitted until that date. A replacement for this ship, the *Reykjafoss* has been found and we expect to re-install pCO_2 and TSG instruments in a near future pending permission from the owner and operator (Eimskip lines).

AOML supports XBT operations on the M/V *Oleander* (Figure 2) and will do so for the *Reykjafoss* through provision of 1 pallet of XBTs per year, hand launcher, MK21 board, antennas, PC shuttle and transmission costs.

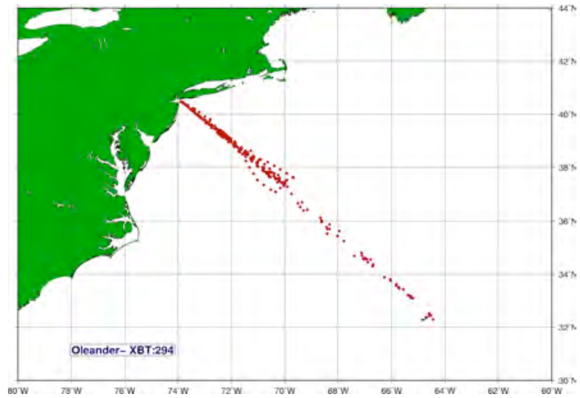

Figure 2. *M/V Oleander XBT drops, October 2007 - September 2008.*

3. In addition to leading the effort on the *Palmer* the LDEO group has provided a global ocean database which includes 4.1 million surface ocean pCO_2 observations made in 1970 - 2007 and which has been assembled in a single uniform format (LDEO Database, version 2007, Takahashi et al., 2008). It is accessible to the public through the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge National Laboratory, TN (http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/LDEO_home.html). This is an updated and improved version of the earlier release (version 1.0), which contained about 3.4 million pCO_2 measurements. For the members of the (VOS) consortium, the participants are able to access the data in a uniform electronic format. For this purpose, an open web site has been established at the following URL: http://www.ldeo.columbia.edu/CO2. The site provides not only the numerical data, but also maps showing the ship's tracks for each data file. The new data will be accessible only to the VOS participants for a period of three years, and will be released to the public after this period. A synthesis of the data set has been accepted for publication in the Surface Ocean CO_2 Variability and Vulnerabilities (SOCOVV) Symposium volume of "Deep-Sea Research".

4. Through two separate efforts, we collected data in the Arctic region where data is sparse. A pCO_2 system was installed on board the R/V *Knorr* to measure the pCO_2 during the International Chemistry Experiment in the Arctic LOwer Troposphere (Icealot) Cruise. The aim of the cruise was to study different aerosols and pollutants over an ice-free region of the Arctic. The system was installed in March and removed in June of this year. The system was operated by the survey technician and scientists on the cruise with oversight from our group on shore.

Last year the AOML group installed a pCO_2 system on the Chinese icebreaker *Snow Dragon (Xue Long)* as part of collaboration with the Third Institute of Oceanography in the People's Republic of China. Although the real-time transmission of the data has been problematic, the system continues to perform well. After completing the work in the Antarctic, the *Xue Long* sailed to the Arctic where she performed several cruises before going back to Shangai. It will sail again to the Antarctic this winter and we expect to collect data at least until April 2009.

In support of our Northern Gulf of Mexico collaborative project, we also installed a system on the NOAA ship *Gordon Gunter.* The system has been collecting data since March of 2008 and will provide a data set which is needed in the region. While operation on these ships, and several other ships overseen by participants from LDEO and PMEL (see below), are covered by other sources, the data undergoes the same rigorous data reduction and quality control procedures and are included in the (global and coastal) data sets that are currently being assembled.

The responsibilities of the different groups are summarized in the flow diagram below.

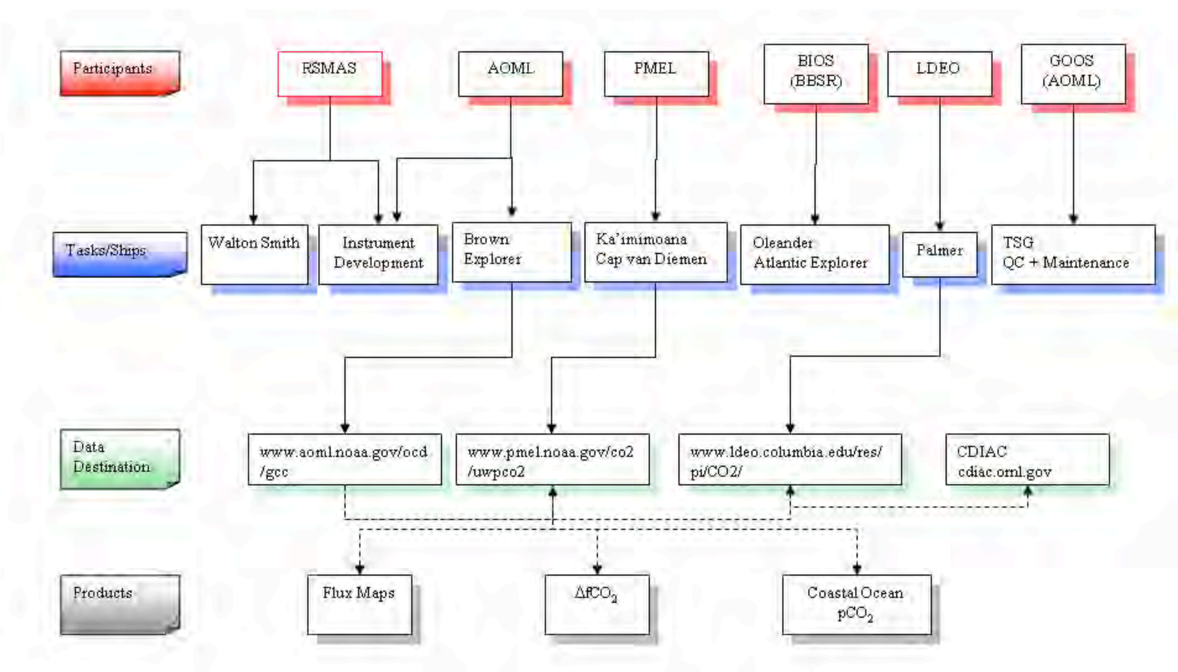

Figure 3. Organizational chart of the VOS project.

A short summary of the efforts on each ship are listed below:

***NOAA* ship *Ronald H. Brown*- AOML lead**

Data Site:
www.aoml.noaa.gov/ocd/gcc/rvbrown_data2007.php
Number of cruises: 9
Number of fCO_2 data points: 60,148
% Data return: 85%.

Causes for non-return: The underway pCO_2 system on the *Brown* performed well with over a 85 % data return. This year, we participated in many of the cruises on the *Brown*, which allowed us to fix any problem that arose immediately. We finally performed the upgrade of the old system to the new ones from General Oceanics, Inc (GO). Both the old and the new system were installed and run during the GOMECC cruise from last year and the GasEx III cruise from this year such that a side-by-side comparison could be performed avoiding possible data biases that sometimes occurs when observing system elements are upgraded. In May of 2008, at the end of the season, both systems were removed and the GO system was re-installed in October, along with a Seabird-45 salinity and temperature sensor. The cruises that used the old system suffered from several problems, due to the age of the system which was first installed in 2000. For example, in two instances, gas flow through the equilibrator failed due to a blockage in the needle valve that controls the flow and the operator did not notice or correct the problem. The thermistor also developed a problem in which it would not record temperatures below ~6 ^oC. Finally, during a cruise in 2007, the mass flow meter that measures the flow through the sample cell gave inaccurate readings, causing incomplete flushing of the sample cell for the first half of the cruise. This explains the slightly lower percentage in data return compared to previous years and increased difficulties with data reduction. We expect the new system to yield higher returns.

Description: The cruise tracks for each cruise of the *Brown* for FY 2008 are shown at http://www.aoml.noaa.gov/ocd/gcc/rvbrown_data2007.php. The cruises include both legs of the CLIVAR P18 line as well as the Southern Ocean Gas Exchange Experiment which took place from February to April of 2008 (http://www.ldeo.columbia.edu/~david/duck-rabbit/so_gasex). Figure 4 shows the pCO_2 along the P18 cruise track.

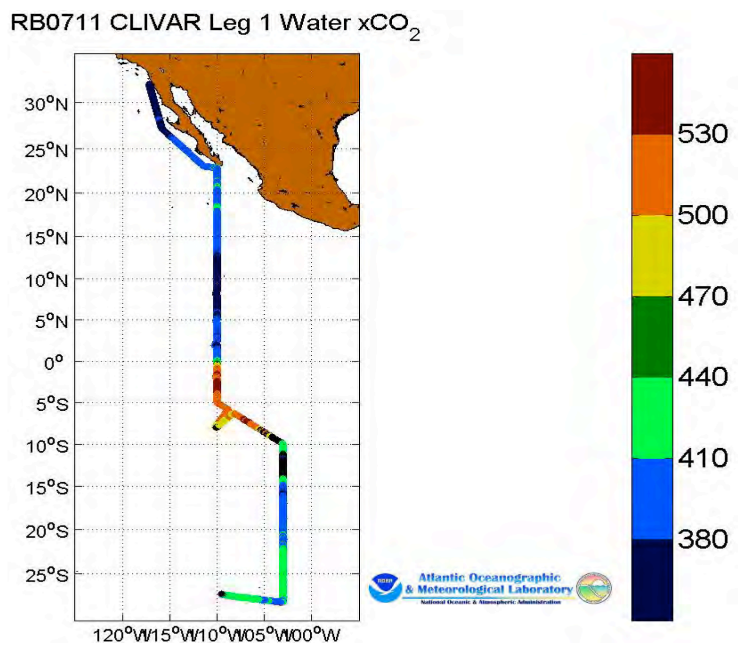

Figure 4. P18 Leg 1 cruise track and surface pCO_2 values**.**

NOAA ship *Ka'imimoana*- PMEL lead

Data Site:
http://www.pmel.noaa.gov/co2/uwpCO2
Number of cruises: 7
Number of fCO_2 data points: 189,782
% Data return: 97%.

Causes for non-return: The underway *f*CO_2 system on the *Ka'imimoana* yielded a 97% data return during FY 2008. A small amount of data was rejected due to stack gas contamination when the ship was on station to service and deploy buoys.

Description: From October 2007 through September 2008 the *Ka'imimoana* was involved in studies in the Equatorial Pacific between 95°W and 165°E. Prior to the 2007-2008 field season, the *f*CO_2 system was updated with new software, pumps and filters. During the time under review, PMEL collected and processed 189,782 *f*CO_2 data values from the *Ka'imimoana* on 7 separate cruises in the equatorial Pacific. The cruise data can be obtained from our website located at**:** http://www.pmel.noaa.gov/co2/uwpco2. A summary of the cruise results from November 1997 through July 2008 is shown in Figure 5. The results show weak seasonal and strong interannual variability of CO_2 fluxes from the oceans to the atmosphere. A ten-year record of observations is shown in Figure 6. Comparison with the ENSO index (Figure 7) shows a strong correlation between negative/positive indices and strong/weak CO_2 sources in the region. All data collected from the *Ka'imimoana* during the 2007-2008 fiscal year are in final processing and will be submitted to CDIAC for archiving.

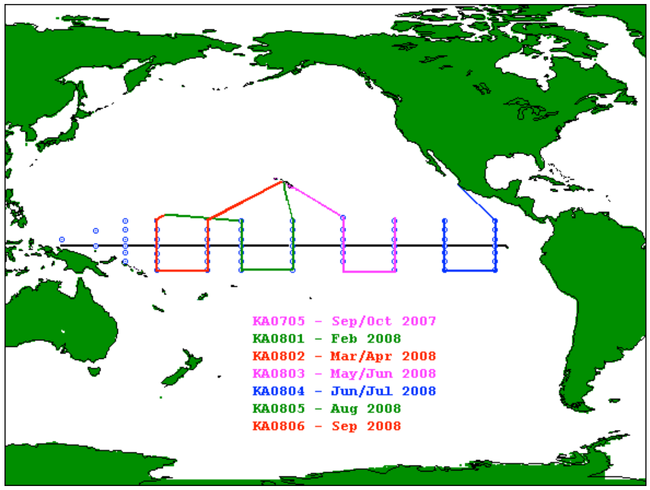

Figure 5. Ka'imimoana track lines occupied during FY 2008.

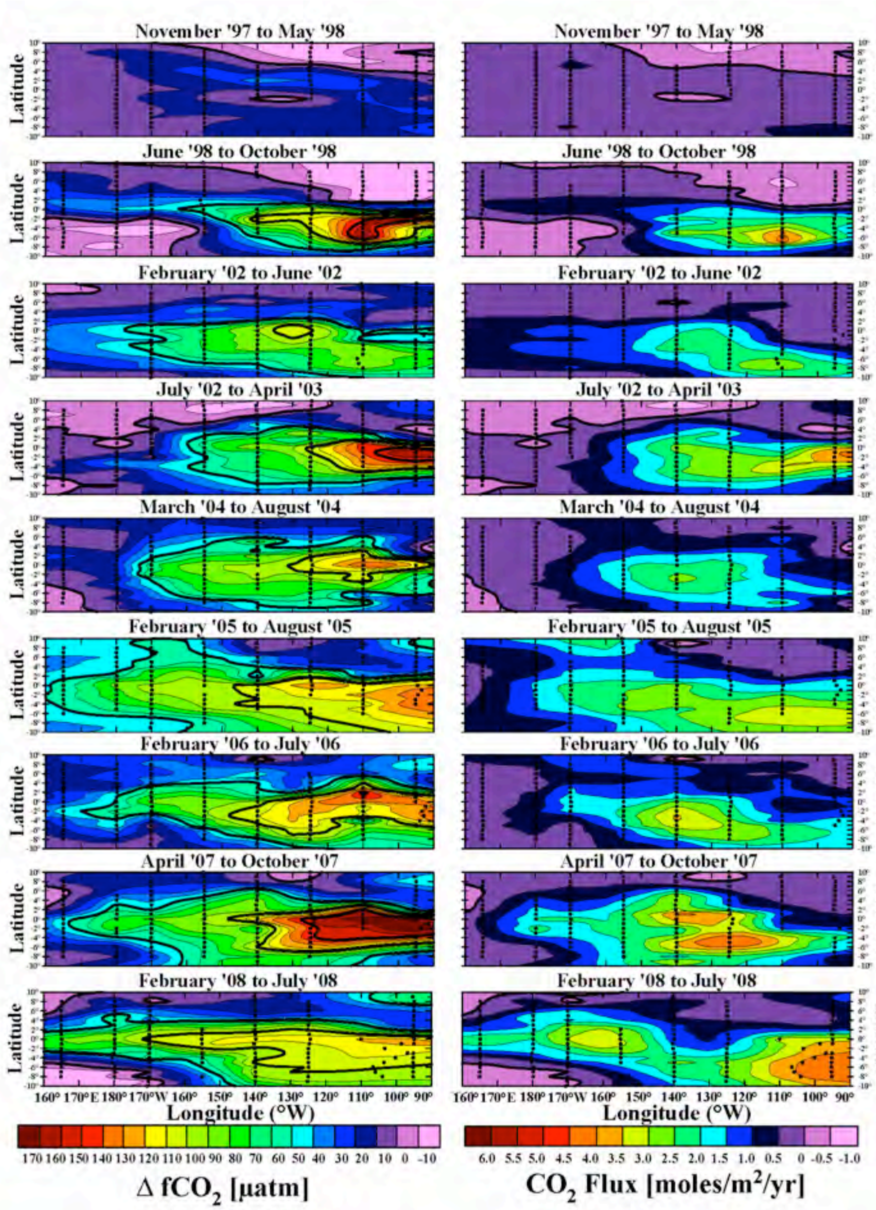

Figure 6. Time-Series of surface water fCO_2 levels in the tropical Pacific resulting from Ka'imimoana repeat observations from 1997 thru 2008.

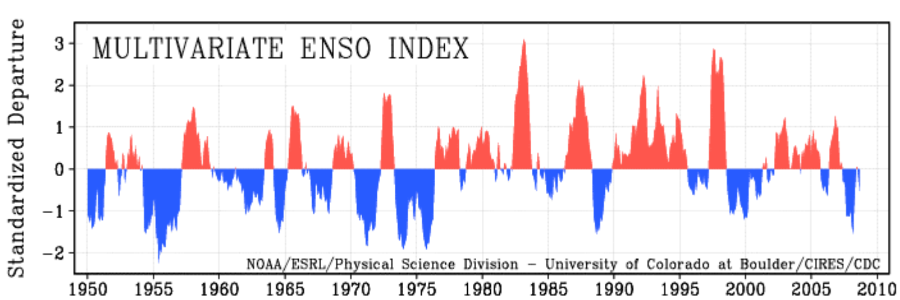

Figure 7. ENSO events through October 2008. Positive values (red) relate to El Niño events and negative values (blue) relate to La Niña events.

Container ship *Albert Rickmers* - PMEL lead

Data Site: [http://www.pmel.noaa.gov/co2/uwpCO₂](http://www.pmel.noaa.gov/co2/uwpCO2)
Number of cruises: 1
Number of fCO_2 data points: 5945
% Data return: 91%.

Causes for non-return: The underway fCO_2 system on the *Albert Rickmers* resulted in a 91% data return during 2007. There were problems associated with inadequate flushing time prior to equilibrator measurements, resulting in rejection of a small fraction of the seawater fCO_2 values.

Description: During October 2007, an fCO_2 system was deployed on the container ship *Albert Rickmers*. The *Albert Rickmers* is involved in studies in the tropical and subtropical Pacific (Figure 8). All data collected on the *Albert Rickmers* has been submitted to CDIAC for archiving, and can also be obtained from our website: http://www.pmel.noaa.gov/co2/uwpco2.

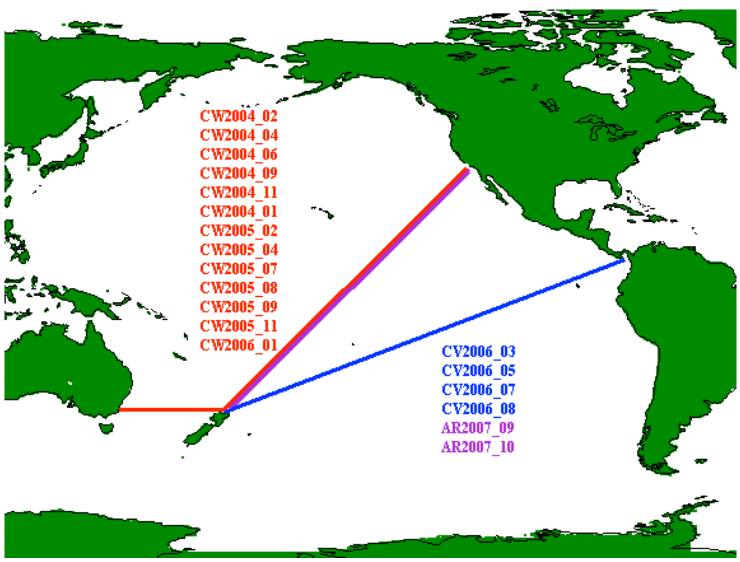

Figure 8. Cruise Tracks of the Columbus Waikato (red), Cap Victor (blue) and Albert Rickmers (purple) occupied during FY2004-2008.

A summary of the cruise results from Fall 2005 to November 2007 is shown in Figure 9. The results show strong seasonal variability of CO_2 fluxes in the southern and northern subtropical Pacific Ocean, that are out of phase by 6 months. The most recent data shows high seawater fCO_2 values due to La Niña conditions in the equatorial Pacific.

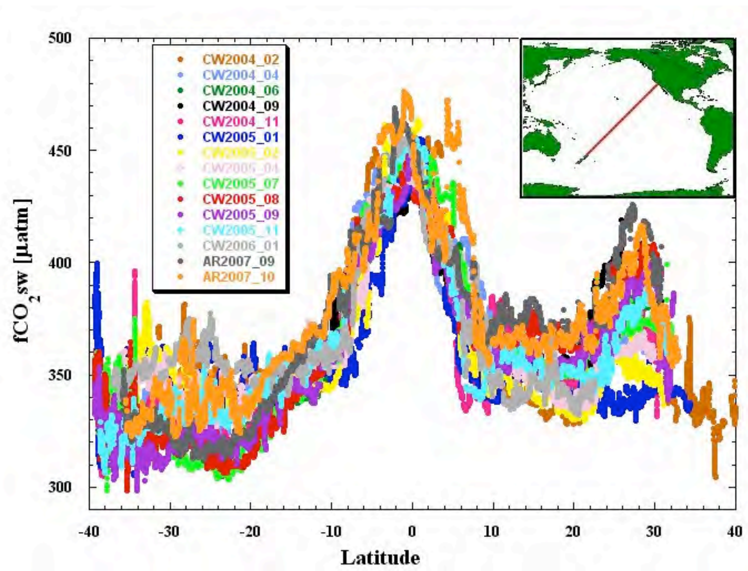

Figure 9. Time-Series of surface water fCO_2 levels in the tropical and subtropical Pacific resulting from Columbus Waikato and Albert Rickmers repeat observations from 2004 to 2007.

In December 2007, the fCO_2 system was removed from the *Albert Rickmer* when the ship changed routes. The Alpha Ship *Cap Van Diemen* was identified as a replacement for the *Albert Rickmers*, and installation of an underway fCO_2 system on the *Cap Van Diemen* began in the summer of 2008.

Container ship *OOCL Tianjin* - PMEL lead

Data Site: http://www.pmel.noaa.gov/co2/uwpCO_2
Number of cruises: 1
Number of fCO_2 data points: 4480
% Data return: 94%.

Causes for non-return: The underway fCO_2 system on the *OOCL Tianjin* resulted in a 94% data return during FY 2008. There were problems associated with inadequate water flow to equilibrator measurements, resulting in rejection of a small fraction of the seawater fCO_2 values.

Description: During the summer of 2008, an fCO_2 system was deployed on the container ship *OOCL Tianjin*. The *OOCL Tianjin* is involved in studies in the North Pacific, an important sink region for atmospheric CO_2. Data will be analyzed to determine how ocean circulation and biological photosynthesis interact to control the rate of exchange of carbon dioxide gas between the atmosphere and North Pacific Ocean. This research is done in collaboration with Dr. Paul Quay of the University of Washington, and Dr. Kitack Lee of the Pohang University of Science and Technology. In addition to supporting our underway

fCO_2 measurements, they are also collecting samples for carbon isotope measurements (Quay) and DIC and nutrients (Lee). For this reason, we have combined resources to place ship riders on each of the cruises. Underway fCO_2 and temperature data from the first cruise on board *OOCL Tianjin* is shown in Figure 10. The cruise data can be obtained from our website**:** http://www.pmel.noaa.gov/co2/uwpco2, and will be submitted to CDIAC for final archival.

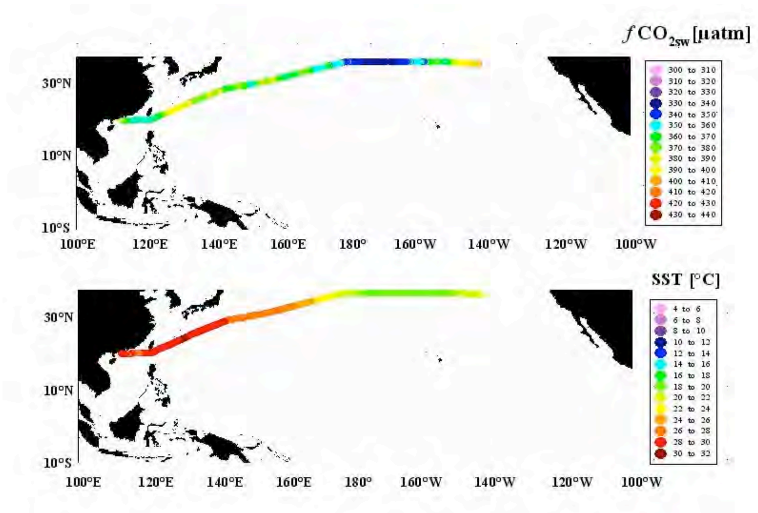

Figure 10. fCO_2sw and SST from the first cruise of the OOCL Tianjin.

RVIB *Palmer* - LDEO lead

Data Site: http://www.ldeo.columbia.edu/CO2
Number of cruises: 8
Number of fCO_2 data points: 76,112
% Data return: 98%.

Description: We have operated successfully a semi-automated surface water pCO_2 system aboard the RVIB *Nathaniel Palmer* with vital operational assistance from the Raytheon Polar Support group. Since RVIB *Palmer*, an ice-breaking research vessel is one of the few research ships which are operated in high latitude areas of the Southern Ocean even during winter months, our CO_2 program aboard this vessel allows us to make observations in hostile environments of the high latitude oceans, where deep and intermediate water masses are formed in winter. The ship was not at sea during the period May 10 through August 27, 2007, for refit in a dry dock and test cruises, and no data were obtained. On September 1, 2007, our measurement program was resumed. During the expeditions, we obtained the following information: pCO_2 in surface ocean water, SST, salinity, wind speeds, barometric pressure and atmospheric CO_2 concentration. The data were obtained successfully for better than 98% of time during the at-sea periods.

The locations of our data obtained since the beginning of this project in 2001 are shown in Figure 11. The total number of surface water pCO_2 data obtained to date is 668,537, of which 76,112 measurements were added to the database during this project year, September, 2007 through August, 2008.

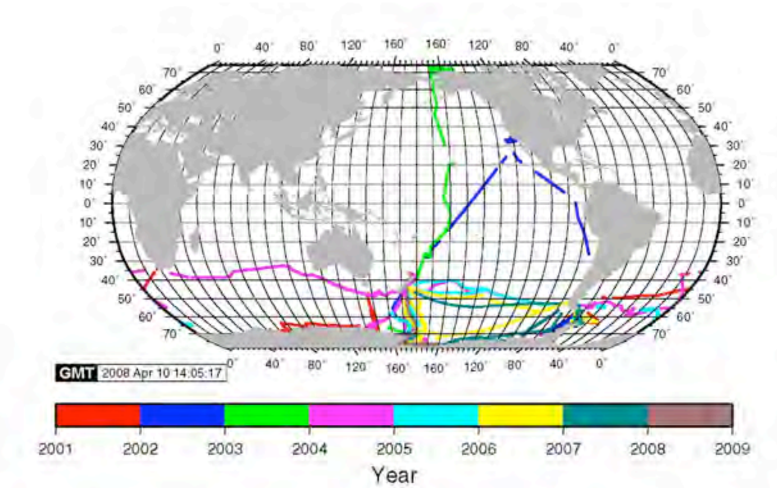

Figure 11. The locations of surface water pCO_2 measurements made aboard the RVIB Palmer since 2001. During the current project year August, 2007-August, 2008 (dark green and brown lines), about 76,112 pCO_2 measurements were obtained.

Cruise ship *Explorer of the Seas*-AOML lead

Data Site: www.aoml.noaa.gov/ocd/gcc/
Number of cruises: 11
Number of fCO_2 data points: 16,466
% Data return: 85%.

Causes for non-return: On the few cruises where we could run the system, it performed quite well with only minimal data loss. We now upgraded the system to the one produced by General Oceanics, Inc. The whole system has been moved to the bow engineering space and upgraded, as explained in the following section, and we are working out the unique operational challenges of the new installation. So far, it performed very well in the new configuration.

Description: Due to lack of funding, the program on board the *Explorer of the Seas* with a dedicated marine technician which was led by the University of Miami's Rosenstiel School of Marine and Atmospheric Science ended abruptly in March of last year, depriving us of the necessary support to run our instrument. After negotiations with Royal Caribbean Cruise Lines, the program has been resurrected on a smaller scale in a fully automated mode, which allowed us to keep a pCO_2 instrument on board but required us to upgrade our system and

relocate it. This was achieved at the end of August of this year. As part of the upgrade an airline to the bow of the ship was installed such that we can now obtain air and surface water fCO_2 measurements. The system can presently only be run by an observer because the automated seawater valve and safety shutoff operations are not in place yet. An upgrade of the support system is underway to make the whole operation completely integrated and autonomous, at which point our instrument will run permanently unattended. In the meantime, we plan to send an observer every three months to run the system and take discrete samples for DIC and TA.
During the last performance period a near-real time data display was instituted where daily pictorial updates of concentrations along the cruise track. This will no longer an option but rather the data will be downloaded automatically every week to 10 days when the ship is in its home port in Bayonne, NJ by wireless communication to an on-shore network which will then relay the data to our host computer for display and reduction.

***RV F.G. Walton Smith*- RSMAS lead**

Description: The RV *Walton Smith* is a shallow draft catamaran which is based at the University of Miami. As a University-National Oceanographic Laboratory System (UNOLS) vessel, its destinations vary but range from the Florida Keys, Florida bay to the Caribbean, the Gulf of Mexico and occasionally the east coast. In a typical year, the ship spends about 200 days at sea. It has the capability of routinely measuring sea surface temperature and salinity, as well as chlorophyll.A pCO_2 system has been installed on board the *Walton* Smith in the beginning of July 2008. So far, it has been on 4 cruises.

Causes for non-return: The main problem on the Walton Smith is the seawater supply which is not sufficient when the demand for it is too great. We are working with the crew to fix that problem. Most of the issues that were encountered did not so much cause a loss of data as it caused a loss of quality. One of these issues was the wrong calibration of a standard gas, which prevented the system to be calibrated over the oceanic CO_2 range encountered. One of the standard tanks which was used for the calibration of the analyzer was not opened. Not only the data will have to be re-calculated but the analyzer will not be as well calibrated over that time.

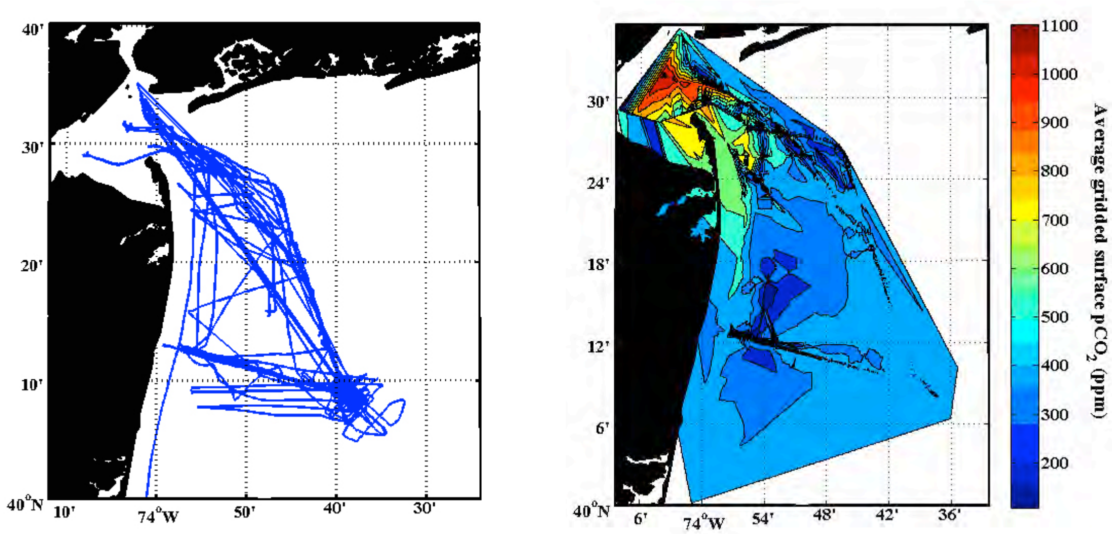

Figure 12. Northern section of the coastal track (left) and average gridded surface pCO_2 values of the R/V F.G. Walton Smith during underway surface sampling along the coast of New Jersey and New York.

Container Ship *Oleander* - BIOS lead

Description: The MV *Oleander* crosses weekly between New Jersey and Hamilton, Bermuda. Given the ~100 crossings a year, this gives excellent temporal and spatial coverage of the North Atlantic subtropical gyre, Gulf Stream, middle Atlantic Bight and coastal zone. The MV *Oleander* transits the region of Subtropical Mode Water (STMW) formation during the winter southeast of the Gulf Stream, and the highly productive coastal zone of the Eastern Seaboard.

R/V *Atlantic Explorer* - BIOS lead

Description: The R/V *Atlantic Explorer* operates in the North Atlantic Ocean (zone NA6), servicing four oceanographic time-series (e.g., Bermuda Atlantic Time-series Study, Hydrostation S, Bermuda Testbed Mooring, Ocean Flux Program) and other research projects. This data stream provides groundtruthing pCO_2 datasets for the subtropical gyre of the North Atlantic Ocean.

2.2. Adherence to monitoring principles

The efforts of the NOAA VOS pCO_2 group have met the important monitoring principle of uniform instrumentation with a quantifiable accuracy. All systems are calibrated with compressed standards that are traceable to the WMO scale. We are actively involved in assuring uniform instrumentation, through close interactions including organizing training session for customers with the manufacturer General Oceanics who is building instruments to our specifications, uniform operating protocol, and uniform data reduction procedures.We are in the process of creating a discussion forum which would be accessible to pCO_2 systems owners where common problems and issues would be discussed and the solutions would be accessible to others. To assure uniform data reduction procedures, we now have two programs, in Excel ® and Matlab ® which automate some of the steps involved. These are outlined in a manuscript by Pierrot et al. 2009. We have started to use them to reduce data and we will make them available to other users soon.
An inter-comparison exercise similar to the one held in 2003 is being organized by the National Institute for Environmental Studies (NIES) in Japan in March 2009 with active involvement of our group. This exercise will involve many international participants, different kind of onboard systems as well as buoys and will improve on the last exercise by reducing the effect of error sources such as the accuracy of temperature sensors. The results will be reported to CDIAC who will make them publicly available along with the 2003 results. This will give good insights into the performance of the systems used in this program.

2.3. Data management and dissemination

An important part of the VOS effort is to disseminate quality controlled data to the community at large in an expedient fashion.

Thermosalinograph (TSG) data from ships of the Ship of Opportunity Program (SOOP) and NOAA fleet are now automatically placed into the GTS by the AOML/GOOS group.

During FY2008 a total of 301,243 TSG quality controlled data from the ships of the SOOP and the NOAA fleet were placed into the GTS. TSG data are being test coded in BUFR (both BUFR Edition 3 and Edition 4 specifications) format, using templates that have been specifically designed to serve operational needs. This effort seeks to improve the future migration from the Traditional Alphanumeric Codes (TACs) to Table-Driven Code Forms (TDCFs), as required by WMO, and has a deadline set to 2010. The current testing will provide the feedback necessary to detect, identify and correct problems that can arise in the migration process, providing a robust framework for near-real-time collection, quality control and distribution of TSG data. The new transmission of TSG data into the GTS in BUFR format constitutes an important improvement because the BUFR message can include metadata and quality control flag information.

During the 2008 fiscal year, the PMEL group wrote new diagnostic software to automatically process daily underway data files when data files arrive via iridium satellite from the *Ka'imimoana*, *OOCL Tianjin*, *Albert Rickmers* and *Cap Van Diemen*. This software creates diagnostic plots of fCO_2, temperature, salinity, barometric pressure, pumps, water flow and gas flow. The plots are posted on an internal website and are used as a diagnostic tool for data processing and quality control of the underway fCO_2 data. During the time in review, data from 7 VOS cruises have been processed and submitted to CDIAC, and data from 2 VOS cruises are in final data processing. All current and previous VOS data files are quality controlled using the data protocol outlined in Pierrot et al. (2009).

The LDEO group, in close interaction with the data acquisition groups, oversees shipboard quality control so that the quality of data and consistency is monitored for the whole group. The participants of the VOS program are able to access the data which are listed in a uniform format. For this purpose, the LDEO group established an open web site at the following URL: http://www.ldeo.columbia.edu/CO2. The site provides not only the numerical data, but also maps showing the ship's tracks for each data file. The new data will be accessible only to the VOS participants for a period of three years, and will be sent to the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN, for the permanent archiving and distribution to the public after this period. This close coupling of the data acquisition with data processing/evaluation and interpretation will guarantee high quality field observation data.

As a part of the VOS program, the LDEO group processed and added to its database the measurements from the 2 other field operations; 1) the R/V *Laurence M. Gould*, which is supported by NSF as a part of the Long-Term Research in Environmental Biology (LTRE) program in the Drake Passage area, Southern Ocean; 2) Yacht *Turmoil* in coastal waters.
A total of approximately 68,403 pCO_2 measurements that were made aboard the R/V *Gould* and 101,053 that were made aboard the Yacht *Turmoil* during the calendar year 2008 have been added to the database. This makes a total of 356,557 pCO_2 measurements for the VOS participants from August, 2007 through August, 2008.

Table 2. Summary of the new data contributed to the database by the VOS participants during this funding period, August, 2007 – August, 2008.

Programs	**PI / Institutions**	**No. of pCO_2 Observations**	**Primary Locations**
RVIB Palmer	Takahashi/LDEO	76,112	Southern Ocean
R/V Gould	Sweeney/ESRL/NOAA Takahashi/LDEO	68,403	Drake Passage, Southern Ocean
Explorer of Seas	Wanninkhof/AOML/NOAA	53,268	Caribbean
R/V Kaimimoana	Feely/PMEL/NOAA	57,721	Tropical Pacific
M/V Oleander	Bates/BIOS	Not reported	N. Atlantic
R/V Atlantic Explorer	Bates/BIOS	Not reported	Bermuda
M/V Turmoil	Takahashi/LDEO	101,053	Coastal
TOTAL FOR AUG. 07-AUG. 08		**356,557**	

2.4. Research highlights

1. We have developed seasonal and interannual fCO_2-SST relationships from shipboard data that were applied to high-resolution temperature fields deduced from satellite data to obtain high-resolution large-scale estimates of the regional fluxes in the Equatorial Pacific (Figure 6). The data were gathered onboard research ships from November 1981 through September 2008. Data were collected during the warm boreal winter-spring season (January through June) and during the cooler boreal summer-fall season (July through December) of each year making it possible to examine the interannual and seasonal variability of the fCO_2-SST relationships. A linear fit through the equatorial Pacific data sets yields an inverse correlation between SST and fCO_2, with both interannual and seasonal differences in slope. In particular, the results indicate a strong interannual El Niño – Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and weaker seasonal variability. There is also a slight increase in the out-gassing flux of CO_2 after the 1997–1998 PDO mode shift. Most of this increase is due to increase in wind speeds after the spring of 1998 (Figure 6). These increases are consistent with the recent rebound of the shallow water meridional overturning circulation in the tropical and subtropical Pacific after the PDO 1997-98 shift. In the summer of 2007, equatorial CO_2 flux values were extremely high, resulting from the development of La Niña conditions in the late summer of 2007 which persisted into the summer of 2008 (Figure 7).

2. A unique and novel application of our 4-year time series of data in the Caribbean Sea from the *Explorer of the Seas* has been the assessment of ocean acidification in the region. Utilizing the in situ fCO_2, salinity, and SST data along with high resolution remotely sensed and assimilated SST, wind and salinity data a ten-year record of ocean acidification was produced (Figure 13) (Gledhill et al., 2008). This product is now being served through NESDIS Coastwatch. This analysis was covered under other grants but it illustrates the wide reach of collaboration and application of the datasets.

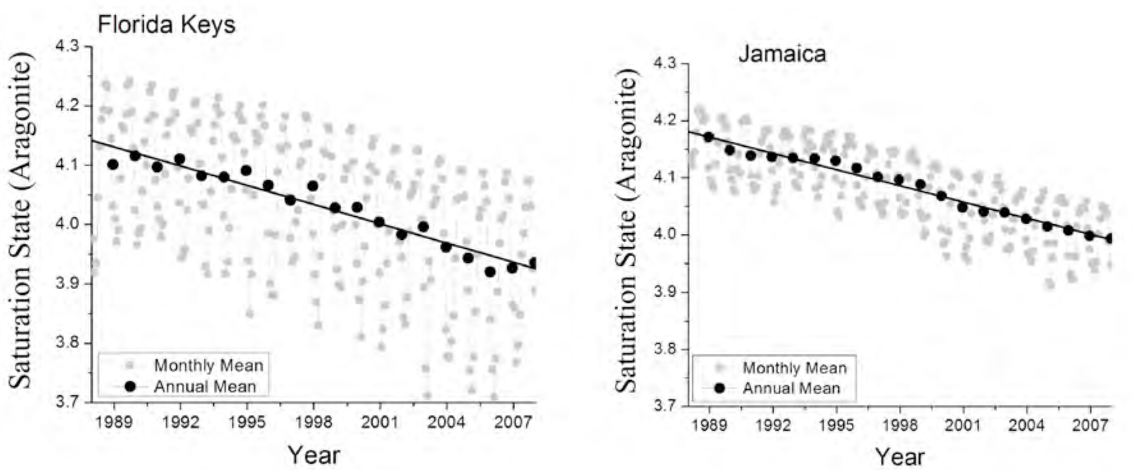

Figure 13. Increases in surface water fCO_2 lead to decreases in saturation state that is unfavorable for coral growth in the Caribbean. Data from the Explorer of the Seas along with high resolution remotely sensed and assimilated data were used to obtain the estimates of declining saturation states in different parts of the Caribbean Sea. Note the large seasonal excursions primarily due to seasonal changes in surface water fCO_2 (from Gledhill et al., 2008).

3. The publication of the updated climatology of Takahashi et al. (2009) has been delayed because of issues with the release of the special volume. Important updates have been made in the interim including addition of 0.8 M data points (many obtained under auspices of this effort). New findings include a breakdown of the estimate's uncertainty into the uncertainty in the ΔfCO_2, the uncertainty in the gas transfer velocity, and the uncertainty introduced by mapping the data onto a single year and the assumptions about the trend of surface seawater fCO_2 over the 3 decades that span the climatology (Table 3). In addition, the updates show an increase in surface water fCO_2 in the Southern Ocean that is greater than the atmospheric increase pointing towards a decreasing sink (Figure 14).

Table 3. Breakdown of error in air-sea CO_2 flux estimate[1] (from Takahashi et al. 2009).

Error	% Error	Source
± 0.18 Pg-C yr^{-1}	± 13%	ΔpCO_2 measurements
± 0.42 Pg-C yr^{-1}	± 30%	scaling factor for the gas transfer velocity parameterization,
± 0.28 Pg-C yr^{-1}	± 20%	wind speeds
± 0.5 Pg-C yr^{-1}	± 35%	mean rate of change in ocean water

[1]the total flux is estimated at 1.6 Pg-C yr^{-1} and the anthropogenic CO_2 flux at 2 Pg-C yr^{-1}.

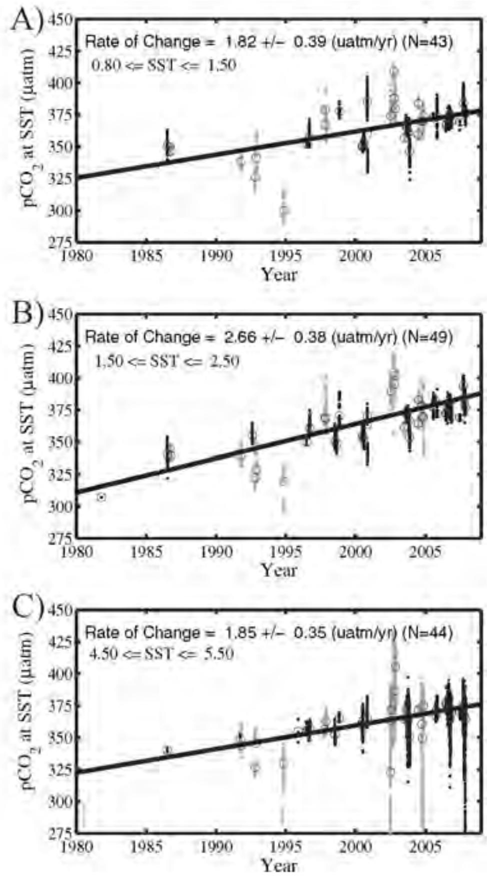

Figure 14. Rates of increase in surface water pCO_2 in the subpolar region (south of 50˚S) of the Southern Ocean in the winter months (Julian dates from 172 to 326) during the period from 1986 to 2006. The top panel is for SST between 0.8 to 1.5˚C; the middle panel for SST between 1.5 and 2.5˚C; and the bottom panel for SST between 4.5 and 5.5˚C. (From Takahashi et al. (2009).

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Doney, S. C., I. Lima, J. K. Moore, K. Lindsay, M. Behrenfeld, N. Mahowald, M. Maltrud, D. M. Glover, D. McGillicuddy, and T. Takahashi, 2008: Skill metrics for confronting global upper ocean ecosystem-biogeochemistry models against field and remote sensing data. *Jour. Marine Systems*, *Special Issue* "Skill Assessment for Coupled Biological/Physical Models of Marine Systems" (Available on line, May 29, 2008), in press.

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Takahashi, T. Rik Wanninkhof, Colm Sweeney, Richard A. Feely, Burke Hales, Jon Olafsson and Stewart C. Sutherland, 2007: Decadal change and climatological mean surface ocean $p$$CO_2$, and net sea-air CO_2 flux over the global oceans. Invited presentation at the Gordon Research Conference, July, 2007, Meriden, NH.

Takahashi, T. et al., 2007: Climatological mean and decadal change in surface ocean $p$$CO_2$, and net sea-air CO_2 flux over the global oceans. A key note address at the 16th meeting of the North Pacific Marine Science Organization (PICES), October, 2007, Victoria, CANADA.

Takahashi, T., Sutherland, S. C. and Kozyr, A., 2008: Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed during 1968-2006 (Version 1.0). ORNL/CDIAC-152, NDP-088. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, TN 37831, pp.20. (With 3.4 million pCO$_2$ measurements in global surface ocean waters).

Takahashi, T., Sutherland, S. C. and Kozyr, A., 2008: Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed during 1968-2007 (Version 2007). ORNL/CDIAC-152, NDP-088. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, TN 37831, pp.20. (With 4.1 million pCO$_2$ measurements in global surface ocean waters).

APPENDIX

Underway CO_2 Measurements aboard the RVIB Palmer and Data Management of the Global VOS Program

Taro Takahashi
Lamont-Doherty Earth Observatory of Columbia University, Palisades NY

1. SCIENTIFIC OBJECTIVES

The sea-air net flux of CO_2 is governed by the difference between pCO_2 in surface ocean water and the overlying atmosphere as well as by the gas transfer rate across the sea-air interface. The former depends primarily on the processes occurring within the sea (such as seawater temperature, biological productivity and upwelling of deep waters), and the latter is controlled mainly by turbulence in the interface zone induced by winds. The primary objective of this proposed investigation is to determine the space-time distribution of the sea-air pCO_2 difference. In conjunction with CO_2 gas transfer coefficients which are being improved by other scientific groups, a reliable net sea-air flux of CO_2 estimate over regional to global scales can be obtained using improved sea-air pCO_2 difference data.

2. THE LDEO PROGRAM

2.1. Field Program:

The field work by the LDEO group is primarily focused in the southern high latitude ocean areas surrounding the Antarctic continent. The LDEO group operates a semi-automated surface water pCO_2 system aboard the RVIB Nathaniel Palmer with significant operational assistance from the Raytheon Polar Support group (funded by NSF). RVIB Palmer is an ice-breaking research vessel, one of the few research ships operated, even during winter months, in the high latitude Southern Ocean areas including the Weddell and Ross Seas and the formation areas for the deep and intermediate water masses. Hence, this program yields observations critical to our understanding of the role of the Southern Ocean in the global carbon cycle (see Figure 1). Our Southern Ocean study is further strengthened by the cooperation with the NSF's Drake Passage CO_2 program aboard the R/V Laurence M. Gould, that is conducted jointly with Colm Sweeney of ESRL/NOAA and the LDEO group.

In order to document time-space distribution of surface water pCO_2 in the Arctic, we have initiated a program with U. S. Coast Guard and NSF for a long-term operation of our pCO_2 system aboard USCGC Healy, which is operated primarily in the Arctic Ocean. Our proposed program has been approved by the Arctic Icebreaker Coordinating Committee (consisting of the representatives of USCG, NSF and researchers), and is in progress (see Section 3.2.).

2.2. Data Management Program

Under this grant, the Lamont-Doherty Observatory group is responsible for quality-control and management of the data produced by the NOAA-supported groups as well as those from international collaborators from Japan, Iceland, Germany, UK and France. Pooling of the data from these participants allows us to cover a large part of the global oceans. During this grant period, a global ocean database which includes 4.1 million surface ocean pCO_2 observations made in 1970 through the end of 2007 has been assembled in a single uniform format (LDEO Database, version 2007) and is accessible to the public through the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge National Laboratory, TN (Takahashi et al., 2008: http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/LDEO_home.html). This is an updated and improved version of the earlier release (version 1.0), which contains about 3.4 million pCO_2 measurements. The detailed data in current years are also accessible to the VOS participants via the LDEO web site (www.ldeo.columbia.edu/CO2).

3. PROGRESS TO DATE, LDEO Program

The progress made during the current funding period September, 2007 through August, 2008, is described in this section.

3.1. LDEO Field Program aboard the RVIB Palmer

The Lamont group is primarily responsible for the acquisition of the surface water pCO_2 data aboard the RVIB Palmer. The ship was not at sea during the period May 10 through August 27, 2007, for refit in a dry dock and test cruises, and no data were obtained. On September 1, 2007, our measurement program was resumed. During the expeditions, we obtained the following information: pCO_2 in surface ocean water, SST, salinity, wind speeds, barometric pressure and atmospheric CO_2 concentration. The data were obtained successfully for better than 98% of time during the at-sea periods.

The locations of our data obtained since the beginning of this project in 2001 are shown in Figure 1, and the dates, location and number of measurements are listed in Table 1. The total number of surface water pCO_2 data obtained to date is 668,537, of which 76,112 measurements were added to the database during this project year, September, 2007 through August, 2008.

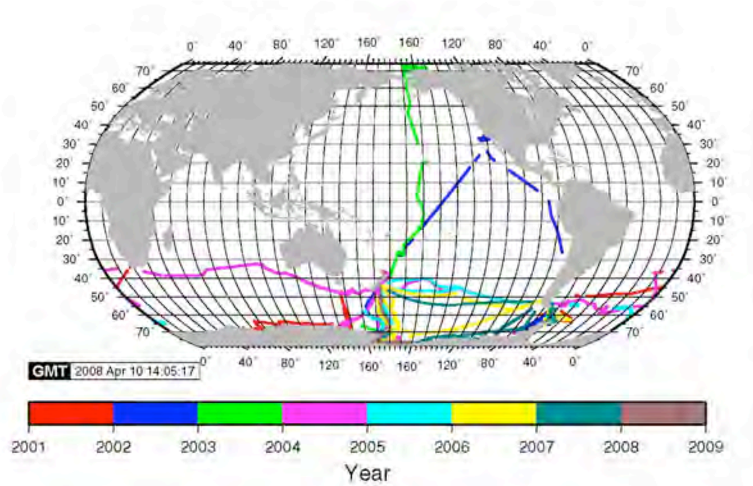

Figure 1. The locations of surface water pCO_2 measurements made aboard the RVIB Palmer since 2001. During the current project year August, 2007-August, 2008 (dark green and brown lines), about 76,112 pCO_2 measurements were obtained.

Table 1. List of the RVIB N. B. Palmer expeditions and the number of surface water pCO_2 measurements obtained from January, 2001 through August, 2008.

Cruise No.	Project Name	Dates	No. Obs.	Annual No.
01/1	East Antarctic Margin	30 Jan - 20 Mar 2001	12,300	
01/2	SouthWest Pacific	01-19 Apr 2001	6,541	
01/3	SO-GLOBEC	23 Apr - 06 Jun 2001	20,446	
01/4	SO-GLOBEC	21 Jul - 01 Sep 2001	14,960	
01/5	Antarctic Peninsula	07 Sep - 26 Oct 2001	27,312	
01/6	SO-GLOBEC	09 Nov- 01 Dec 2001	10,317	
01/7	Antarctic Peninsula	05 Dec 01 - 12 Jan 02	22,627	**114,503**
02/1	Antarctic Penninsula	18 Jan - 04 Mar 02	24,542	
02/2	GLOBEC III	09 Apr - 21 May 2002	25,327	
02/4	GLOBEC IV	31 Jul - 09 Sep 2002	29,640	
02/5	Transit along W. South America	23 Sep - 19 Oct 2002	8,317	
02/6	USCG Inspection	30 Oct - 08 Nov 2002	6,732	
02/7	Reconst. of Paleo S. Pac.	10 Nov - 06 Dec 2002	5,702	
02/9	ANSLOPE, Transit fm Lyttleton to McMurdo	11 Dec 2002 - 03 Jan 2003	6,925	**107,185**
03/1	Ross Ice Shelf Survey	5 - 30 Jan 2003	8,062	
03/1A	Ross Sea Research	2-20 Feb 2003	7,227	
03/2	Ross Sea Research	25 Feb - 09 Apr 2003	13,897	
03/4	Transit N.Z to Alaska	23 May - 02 Jul 2003	9,864	
03/4A	Alaska North Slope	06 Jul - 18 Aug 2003	17,136	
03/5	Southern Ocean near 175E	26 Oct - 13 Dec 2003	7,427	
03/5A	Ross Sea Research	18 Dec 2003 - 02 Jan 2004	4,501	**68,114**
04/1	Western Ross Sea	20 Jan - 19 Feb 2004	12,299	
04/2	ANSLOPE III	26 Feb - 11 Apr 2004	17,708	
04/3	Transit New Zealand to Chile	16 Apr - 12 May 2004	9,463	
04/4	Ice Fish	18 May - 19 Jul 2004	22,755	
04/6	Transit, South Africa to New Zealand	27 Jul - 04 Sep 2004	14,277	
04/8	ANSLOPE IV	12 Oct - 06 Dec 2004	21,958	

04/9	Biochemical Research	18 Dec 2004 - 25 Jan 2005	14,443	**112,903**
05/1	ANSLOPE/IVARS	28 Jan - 15 Feb 2005	5,736	
05/1B	N.Z. to Chile Transit	03 - 22 Mar 2005	7,494	
05/2	Antarctic Penninsula	02 - 24 Apr 2005	8,235	
05/5	Coastal Chile	23 Jun - 14 Jul 2005	3,983	
05/6	Maud Rise	20 Jul - 18 Sep 2005	19,066	
05/7	Chile to N.Z. Transit	23 Sep - 21 Oct 2005	9,554	
05/8	Ross Sea Biology	26 Oct - 12 Dec 2005	18,387	**72,455**
06/1	Interaction of Iron, Light, & CO2	17 Dec 05 - 30 Jan 06	16,174	
06/2	Late Cretaceous & Cenozoic Recreations	03 Feb - 23 Mar 2006	7,740	
06/3	Paleo History of Larsen Ice Shelf	12 Apr - 05 May 2006	10,005	
06/6	Plankton Community Struct & Iron Concent.	03 Jul - 18 Aug 2006	17,565	
06/8	Ross Sea Plankton Dynamics	01 Nov - 15 Dec 2006	17,257	**68,741**
07/1	Geological Research	22 Dec 2006 - 29 Jan 2007	14,963	
07/2	Amundsen Sea Research	03 Feb - 25 Mar 2007	20,780	
07/3	Collaborative Research	31 Mar - 05 May 207	12,781	
07/4	Open Period	10 May - 20 Jun 2007	no data	
07/5	Transit to Maintenance Period	21 - 25 Jun 2007	no data	
07/6	Dry dock	25 Jun - 28 Jul 2007	no data	
07/7	Transit to Punta Arenas, Chile	28 Jul - 02 Aug 2007	no data	
07/8	Open Period	02 - 27 Aug 2007	no data	
07/9	Sea Ice Balance in the Antarctic	01 Sep - 31 Oct 2007	14,616	
07/10	Palmer Station Resupply	14 Nov - 07 Dec 2007	8,548	
07/11	Transit, Chile - New Zealand	14 - 30 Dec 2007	6,355	**78,043**
08/1	Ross Sea Research	08 - 27 Jan 2008	6,876	
08/2	Ross Sea Research	29 Jan - 20 Feb 2008	8,562	
08/3	Ross Sea Research	23 Feb - 17 Mar 2008	8,330	
08/4	Transit, New Zealand to Chile	21 Mar - 14 Apr 2008	9,300	
08/5	Drake Passage, Scotia Sea Research	18 Apr - 25 May 2008	13,525	
08/6	Weddell Sea	31 May - 30 Jun 2008	pending	
08/7	Not Used			
08/8	Drake Passage	Pending	pending	**46,593**
GRAND TOTAL SINCE THE BEGINNING OF THE PROJECT				**668,537**

3.2. LDEO Field Program aboard the R/V Marcus Langseth and USCGC Healy

We are working toward adding our underway pCO_2 systems on two ships. R/V Marcus Langseth, which is newly acquired by the Lamont-Doherty Earth Observatory with support from NSF, has undergone the first sea trial in March, 2008, and an underway pCO_2 system has been installed on board in May, 2008. However, its underway pumping system for scientific water samples has been found to be unreliable and problematic. For this reason, no reliable pCO_2 data have been obtained through the end of September, 2008, the terminal day for the NSF's ship operation funding for 2008. Our pCO_2 program will resume when the ship will be put to the sea in 2009.

A pCO_2 system for USGCC Healy has been completed ahead of the schedule and is ready for the installation as soon as a new, improved underway pumping system for scientific purposes (funded by NSF) is completed aboard the ship. However, it appears that the completion of the pumping system may be delayed until the later half of 2009. As soon as the pumping system is completed, our measurement program in the Arctic Ocean will be started.

3.3. pCO_2 Data Processing and Management at LDEO for the VOS Program

Under this grant, the Lamont-Doherty Observatory group is responsible for quality-control and management of the data produced by the NOAA-supported Volunteer Ocean Survey (VOS) groups as well as those from international collaborators from Japan, Iceland, Germany, UK and France. A global ocean database which includes 4.1 million surface ocean pCO_2 observations made in 1970 - 2007 has been assembled in a single uniform format (LDEO Database, version 2007, Takahashi et al., 2008) and is accessible to the public through the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge National Laboratory, TN (http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/LDEO_home.html). This is an updated and improved version of the earlier release (version 1.0), which contained about 3.4 million pCO_2 measurements.

For the members of the (VOS) consortium, the participants are able to access the data in a uniform electronic format. For this purpose, we have established an open web site at the following URL: http://www.ldeo.columbia.edu/CO2. The site provides not only the numerical data, but also maps showing the ship's tracks for each data file. The new data will be accessible only to the VOS participants for a period of three years, and will be released to the public after this period. The field data from the following field operations constitute major additions to the database; 1) the RVIB Palmer program in the Southern Ocean; 2) the R/V Laurence M. Gould program, which is supported by NSF as a part of the Long-Term Research in Environmental Biology (LTRE) program in the Drake Passage-Antarctic Peninsula area, Southern Ocean; 3) the "Explorer of the Seas" program in and around the Caribbean Sea (R. Wanninkhof); 4) the Kaimimoana program in the equatorial Pacific (R. A. Feely); 5) the Container Ship Oleander and Atlantic Explorer programs (N. Bates, BIOS) in the temperate western North Atlantic); and 6) the M/V Turmoil program for coastal waters (T. Takahashi).

The number of surface water pCO_2 observations reported to us for incorporation into our database is summarized in Table 2. During this funding period, 332,845 pCO_2 data accompanied with SST, salinity and other information have been added to the database.

Table 2. Summary of the new data contributed to the database by the VOS participants during this funding period, August, 2007 – August, 2008.

Programs	**PI / Institutions**	**No. of pCO_2 Observations**	**Primary Locations**
RVIB Palmer	Takahashi/LDEO	76,112	Southern Ocean
R/V Gould	Sweeney/ESRL/NOAA Takahashi/LDEO	68,403	Drake Passage, Southern Ocean
Explorer of Seas	Wanninkhof/AOML/NOAA	53,268	Caribbean
R/V Kaimimoana	Feely/PMEL/NOAA	57,721	Tropical Pacific
M/V Oleander	Bates/BOIS	Not reported	N. Atlantic
R/V Atlantic Explorer	Bates/BIOS	Not reported	Bermuda
M/V Turmoil	Takahashi/LDEO	101,053	Coastal
TOTAL FOR AUG. 07-AUG. 08		**356,557**	

3.4. LDEO Data Analysis and Synthesis

The pCO_2 data obtained and archived by the present grant have been used extensively in the following research papers and government reports, that have been prepared during this grant period, 2007-08.

Takahashi, T., Sutherland, S. C. and Kozyr, A., 2008: Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed during 1968-2006 (Version 1.0). ORNL/CDIAC-152, NDP-088. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, TN 37831, pp.20. (With 3.4 million pCO_2 measurements in global surface ocean waters.)

Takahashi, T., Sutherland, S. C. and Kozyr, A., 2008: Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed during 1968-2007 (Version 2007). ORNL/CDIAC-152, NDP-088. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, TN 37831, pp.20. (With 4.1 million pCO_2 measurements in global surface ocean waters.)

Takahashi, T. S.C. Sutherland, R. Wanninkhof, C. Sweeney, R. A. Feely, D. W. Chipman, B. Hales, G. Friederich, F. Chavez, A. Watson, D. C. E. Bakker, U. Schuster, N. Metzl, H. Yoshikawa-Inoue, M. Ishii, T. Midorikawa, Y. Nojiri, C. Sabine, J. Olafsson, Th. S. Arnarson, B. Tilbrook, T. Johannessen, A. Olsen, Richard Bellerby, A. Körtzinger, T. Steinhoff, M. Hoppema, H. J. W. de Baar, C. S. Wong, Bruno Delille and N. R. Bates: Climatological mean and decadal changes in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. *Deep-Sea Res. II*, in press.
S. C. Doney, I. Lima, J. K. Moore, K. Lindsay, M. Behrenfeld, N. Mahowald, M. Maltrud, D. M. Glover, D. McGillicuddy, and T. Takahashi: Skill metrics for confronting global upper ocean ecosystem-biogeochemistry models against field and remote sensing data. Jour. *Marine Systems*, Special Issue "*Skill Assessment for Coupled Biological/Physical Models of Marine Systems*" (Available on line, May 29, 2008), in press.

Sabine, C. L., Feely, R. A., Wanninkhof, R. and Takahashi, T.: The global ocean carbon cycle. *Bulletin of the American Meteorological Society*, in review.

3.5. Public presentations

Taro Takahashi, Rik Wanninkhof, Colm Sweeney, Richard A. Feely, Burke Hales, Jon Olafsson and Stewart C. Sutherland, 2007: Decadal change and climatological mean surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. Invited presentation at the Gordon Research Conference, July, 2007, Meriden, NH.

Taro Takahashi et al., 2007: Climatological mean and decadal change in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. A key note address at the 16^{th} meeting of the North Pacific Marine Science Organization (PICES), October, 2007, Victoria, CANADA.

Jon Olafsson, Taro Takahashi, Thorarinn.S. Arnarson, Solveig.R. Olafsdottir and Magnus Danielsen, 2008: Time series observations, 1983-2006, of inorganic carbon and nutrients in high latitude North Atlantic. ASLO-Ocean Sciences meeting, March, 2008, Orlando, FL.

Corinne Le Quere, Taro Takahashi, Christian Rödenbeck, Erik T. Buitenhuis, Steward C. Sutherland, 2008: Recent trend in the global oceanic CO_2 sink. International Symposium on the Effects of Climate Change on the World Oceans, May, 2008, Gijon, Spain.

L. Barbero-Munoz, J. Boutin, L. Merlivat, J. B. Sallee, T. Takahashi and S. C. Sutherland, 2008: Sea surface pCO2 in the subantarctic zone of the Southern Ocean from CARIOCA buoys and ship data. International Symposium on the Effects of Climate Change on the World's Oceans, May 19 - 23, 2008, Gijon, Spain.

4. HIGHLIGHT OF THE LDEO PROGRAM

An extensive database for the surface water pCO_2 over the global oceans has been released through the Carbon Dioxide Information Center (CDIAC) to the public. This database contains about 4.1 million surface ocean water pCO_2 data accompanied with associated information such as the dates and positions of measurements, sea surface temperature, salinity and barometric pressures. This is an updated version of the earlier release (version 1.0) which contains about 3.4 million pCO_2 data.

A synthesis of the global surface ocean pCO_2 data has been accepted for publication in the SOCOVV Symposium volume of “Deep-Sea Research” (Takahashi et al., Deep-Sea Research, in press). The ocean uptake of CO_2 is estimated to be about 1.6 ± 0.9 Pg-C for the year 2000.

High-Resolution Ocean and Atmosphere pCO_2 Time-Series Measurements

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1. PROJECT SUMMARY

Fossil fuel carbon sources and the growth of atmospheric carbon dioxide (CO_2) are reasonably well known based on economic reconstructions and atmospheric monitoring. Global carbon budgets suggest that over decadal timescales the ocean is absorbing, on average, approximately one third of the CO_2 released from human activity. However, the interannual variability in the ocean uptake and variability in the basic regional patterns of the air-sea CO_2 fluxes are poorly known at this time.

Ocean carbon measurements have shown significant biogeochemical variability over a wide range of timescales from sub-diurnal to decadal periods. In situ measurements are also providing a growing body of evidence that episodic phenomena are extremely important causes of variability in CO_2 and related biogeochemical properties. Year-to-year variations in physics (e.g., upwelling, winter mixing, lateral advection), bulk biological production, and ecological shifts (e.g., community structure) can drive significant changes in surface water CO_2, and thus air-sea flux. Changes in large-scale ocean-atmosphere patterns such as El Niño/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO) appear to drive much of the interannual variability, and this variability is expressed on regional (several hundred-to-thousands of kilometers) rather than basin-to-global scales. The slower, decadal time-scale ocean responses are not as well characterized as the interannual responses, though there is tantalizing evidence for large-scale biogeochemical regime shifts (or perhaps secular trends) and long-term changes in nutrient and carbon distributions. Distinguishing a human-induced, climate-change signal from natural decadal variability on this timescale is often singularly difficult, particularly given the relatively short duration of most oceanographic data records. But model projections suggest that anthropogenic impacts are accelerating and may become more evident in the near future.

Time-series records are essential for characterizing the natural variability and secular trends in the ocean carbon cycle and for determining the physical and biological mechanisms controlling the system. The biological and chemical responses to natural perturbations (e.g., ENSO, dust deposition events) are particularly important with regard to evaluating potential responses to anthropogenic forcing and for evaluating the prognostic models used in future climate projections. Ship-based time-series measurements are impractical for routinely measuring variability over intervals from a week to a month, they cannot be made during storms or high-sea conditions, and they are too expensive for remote locations. Instrumental advances over the past 15 years have led to autonomous moorings capable of sampling properties of chemical, biological, and physical interest with resolutions as good as a minute and duty cycles of a year or more. Although these new technologies are still underutilized, they have been identified as a critical component of the global ocean observing system for climate.

In 2004, the moored CO_2 program was initiated by the Office of Climate Observations (OCO) as part of the ocean observing system. The moored CO_2 network is still in its infancy, but is quickly expanding into a global network of surface ocean and atmospheric CO_2 observations that will make a substantial contribution to the production of seasonal CO_2 flux maps for the global oceans. The long-term goal of this program is to populate the network of OCEAN Sustained Interdisciplinary Time-series

Environment observation System (OceanSITES; http://www.oceansites.org/) so that CO_2 fluxes will become a standard part of the global flux mooring network. This effort has been endorsed by the OceanSITES science team. The moored CO_2 program directly addresses key element (7) Ocean Carbon Network, as outlined in the Program Plan, but also provides a value added component to elements (3) Tropical Moored Buoys and (6) Ocean Reference Stations. Additional information about the moored CO_2 program can be found at: http://www.pmel.noaa.gov/co2/moorings/.

2. ACCOMPLISHMENTS

2.1. Measurements and Network Development

The PMEL built moored pCO_2 systems ($MAPCO_2$) collect CO_2 and O_2 data from surface seawater and marine boundary air every three hours. A summary file with each of the measurements is transmitted and plots of the data are posted to the web once per day. MBARI also operates moored pCO_2 systems at two equatorial sites. In addition to the moored pCO_2 data, MBARI has been collecting nutrient and chlorophyll measurements on the 155°W and 170°W TAO cruises. One person participates on these cruises and analyzes samples from the shipboard uncontaminated seawater supply and from CTD casts performed in-between buoy maintenance. These data have proven to be very helpful at interpreting the buoy based measurements and ultimately trying to examine the mechanisms controlling the observed variability in pCO_2.

In FY08, PMEL/MBARI maintained eight of the sites from FY07. A ninth CO_2 mooring site was located off of Bermuda at the Bermuda Atlantic Time Series (BATS) station, but the mooring at that location (BTM; Tommy Dickey) had to be pulled near the beginning of FY08 due to lack of funding. There were a total 13 servicing visits to these sites in FY08. New pCO_2 systems were needed to replace older systems or systems that were lost at sea earlier in the year.

The long term goal of this program is to populate 50 OceanSITES flux reference moorings with pCO_2 systems (Figure 1). With eight moorings currently fitted with pCO_2 systems (plus the Papa mooring currently funded by NSF), we are currently at 18% completion of the open ocean moored CO_2 program goal.

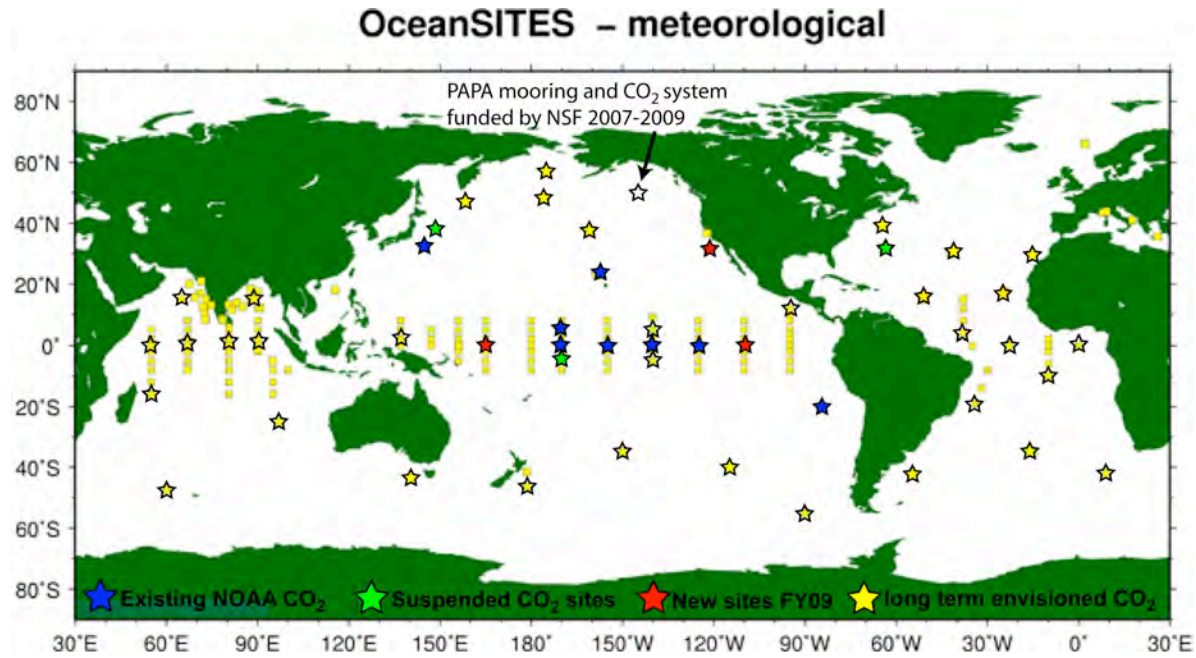


Figure 1. Map of moored pCO_2 systems currently planned and deployed as part of this program.

2.2. Instrument/Platform Acquisitions

Here we summarize the deployment schedules and instrument performance over the last year. Systems are grouped into three categories. Five systems are located in the equatorial Pacific on the TAO moorings. Three systems are on Woods Hole buoys located in the North Pacific subtropical gyre, North Atlantic subtropical gyre and in the South Pacific upwelling region off of Chile. Two of the Woods Hole buoys are co-located with shipboard time-series study sites at Hawaii and Bermuda. One system is located off of Japan in a high-latitude buoy operated by Meghan Cronin (PMEL) as part of an OCO funded OceanSITES flux mooring.

Equatorial Pacific on TAO Moorings:

125°W, 0° - At the start of FY08, the mooring originally deployed at this location was adrift. On October 16th, a new buoy was deployed. This $MAPCO_2$ system has not yet been recovered and the system is still fully operational. The data are still preliminary, but they indicate that this system operated well the entire year. The percent data return (only counting times when both seawater and atmospheric measurements were considered good) is as follows, FY08: 96% and Lifetime: 57%

140°W, 0° - This $MAPCO_2$ system was functional at the start of FY2008. The detector was somewhat noisy, but the data can be cleaned up with post recovery processing of the data. On September 30, 2007, NDBC made an attempt to replace the system during a buoy ride, but due to rough conditions, the replacement system was damaged. On November 20th, the buoy went adrift. While adrift, the system continued to collect atmospheric pCO_2, but the seawater readings were compromised. On May 9, 2008 a new buoy was deployed and the system was fully operational for the remainder of the year. The percent data return (only counting times when both seawater and atmospheric measurements were considered good) is as follows, FY08: 54% and Lifetime: 53%

155°W, 0° - This MBARI-built system lost its battery pack during a vandalism incident in September 2007 thus was not working at the beginning of FY08. The buoy was not serviced until February 2008. Once the system was replaced, the instrumentation worked well until the buoy was recovered in September 2008. Currently the system is collecting atmospheric values, but there is a problem with the equilibrator and the seawater data are not useable. The percent data return (only counting times when both seawater and atmospheric measurements were considered good) is as follows, FY08: 52% and Lifetime: 35%

170°W, 2°S – Moved to 170°W, 2°N in July 2007.

170°W, 2°N - This MBARI-built system was moved to this location from the historic 170°W, 2°S in July 2007 when NDBC was not able to deploy this buoy at 170°W, 2°S. This system was fully operational from the beginning of the fiscal year until August when the system was recovered and redeployed. Currently the system is collecting atmospheric values, but there is a problem with the equilibrator and the seawater data are not useable. The percent data return (only counting times when both seawater and atmospheric measurements were considered good) is as follows, FY08: 90% and Lifetime: 95%

170°W, 0° - This $MAPCO_2$ system was operational the entire year. On November 29^{th}, the calibration gas delivery pressure decreased by 50% which, over the course of the remaining deployment caused the detector to drift. The wells which house the pCO_2 calibration cylinder on this buoy were defective and seawater was able to penetrate inside. The regulator on the calibration gas became corroded and had begun to fail. This system was just returned to the lab, but preliminary data returns suggest that the detector was reading 12 ppm low by the time it was recovered. Once the data are re-processed, it is reasonable to expect that this drift can be corrected. This system was recovered and a new system was deployed on August 20, 2008. This system was fully operational the remainder of the year. The percent data return (only counting times when both seawater and atmospheric measurements were considered good) is as follows, FY08: 100% and Lifetime: 81%

Nutrient and Chlorophyll - Bottle samples were collected and processed by MBARI personnel from the NOAA ship *Ka'imimoana* during the two occupations of the 155°W lines and during the summer occupation of the 170°W line. Approximately 280 chlorophyll and 224 nutrient samples were collected and analyzed. The percent data return is as follows, FY08: 100%.

WHOI designed buoys

MOSEAN at Hawaii Ocean Time-series site (158°W, 22°N) – The MOSEAN buoy was pulled by Tommy Dickey's group at UCSB due to lack of funding in July 2007. A $MAPCO_2$ system was deployed on this buoy for three years. The percent data return is as follows, Lifetime: 88%.

WHOI Hawaii Ocean Time-series Station (WHOTS) (157°W, 22°N) – The WHOTS mooring was co-located with the MOSEAN mooring, so when we found out that MOSEAN was being pulled in 2007 we put a $MAPCO_2$ system on WHOTS to continue the time series. The CO_2 system at this location was operational for all of FY08. The system ceased to transmit daily data in late February, but it continued to run and store data internally. In June, the buoy and $MAPCO_2$ system were recovered and a fresh buoy and $MAPCO_2$ were deployed. The percent data return is as follows, FY08: 100% and Lifetime: 100%.

Bermuda Testbed Mooring (BTM) (64.2°W, 31.7°N) – This mooring was pulled by Tommy Dickey's group at UCSB in early October 2007 due to lack of funding. We are communicating with several investigators that are working hard to re-establish a mooring at this important time series site. We are hopeful that a new mooring will be deployed in FY09 and are prepared to place our CO_2 system on whichever platform becomes available. The percent data return is as follows, Lifetime: 100%.

Stratus (19.7°W, 85.5°N) – The $MAPCO_2$ system was fully operation for the entire fiscal year at this location. In October, the buoy and $MAPCO_2$ system were recovered and a fresh buoy and $MAPCO_2$ were deployed. The percent data return is as follows, FY08: 100% and Lifetime: 100%.

OceanSITES Flux Moorings

Kuroshio Extension Observatory (144.5°E, 32.3°N) – This past year was the first successful deployment at this location. Previous KEO deployments used an ATLAS type buoy and our CO_2 system did not operate properly in that buoy configuration under the high current and wave conditions of the North Pacific. In September 2007, a high latitude mooring replaced the Atlas style mooring at this location. The $MAPCO_2$ system deployed at the KEO site was operational for most of FY08. In mid August 2008 the equilibrator readings became very noisy. In September, the site was serviced and a new buoy and $MAPCO_2$ system were deployed. Recovery of the old system indicated that the equilibrator had become jammed by a piece of debris, but only one month of data were lost. Preliminary data returns from the new system suggest that it is operating well. The percent data return is as follows, FY08: 91%.

Japanese Kuroshio Extension Observatory (146.5°E, 38°N) – In February 2007, when this buoy was first deployed, the KEO system was not operational. We decided to add a $MAPCO_2$ system in an effort to begin the data collection in the region. The $MAPCO_2$ system at this site was operational during the remaining part of FY07. In October of FY08, an attempt was made exchange the $MAPCO_2$ system during a buoy ride. The attempt resulted in a faulty installation of the $MAPCO_2$ system. While we were able to collect atmospheric pCO_2, we were unable to collect seawater pCO_2 data. The PMEL buoy was recovered in the winter and a Japanese buoy was deployed in its place. Since the $MAPCO_2$ was operational at the KEO, a new $MAPCO_2$ was not deployed at JKEO.

2.3. Logistical Considerations and Improvements

The pCO_2 systems are mounted in buoys that are deployed from a ship. Currently all of our deployments are in conjunction with another project that is covering the buoy deployment and maintenance costs and has already allocated ship time. The pCO_2 systems are typically sent out on a cruise and are set up and deployed by a member of the scientific party as an ancillary task. This arrangement requires about 4 hours for setup and then approximately 10 additional man hours during the cruise. To keep expenses down we generally request that someone already involved in the cruise be trained to deploy the systems so we do not have to pay to send our people to sea for every deployment. As we have learned over the past year, this approach requires that the systems be very robust. Although we have had some problems this past year with inexperienced people deploying the systems, we still believe that this is the most efficient approach and are striving to make the deployment procedures as simple and fool-proof as possible.

During FY08, upgrades were made to the MAPCO_2 software giving more control via satellite to the personnel at PMEL. During every deployment, someone from the PMEL CO_2 group is standing by to remotely turn on the system after the buoy is deployed and to ensure that is running properly before the ship leaves the site. In addition to being able to turn the system on and off, several parameters can be changed remotely to optimize data collection.

The majority of the MAPCO_2 system failures are due to the breakdown of the equilibrator portion of the system. The TAO buoys are often the target of fishing and vandalism and on many occasions the equilibrator pipe was found bent when it was serviced. Biofouling continues to be a problem in highly productive areas. To make the MAPCO_2 easier to service on the buoy, we designed and manufactured a quick disconnect that goes in between the electronics package and the airblock/equilibrator assembly. With this quick disconnect, personnel can easily swap out the equilibrator assembly during a buoy ride. We have been searching for a quick disconnect that is both robust enough, yet affordable for the last three years. The quick disconnect assembly is a mix of off the shelf and customized parts. The first quick disconnect was deployed this summer. By next year, we hope to have a quick disconnect at all locations.

In September 2007, the Atlas-style mooring at the KEO site was replaced with a mooring designed by PMEL to withstand the conditions at high latitudes. This is also the first successful year with the MAPCO_2 system at KEO. It is hard to say for certain, but deploying on the more stable platform in this high current, typhoon-laden area may have been the key to successfully collecting data with the MAPCO_2 system.

2.4. Data Processing

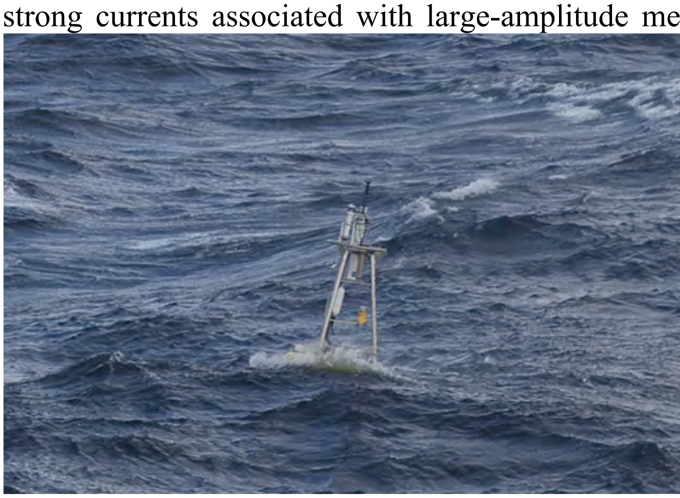
All the PMEL summary files are processed and graphed on a website that is updated daily <http://www.pmel.noaa.gov/co2/moorings/>. The data are currently stored at PMEL and are available from Christopher Sabine at PMEL. The MBARI data are available from Francisco Chavez at MBARI. The carbon data management and synthesis teams are in the process of integrating the moored pCO_2 data together with the underway pCO_2 data from a related OCO project. Ultimately all of the surface CO_2 data will feed into the seasonal CO_2 flux map effort that is currently under development.

All systems are thoroughly tested and calibrated over a range of CO_2 concentrations using WMO traceable standard gases in the laboratory before deployment. The systems are then calibrated with a zero and WMO traceable span gas at the beginning of every three hour measurement cycle during the deployment. We have developed a system for processing the moored pCO_2 data that is collected utilizing automated quality control procedures. Based on the calibration, atmosphere, and seawater information as well as other diagnostic measurements for each identified point relative to the surrounding points, the data point may be flagged as questionable or bad. Typically less than 1% of the data are flagged as questionable or bad. To finalize a dataset, the data are compared to any underway pCO_2 data that are available as well as the Marine Boundary Layer (MBL) atmospheric CO_2 concentrations for a given buoy location as provided by NOAA's GLOBALVIEW-CO_2 network. Based on these comparisons and various diagnostics of the automated system calibration information, the entire data set (air and water values) may be adjusted to match these higher accuracy measurements. Typically these adjustments are less than a couple of parts per million. The data are then merged with sea-surface temperature and salinity data collected by other groups on the same buoy. As all data become available, final calibrated data are archived at the Carbon Dioxide Information Analysis Center (CDIAC) and the National Oceanographic Data Center (NODC) on a yearly basis. During the field season it is difficult to keep up with the data processing, but now that the season has ended we are on target to have all the data through March 2008 finalized and submitted to CDIAC for public release by February 2009. We anticipate being able to maintain the one year final data release from the date of recovery for the foreseeable future.

2.5. Analysis and Research Highlights

The highlight of this past fiscal year was the successful collection of the first full year of CO_2 data from the Kuroshio Extension Observatory (KEO). Excess heat received in the tropics is carried poleward by strong western boundary currents—the Gulf Stream in the North Atlantic, and the Kuroshio in the North Pacific. In particular, the Kuroshio Extension carries warm water at a rate of nearly 140 million cubic meters per second (140 Sv) into the North Pacific. As cold dry air of continental origin comes in contact with this warm water, heat and moisture are extracted from the surface, resulting in deep convection and rainfall. This excess heat from the tropics is then carried further poleward in the atmosphere through the action of storms, thereby maintaining a global balance of heat. The regions of intense air-sea heat fluxes in the Gulf Stream and Kuroshio Extension are also characterized by intense uptake of CO_2, while regions of strong upwelling, such as in the eastern equatorial Pacific, are characterized by CO_2 outgassing. Without the oceans to absorb significant amounts of the CO_2 released from human activity, the climate change would be much more pronounced. Thus air-sea heat and carbon dioxide flux measurements, particularly within western boundary current regions, are a critical element of the global earth observing system of systems (GEOSS).

The challenges of mooring a surface buoy in a western boundary current regime are considerable. Water depth in the Kuroshio Extension (KE) region is nearly 6000 m. In the core of the KE jet, current speeds can exceed 3 knots at the surface and 0.5 knots in the bottom 3000 m, placing significant strain on the mooring. Typhoons and winter storms can generate damaging winds and waves. Additionally, surface buoys can be vulnerable to shipping traffic and fishing vandalism. To survive the strong currents associated with large-amplitude meanders in the KE jet, PMEL leveraged the design experience gained from equatorial Tropical Atmosphere and Ocean (TAO) moorings and Deep ocean Assessment and Reporting of Tsunami (DART) moorings, making changes specific to the KE conditions. The buoy used for the first few KEO deployments was based on the tropical ATLAS design. While this design generally worked for the meteorology instruments during normal conditions, the buoy did not appear to have sufficient flotation and stability for the CO_2 systems to operate properly and was clearly not stable under extreme conditions (see picture to left). Thus, in FY08 the KEO ATLAS buoy was replaced with a larger PMEL high latitude buoy design. With the new, more



stable buoy, the $MAPCO_2$ system was able to function properly and we were able to get a first high resolution assessment of the CO_2 concentrations in the Kuroshio Extension.

Figure 2 shows the FY08 seasonal cycle of CO_2 and temperature at KEO. Surface water CO_2 values are below atmospheric for all but one month out of the year making this area a significant sink for atmospheric CO_2. The drop in surface water CO_2 during the winter months is primarily driven by the drop in sea surface temperature. In the spring, however, biological productivity continues to keep the CO_2 values low even as sea surface temperature begins to rise. The seasonal range in surface water CO_2 is approximately 100-120 ppm.

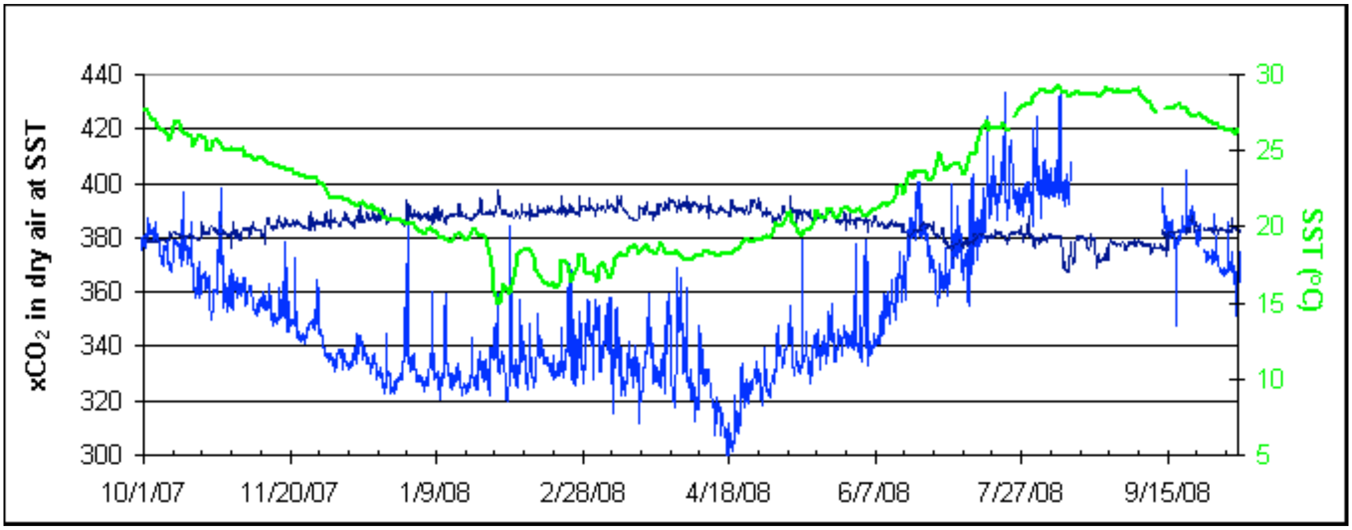


Figure 2. Time series plot of surface water CO_2 mole fraction (light blue), atmospheric CO_2 mole fraction (dark blue), and sea surface temperature (green) for FY08 (146.5°E, 38°N) on the northwestern edge of the North Pacific subtropical gyre.

In contrast to the northwestern North Pacific, the seasonal range at the Hawaii Ocean Time series site in the southeastern North Pacific is only 50-60 ppm and is a much smaller net sink for atmospheric CO_2 (Figure 3). The smaller seasonal cycle partially results from a smaller temperature range, but Hawaii also does not have a strong spring phytoplankton bloom to maintain the low seawater CO_2 concentrations. The minimum CO_2 values off Hawaii occur in January to February while at KEO the minimum occurs about three months later.

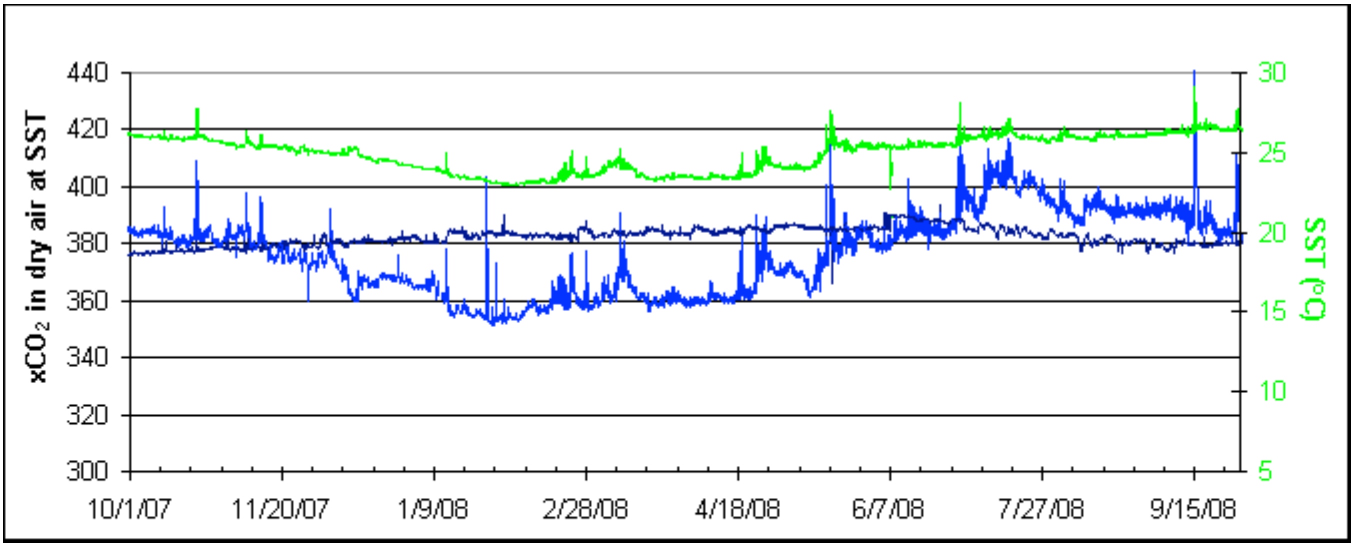


Figure 3. Time series plot of surface water CO_2 mole fraction (light blue), atmospheric CO_2 mole fraction (dark blue), and sea surface temperature (green) for FY08 at the Hawaii Ocean Time-series site (157°W, 22°N) in the south eastern edge of the subtropical North Pacific gyre.

Of course the value of time series observations grows as the data sets become longer. The moored time-series program in the equatorial Pacific is among the longest in the world. These data have been able to directly document the increase in surface water CO_2 over time (see figure 4).

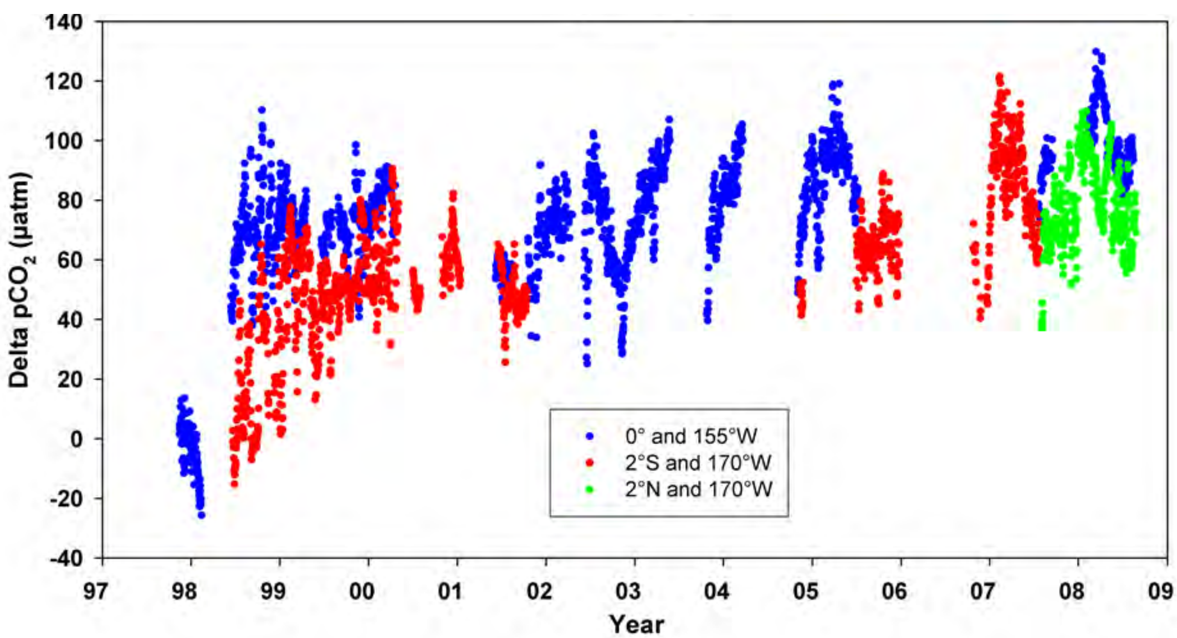


Figure 4. Daily average sea-air pCO_2 observations on the equator at 155°W, 2°S, 170°W and 2°N, 170°W from 1997 to present. An increase in pCO_2 cover the course of the record can be seen.

The time series of mooring based pCO_2 measurements in the equatorial Pacific have also been enhanced by the collection and analysis of discrete chlorophyll and nutrient samples in the upper 200 meters. About 500 samples per year have been processed from these cruises since 1997. Time series of the averaged nitrate and chlorophyll data along 155°W are shown in Figure 5. Although these data do not show the secular increases that are observed in CO_2, they do show inter-annual variations that correlate well with CO_2 variability. These changes are primarily associated with changes in upwelling strength.

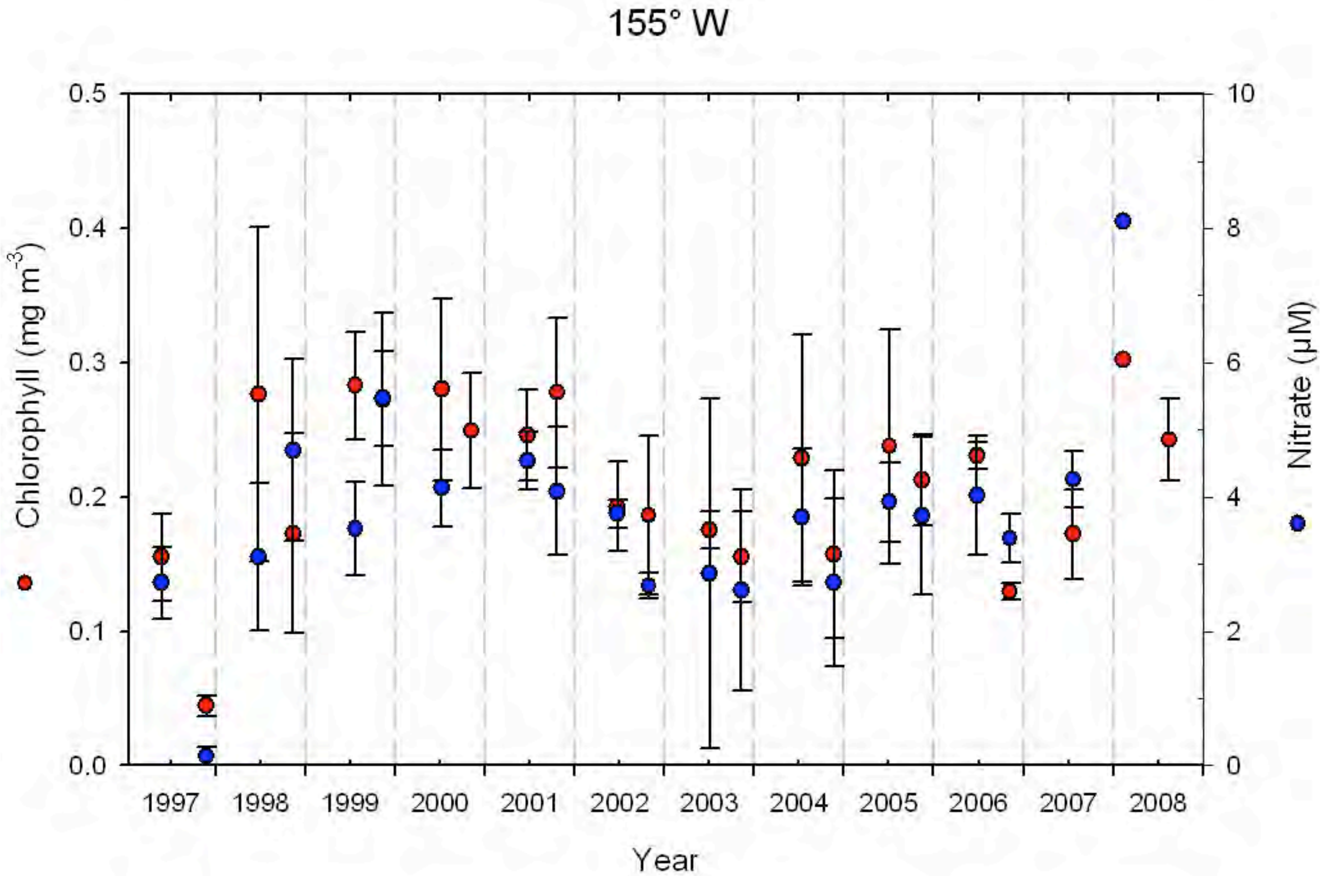


Figure 5. Average sea surface chlorophyll and nitrate levels along 155°W during the spring and autumn cruises from 1997 until 2008. The close correlation between chlorophyll and nitrate is evident.

2.6. Relevant FY08 Publications Resulting From This Project

Chavez, F.P., T. Takahashi, W.-J. Cai, G. Friederich, B. Hales, R. Wanninkhof, and R.A. Feely, 2007: Coastal Oceans. In: *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research[King, A.W., L. Dilling, G.P. Zimmerman, D.M. Fairman, R.A. Houghton, G. Marland, A.Z. Rose, and T.J. Wilbanks (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, pp. 157-166.

Cronin, M.F., C. Meinig, C.L. Sabine, H. Ichikawa, and H. Tomita, 2008: Surface mooring network in the Kuroshio Extension. IEEE Systems Special Issue on GEOSS, 2(3), 424–430.

Friederich, G.E., J. Ledesma, O. Ulloa and F.P. Chavez, 2008: Air-Sea carbon dioxide fluxes in the coastal southeastern tropical Pacific. *Progress in Oceanography*, in press.

Kamphaus, R., M. Cronin, C. Sabine, S. Emerson, C. Meinig, and M. Robert, 2008: New surface mooring at Station Papa monitors climate. PICES Press, 16(2), 26–27.

Pennington, J.T., Castro, C.G., Collins, C.A., Evans, W.W. IV, Friederich, G.E., Michisaki, R.P., Chavez, F.P., 2008: A carbon budget for the northern and central California coastal upwelling system. Continental Margins Task Team, The Synthesis Book. Chapter 2.2, California Current System, in press.

Sabine, C.L., R.A. Feely, and R. Wanninkhof, 2008: The global ocean carbon cycle. In *State of the Climate in 2007*, D. H. Levinson and J. H. Lawrimore (eds.). *Bull. Am. Meteorol. Soc.*, 89(7), S52–S56.

Strutton, P. G., W. Evans, and F. P. Chavez, 2008: Equatorial Pacific chemical and biological variability, 1997–2003, *Global Biogeochem.Cycles*, 22, GB2001, doi:10.1029/2007GB003045.

Takahashi, T., S.C. Sutherland, R. Wanninkhof, C. Sweeney, R.A. Feely, D.W. Chipman, B. Hales, G. Friederich, F. Chavez, A. Watson, D.C.E. Bakker, U. Schuster, N. Metzl, H. Yoshikawa-Inoue, M. Ishii, T. Midorikawa, C. Sabine, M. Hopemma, J. Olafsson, T.S. Arnarson, B. Tilbrook, T. Johannessen, A. Olsen, R. Bellerby, H.J.W. de Baar, Y. Nojiri, C.S. Wong, and B. Delille, 2008: Climatological mean and decadal change in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. *Deep-Sea Res.*, in press.

Vandemark, D., R. K. Varner, P. Beckman, J. Salisbury, R. Talbot, V. R. Sawyer, W. R. McGillis, and C. L. Sabine, 2008: Atmospheric CO_2 in the coastal marine boundary layer: observations and implications. *Mar. Chem.*, submitted.

8. Arctic Ocean Obs System

a. Arctic Sea Ice Thickness Observations

b. Rusalca: The Pacific Gateway to the Arctic Quantifying and Understanding Bering Strait Oceanic Fluxes

- Cruise Report For Bering Strait Mooring Project 2008, RUSALCA 2008 Russian Vessel Lavrentiev - *Nome, 1st October 2008 – Nome, 10th October 2008*

Arctic Sea Ice Thickness Observations

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1. GOAL

To continue and expand the critical network of observations aimed at monitoring and understanding changes in the thickness and mass balance of the Arctic sea ice cover to a) improve the fundamental understanding of the role of the sea ice cover in the global climate system and b) explore the sensitivity of the sea ice cover as an indicator and potential amplifier of climate change.

2. OBJECTIVE

To achieve these goals the primary activities of this ongoing program are to: (a) establish and maintain a large-scale sea ice mass balance observing system, (b) provide near real time access to the data, (c) integrate the ice observations with atmosphere and ocean measurements, and (d) analyze the data to improve the understanding of changes in the mass balance of the Arctic sea ice cover.

3. APPROACH

Understanding the ongoing changes in the Arctic sea ice cover requires a system approach, integrating ocean, ice, and atmosphere studies. We look to continue our efforts to observe and attribute changes in the mass balance of the sea ice cover. This project is designed to be an integral part of the Arctic Observing Network (AON), acting in coordination with other ongoing efforts that have extensive oceanographic and atmospheric components. These collaborating programs currently include the North Pole Environmental Observatory (NPEO), Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies (DAMCOLES), the Beaufort Gyre Observing System (BGOS), and the Seasonal Ice Zone Network (SIZONET). The overarching goal of this work is to enhance these and other similar programs by exploring what ice thickness changes are occurring and how these changes occur.

The sea ice thickness observing system consists of an array of drifting ice mass balance buoys (IMBs) and a sea floor mounted ice profiling sonar (IPS). The IMB is an autonomous, ice-based system (Richter-Menge et al., 2006). Data from the IMB provide a time series of snow accumulation and ablation, ice growth, ice surface and bottom melt, internal ice temperature fields, and temporally-averaged estimates of ocean heat flux. Taken together these data delineate whether there has been a change in the mass balance of the ice due to ice growth, surface melt, bottom ablation, or snow accumulation. The important capability of the IMB to gain insight on the driving forces behind the change cannot be duplicated by any other in situ or remote autonomous measurement system currently available. The IMB buoys are also equipped to measure position, sea level pressure (SLP), and surface air temperature (SAT). Data on SLP and SAT are designed to be compatible with similar data collected from the more basic drifting buoys deployed under the International Arctic Buoy Program (IABP). The IMBs are deployed in coordination with other programs. This approach helps reduce the logistics costs and, more importantly, facilitates the co-location of complementary instrument packages designed to measure oceanic and atmospheric conditions.

The IPS provides a direct measurement of the ice draft and, assuming isostatic equilibrium, an indirect estimate of total ice thickness (Melling et al, 2005; Melling and Riedel, 1996). Following the guidance from a state-of-the-art sea ice dynamics model (Lindsay and Zhang, 2006), the moored IPS site was established in August 2003 on the Chukchi Plateau at 75°06.0' N, 168° 00.0' W. This site has been designated CH01. Instruments presently on the mooring have sufficient battery and data storage capacity to operate for two years. In 2006, the single release (2-year rating) was replaced with a tandem release assembly with 3-4 year endurance. Support for the servicing of the CH01 mooring site and analysis of the data are provided by RUSALCA.

Data collected from the IMBs and IPS are made widely available via the web site:
http://imb.crrel.usace.army.mil/.

4. PROGRESS

NOAA began its support of the ice thickness observing system in 2003. Since then and in collaboration with other programs, a total of 38 IMBs have been deployed in the Arctic Ocean. The IMBs provide a means to observe changes in the sea ice mass balance. These observations can then be integrated with other data to understand the changes in sea ice. For instance Perovich et al. (2008) combined the IMB data with model results and satellite observations to explain a dramatic increase in bottom melting in the Beaufort sector in 2007, which was more than six times the annual average value for the 1990s (Figure 1). Perovich et al. determined that an increase in open water fraction triggered a 500% positive anomaly in solar heat to the upper ocean providing the primary source of heat for the observed bottom ablation. This case exemplifies the ability of IMB results to attribute observed changes and to enhance our understanding of those changes.

The IMB data are being used by the remote sensing community for the development and evaluation of algorithms and to interpret satellite observations. IMB ice temperature data have been used to evaluate and improve QuikSCAT retrievals of the onset of melt in spring and freezeup in fall (Nghiem et al., 2007). IMB snow depth and ice thickness observations have been used to demonstrate that ICESat freeboard retrievals are within 10 cm of IMB surface-based measurements (Kwok et al., 2007). IMB results can continue to give baseline data to support the development of sensors and algorithms to remotely sense snow depth, ice thickness, and the onset of melt and freezeup. The IMB results can also be used to understand remotely observed changes in ice thickness. For example, semiannual airborne and satellite surveys of ice thickness can measure seasonal and interannual changes in ice thickness. Surface based IMB observations can attribute those changes to ice growth, surface melt, or bottom melt (e.g. Haas, 2008; Giles et al., 2008).

As currently designed, the IMB is limited to deployment in thick, multiyear ice. We have begun work on a new version of the IMB that can be deployed in thinner seasonal ice. A fundamental change is to go from a unit that uses a main housing and instruments attached via umbilical to a single hull design. This version would be easier to install, requiring only 1 drill hole and would have no exposed wires. Additionally, the new version IMB would be neutrally buoyant, facilitating its deployment in thinner ice conditions.

The CH01 mooring site has been recovered and redeployed four times, in 2004, 2005, 2007 and 2008. Ice conditions prevented it's recovery in 2006, however a second mooring was deployed in 2006 to avoid a lapse in the data set. Data from the first two cycles has been analyzed in preparation for posting on the web site.

The web site has been developed to provide a near real time reporting capability for IMBs that are actively transmitting data. These data are posted with a cautionary note indicating that they are provisional. Once an IMB stops transmitting, the data are thoroughly reviewed, archived, and posted on the web site. Data will also be submitted to the Cooperative Arctic Data and Information Service (CADIS) archive, consistent with the protocol of the Arctic Observing Network.

5. REFERENCES

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Haas, C., A. Pfaffling, S. Hendricks, L. Rabenstein, J.-L. Etienne, and I. Rigor, 2008: Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat, *Geophys. Res. Lett.*, 35, L17501, doi:10.1029/2008GL034457.

Kwok, R., G. F. Cunningham, H. J. Zwally, and D. Yi, 2007: Ice, Cloud, and land Elevation Satellite (ICESat) over Arctic sea ice: Retrieval of freeboard, *J. Geophys. Res.*, 112, C12013, doi:10.1029/2006JC003978.

Lindsay, R. W. and J. Zhang, 2006: Arctic Ocean ice thickness: modes of variability and the best locations from which to monitor them, *J. Physical Ocean,* 36: 496-506.

Melling H., D. A. Riedel and Z. Gedalof, 2005: Trends in the draft and extent of seasonal pack ice, Canadian Beaufort Sea, *Geophys. Res. Lett*., 32, L24501, doi:10.1029/2005GL024483.

Melling, H. and D.A. Riedel, 1996: Development of seasonal pack ice in the Beaufort Sea during the winter of 1991-1992: A view from below. *Journal of Geophysical Research,* 101(C5), 11975-11991.

Nghiem, S.V, I.G. Rigor, D.K. Perovich, P. Clemente-Colon, J.W. Weatherly and G. Neumann, 2007: Rapid reduction of Arctic perennial sea ice, *Geophys. Res. Lett.,* 34*,* L19504, doi:10.1029/2007GL031138.

Perovich, D. K., J. A. Richter-Menge, K. F. Jones, and B. Light, 2008: Sunlight, water, and ice: Extreme Arctic sea ice melt during the summer of 2007, *Geophys. Res. Lett*., 35, L11501, doi:10.1029/2008GL034007.

Richter-Menge, J.A, D.K. Perovich, B.C. Elder, K. Claffey, I. Rigor and M. Ortmeyer, 2006: Ice Mass Balance Buoys: A tool for measuring and attributing changes in the thickness of the Arctic sea ice cover, *Ann. Glaciol.*, 44: 205- 210*.*

6. FIGURES

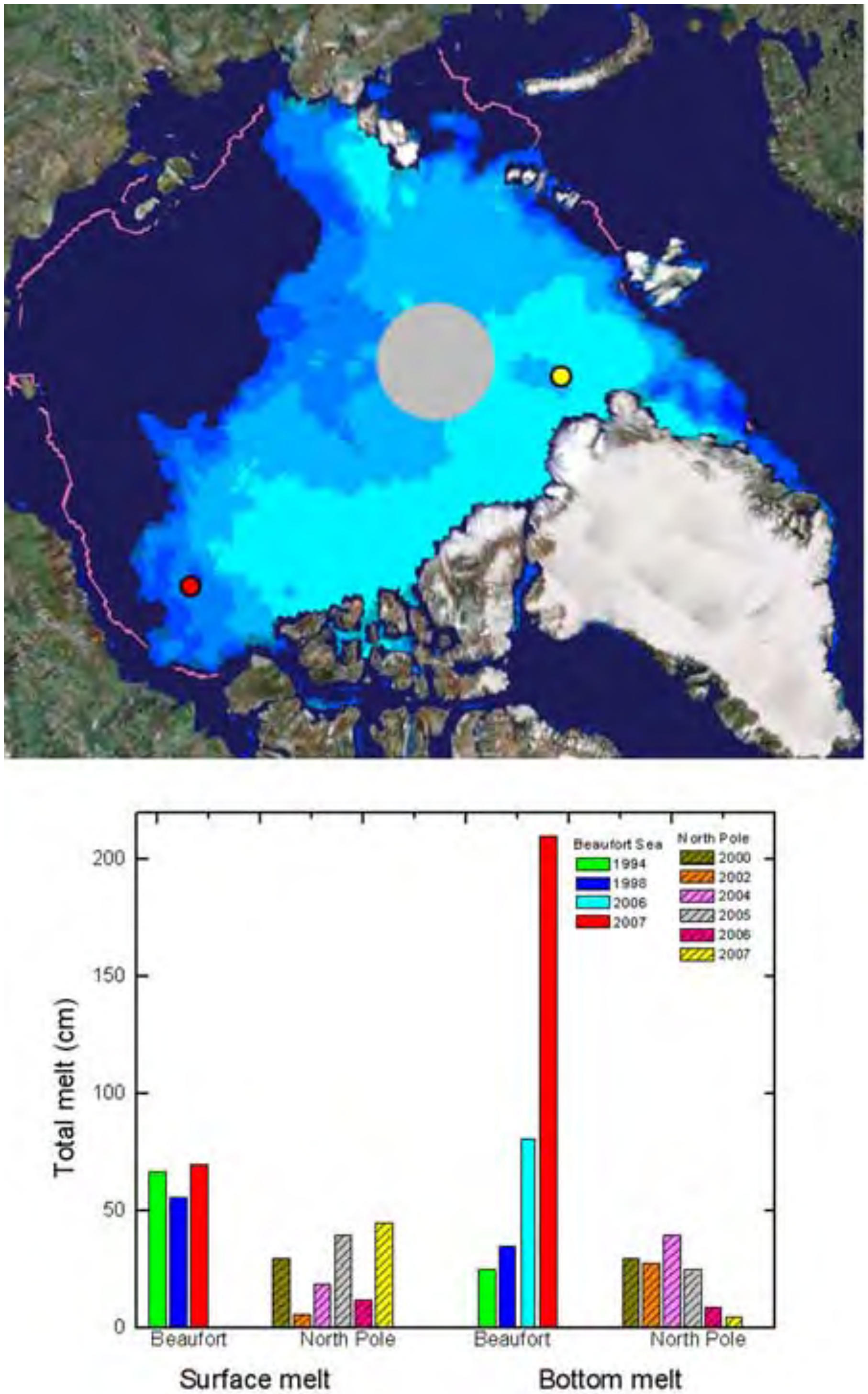

Figure 1. (top) The ice extent on 27 August 2007 courtesy of the National Snow and Ice Data Center and Google maps. The shades of blue show the percent area covered by ice from 0% (dark) to 80–100% (light). The red dot is the position of the Beaufort Sea buoy, and the yellow dot is the position of the North Pole buoy. (bottom) Observations of total surface and bottom melting in different years in the Beaufort Sea and North Pole regions (from Perovich et al, 2008).

Rusalca: The Pacific Gateway to the Arctic
Quantifying and Understanding Bering Strait Oceanic Fluxes

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1. PROJECT SUMMARY

The Bering Strait, a narrow (~ 85 km wide), shallow (~ 50 m deep) strait at the northern end of the Pacific, is the only ocean gateway between the Pacific and the Arctic. Although the flow through the strait is small in volume (~ 0.8 Sv northward in the annual mean), due to its remarkable properties (high heat and freshwater content, low density, high nutrients) it has a startling strong influence, not only on the Chukchi Sea and the Arctic Ocean, but also on the North Atlantic overturning circulation and possibly world climate. Draining the Bering Sea shelf to the south, the Bering Strait throughflow is an integrated measure of Bering Sea change. The comparatively warm, fresh throughflow contributes ~ 1/3rd of the freshwater input and possibly ~ 1/5th of the oceanic heat input to the Arctic, and provides the most nutrient-rich waters entering the Arctic Ocean. Furthermore, the low density of these waters keeps them high in the Arctic water column, giving them a key role in upper ocean ecosystems and physical processes including ice-ocean interactions. At the time when dramatic change, especially the retreat of sea-ice, is observed in the Bering and Chukchi seas and the Arctic, we measured significant increases of Bering Strait fluxes of volume, freshwater and heat, the heat flux in 2004 being the maximum recorded in the last 15 years up to 2004 [Woodgate et al., 2006].

Yet, our understanding of what sets the properties and variability of the Bering Strait throughflow is still rudimentary. Indeed, our ability to measure these fluxes accurately has, in the past, been constrained by lack of data, both from the most nutrient-rich western half of the strait (which lies in Russian waters), and from the upper water column (due to potential ice-keel damage to instrumentation), where stratification and coastal boundary currents (especially the Alaskan Coastal Current in the eastern channel) contribute significantly to freshwater and heat fluxes.

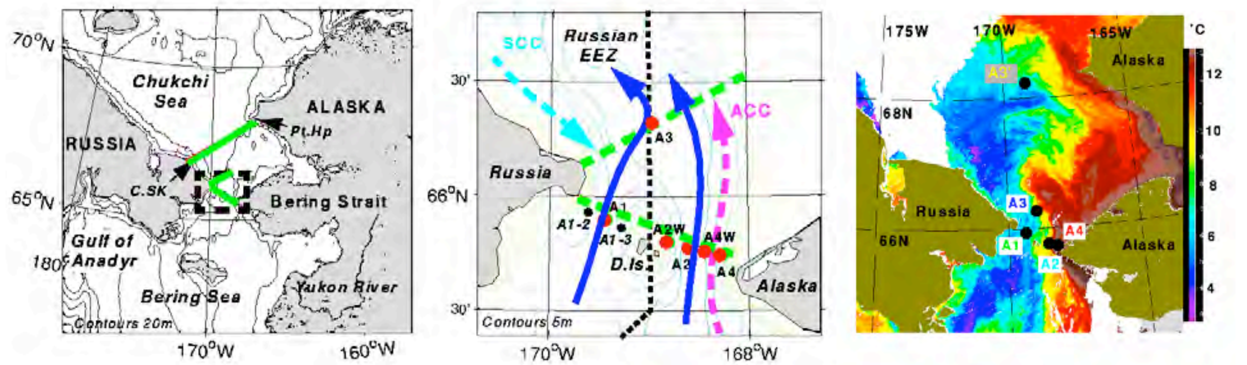

Figure 1. Left: The Bering Strait region, with proposed CTD lines (green). **Middle:** Detail of the Bering Strait, with schematic flows, proposed mooring locations (red dots=this proposal; black dots=collaborative Russian sites) and CTD lines (green). The main northward flow through the strait passes through both channels (dark blue arrows). Topography diverts the western channel flow eastward near site A3. The warm, fresh Alaskan Coastal Current (ACC) (pink dotted arrow) is present seasonally in the east. The cold, fresh Siberian Coastal Current (SCC) (light blue dotted arrow) is present in some years seasonally in the west, on occasion reaching the strait. All these currents may reverse on timescales of days to weeks. **Right:** MODIS sea surface temperature image from 26th August 2004, with historic mooring locations (A1, A2, A3, A3' and A4), occupied variously since 1990. C.SK=Cape Serdtse Kamen. Pt.Hp=Point Hope. D.Is.=Diomede Islands. Black dotted line = EEZ (Exclusive Economic Zone).

This joint NOAA-NSF project (part of the NOAA RUSALCA – Russian US Long Term Census of the Arctic – project) addresses these deficiencies, by providing (in collaboration with Russian, Canadian and Japanese colleagues), an observationally focused study of the entire Bering Strait region, consisting of a high resolution mooring array, deployed from 2007-2010, covering the two channels of the strait and one "climate" site to the north of the strait, supported by annual CTD surveys and mooring servicing, satellite data, and theoretical and modeling results.

In August/Sept 2007, a joint US (UW and UAF) and Russian mooring team deployed the first 8-mooring, high resolution array in the Bering Strait from the Russian vessel Sever [Woodgate et al., 2008a]. Three moorings were deployed across the western (Russian) channel of the strait. Four moorings were deployed across the eastern (US) channel of the strait. A final 8^{th} mooring was deployed ~ 30 nm north of the strait at a "climate site" occupied since 1990 and hypothesized to be a useful average of the flow through the strait. The 8 sites are a combination of 3 sites established in the 1990s, 3 sites established since 2001/2004 and 2 new sites. Together they give the highest resolution to date in the Bering Strait. These moorings included 6 upward looking ADCP (Acoustic Doppler Current Profilers) to measure water velocity in ~ 2 m bins to the surface, and upper-layer temperature salinity sensors in ice-resistant housings (ISCATs). These are the first long-term moored upper-layer measurements made in the strait. Also, during the cruise, one high resolution CTD section was taken across both channels of the strait, to give a spatial setting for the mooring data.

In Oct 2008, a joint US (UW and UAF) and Russian mooring team recovered and redeployed these moorings from the Russian vessel Lavrentiev [Woodgate et al., 2008b]. The mooring operations were successful, despite extreme biofouling especially on the western of the eastern channel. The lateness of the cruise (Oct rather than Aug) was dictated by changes in the ship schedule. We lost 3 days of ship time to bad weather, and returned to port early due to forecasts of extreme icing conditions. This reduction in operational time meant no high resolution CTD section was completed this year. Preliminary finds are discussed below.

The moorings deployed in Oct 2008 are due to be recovered in August 2009. Since all moorings are subsurface (due to ice), data cannot be transferred to satellites during the mooring deployment.

Metadata for all the Bering Strait moorings have been deposited at CADIS (Cooperative Arctic Data and Information System). All calibrated mooring data have been archived at the National Ocean Data Center, are available via our website (http://psc.apl.washington.edu/BeringStrait.html) and are cross linked with CADIS. Voluntary registration at our data website, (averaging 30-50 registrations a month), indicates the data are in demand for studies ranging from climate modeling to King Crab fishing, and our major publications since 2005 have, to date, over 100 citations.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner, 2006: Interannual changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004, *Geophys. Res. Lett.*, 33, L15609, doi:10.1029/2006GL026931.

Woodgate, R. A., 2008a: Mooring Cruise report for RUSALCA Sever cruise to the Bering Strait - Aug/Sept 2007, 17 pp, University of Washington.

Woodgate, R. A., 2008b: Mooring Cruise report for RUSALCA Lavrentiev to the Bering Strait, October 2008, 24pp pp, University of Washington.

available at http://psc.apl.washington.edu/BeringStrait.html.

2. ACCOMPLISHMENTS

At the time of writing, we are engaged in shipping for the August 2009 mooring recovery and deployment cruise, which is entirely NOAA funded.

We report here also on results from the previous 2007-2008 data, recovered in October 2008, which was funded by NSF with ship-support from NOAA. Preliminary results are:

1) Calendar year 2007 has the highest heat flux recorded since mooring records began, and volume and freshwater fluxes match previous maximum values.

Figure 2a shows calendar year means for northward velocity (Vp), temperature (T), salinity (S), Transport (Trans), Heat flux relative to -1.9 deg C (Heat) and freshwater flux relative to 34.8 psu (FW). Colors represent estimates from different moorings. Dark blue is the best estimate for the entire strait, based on mooring A3, the "climate" site just north of the strait. Cyan is the estimate for the eastern channel of the strait based on mooring A2 in the central eastern channel (dark grey is the estimate from A2 for the entire strait). Red shows results from mooring A4 in the Alaskan Coastal Current. Dotted lines indicated estimated uncertainties. All these calculations are based only on near-bottom data, and thus neglect the effects of stratification and contributions to the heat and freshwater fluxes from the ACC. These effects may add 1-2x 10^20 J/yr and 800-1000km3/yr respectively.

These simple calculations suggest that the Bering Strait throughflow in 2007 was around 1 Sv, on a par with previous years of high flow. A slight increase in mean temperature, combined with this high flow, yields the highest heat fluxes yet recorded, ~ 3.5 x 10^20 J/yr, an increase of 0.5-1 x 10^20 J/yr over previous years' measurements. For scale, note that 1 x 10^20 J/yr is enough to melt an area of ~ 300,000 km2 (e.g., 550 km by 550 km) of 1 m thick ice. These estimates are important for the debate about causes of the remarkable 2007 sea-ice retreat.

Results also suggest an increase in freshwater flux to match the previous high value in 2004. This increase is due to the increase in flux, which offsets a slight increase in salinity. The impacts of this increased freshwater flux on the Arctic and beyond are a subject of research.

Both freshwater and heat flux calculations need to be revised in light of the upper layer temperature and salinity data obtained for the first time during these mooring deployments.

2) We have the first ever moored estimate of year-round stratification in the Bering Strait.

- Figure 2b shows preliminary results from the upper-layer ISCAT system on mooring A4 in the Alaskan Coastal current for the first 200 days of the deployment (Sept 2007 to ~ March 2008). Magenta indicates data from the ISCAT deployed at ~ 15m. Black indicates data from the conventional Seabird temperature-salinity sensor at ~ 42 m depth. The top panel shows the depth of the instruments. Strong currents in early winter pull the ISCAT down to ~ 30 m. The bottom two panels show temperature and salinity data from both instruments. The upper layer is warmer and significantly fresher for some months in late summer – the difference in salinity is at times is sizeable, about 4 psu. By January most of the stratification in the water column has gone. The next step is to quantify the contribution of this stratification to the estimates of fluxes for the entire strait.

- Risk of damage from sea ice in the strait has prevented deployment of instruments in the upper layer in previous years. The ISCATs telemeter their data down to a logger at a safe depth, incase the temperature-salinity sensor is itself lost during the deployment. Of the 6 ISCATs deployed in the strait in 2007, only 1 ISCAT upper sensor survived the entire year, the other ISCAT upper sensors were lost at various times in early spring, likely relating to the break-up of ice. Yet, up to the time of loss, the telemeter system worked well and we have recovered the valuable data from the ISCATs up to the time of loss. For 2008, the ISCATs have been deployed uniformly ~ 2 m deeper, in an attempt to mitigate loss, but, the necessity of recording the upper layers means the instruments have to be placed in the ice-risk zone. Note that since the moorings are deployed in the summer, even if instruments are lost in the spring break-up of ice, before that loss they will record what is likely the time of greatest stratification in the strait, i.e., summer through to winter. The ADCP velocity data will also be used to assess stratification, by consideration of velocity shear. This information, combined with ISCAT data, will be used to quantify the importance and estimate the most cost-effective method of monitoring the upper layers.

3) Prior to the recovery of these moorings, older Bering Strait data has been used to assist two efforts to estimate the Bering Strait heat fluxes.

- In collaboration with Jinlun Zhang of UW [Zhang et al., submitted], we considered the role of Pacific water in the dramatic retreat of Arctic Sea ice in 2007. This was primarily a model based study, with model estimates of Bering Strait fluxes compared to mooring estimates. Once verified, the model can then be used to estimate terms not measured by observational data. By tracking model terms, the work concludes that the Pacific water plays a role in ice melting in the Chukchi and Beaufort region all summer long in 2007, likely contributing to up to 0.5 m per month additional ice melting in some area of that region.

- A complementary approach is to use satellite/atmospheric data and statistical relationships based on prior data. In collaboration with Kohei Mizobata of IARC [Mizobata et al., submitted], we considered such an effort, using wind and satellite sea surface height data to estimate the flow and satellite sea surface temperature and an empirical fit to CTD data to estimate vertical temperature structure, combining the two results to estimate heat flux. It will be interesting to compare this approach to the recovered mooring data, which will give information on how the vertical structure of the water column varies through the year.

Zhang, J., M. Steele, and R. Woodgate: The role of Pacific water in the dramatic retreat of arctic sea ice during summer 2007, *Journal of Polar Science*, submitted.

Mizobata, K., K. Shimada, R. Woodgate, S.-I. Saitoh, and J. Wang: Estimation of heat flux through the eastern Bering Strait, *Journal of Oceanography*, submitted.

Figure 2a

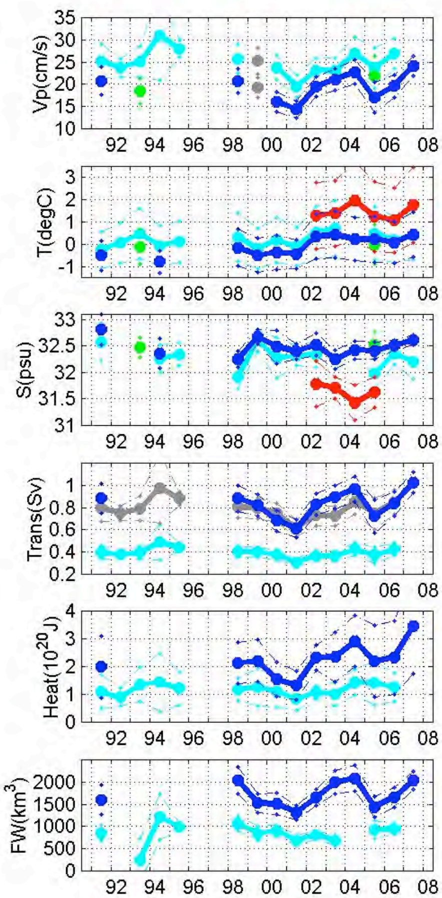

Figure 2b

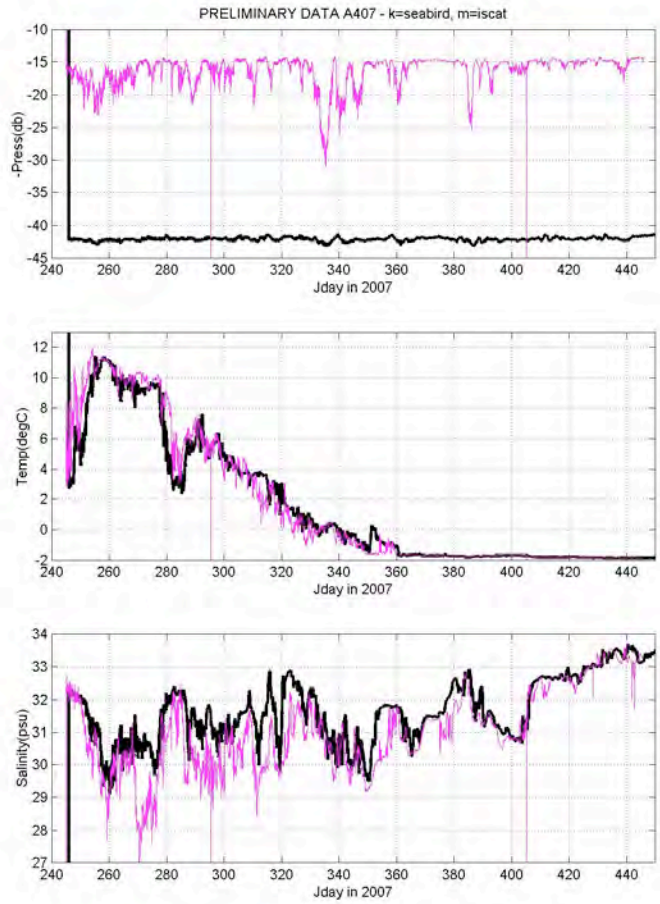

Figure 2a. shows calendar year means for northward velocity (Vp), temperature (T), salinity (S), Transport (Trans), Heat flux relative to -1.9 deg C (Heat) and freshwater flux relative to 34.8 psu (FW). Colors represent estimates from different moorings. Dark blue is the best estimate for the entire strait, based on mooring A3, the "climate" site north of the strait. Cyan is the estimate for the eastern channel of the strait based on mooring A2 in the central eastern channel (dark grey is the estimate from A2 for the entire strait). Red shows results from mooring A4 in the Alaskan Coastal Current. Dotted lines indicated estimated uncertainties. All these calculations are based only on near-bottom data, and thus neglect the effects of stratification and contributions to the heat and freshwater fluxes from the ACC. These effects may add 1-2x 10^20 J/yr and 800-1000km3/yr respectively. These simple calculations suggest that the Bering Strait throughflow in 2007 was around 1 Sv, on a par with previous years of high flow. A slight increase in mean temperature, combined with this high flow, yields the highest heat fluxes yet recorded, ~ 3.5 x 10^20 J/yr, an increase of 0.5-1 x 10^20 J/yr over previous years' measurements. For scale, note that 1 x 10^20 J/yr is enough to melt an area of ~ 300,000 km2 (e.g., 550 km by 550 km) of 1 m thick ice. These estimates are important for the debate about causes of the remarkable 2007 sea-ice retreat.

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3. TRAINING AND DEVELOPMENT

By providing input to University of Washington student classes, this project aids in the training and development of new oceanographers (see Outreach section). Furthermore, the 2008 fieldwork gave an opportunity for on-the-job technical training of a UW technician, Wendy Ermold, previously unfamiliar with mooring work, and UAF students.

4. OUTREACH ACTIVITIES

Our website - http://psc.apl.washington.edu/BeringStrait.html – gives an overview of Bering Strait activities. Our outreach activities on this project are three-fold:

1) To the Science Community – our website includes data access, and links to journal publications. We also present results at national and international conferences. Woodgate was an invited speaker at a retreat considering the 2007 Arctic sea-ice retreat. Information on the Bering Strait throughflow is in popular demand for other Arctic and international projects, including biological studies, model intercomparisons, the ASOF (Arctic SubArctic Ocean Fluxes) studies, freshwater and heat budgets studies. The work is part of the Arctic Observing Network, and contributes to International Polar Year projects Bering Strait, IAOOS (International Arctic Ocean Observing System), and C3O (Canada's three oceans).

2) To students – results of this project are part of an interdisciplinary course "The Changing Arctic Ocean" taught by Woodgate and Deming at the University of Washington School of Oceanography.

3) To the general public – the importance of the Pacific input to the Arctic is one message brought to the public via various outreach activities, including the Polar Science Weekend, held in spring each year at the Pacific Science Center, Seattle's major science museum. This 4-day event (with 2 days focused on school visits) drew over 10,000 visitors in 2007. Woodgate also gave a very well received evening public lecture in February 2008 on the Changing Arctic Ocean as part of the University of Washington's Alumni "Arctic Adventure" series.
Woodgate is an active member of the Arctic Icebreaker Coordination Committee, the WCRP Arctic Climate Panel of the CliC (Climate and Cryosphere) program, and is on the advisory board for the University of Washington's Program on Climate Change and the International Science Steering Committee for the ASOF (Arctic Sub-arctic Ocean Fluxes) community.

5. PUBLICATIONS

5.1. Books or Other One-time Publications

Woodgate, R.A., K.Aagaard and T.Weingarter, 2007: First steps in calibrating the Bering Strait Throughflow, APL internal report, 20pp, http://psc.apl..washington.edu/BeringStrait.html.

Woodgate, R. A., 2008a: Mooring Cruise report for RUSALCA Sever cruise to the Bering Strait - Aug/Sept 2007, 17 pp, University of Washington.
available at http://psc.apl.washington.edu/BeringStrait.html.

Woodgate, R. A., 2008b: Mooring Cruise report for RUSALCA Lavrentiev to the Bering Strait, October 2008, 24pp, University of Washington.
available at http://psc.apl.washington.edu/BeringStrait.html.

5.2. Papers

White, D., L. Hinzman, L. Alessa, J. Cassano, M. Chambers, K. Falkner, J. Francis, B. Gutowski, M. Holland, M. Holmes, H. Huntington, D. Kane, A. Kliskey, C. Lee, J. McClelland, B.Peterson, F. Straneo, M. Steele, R. Woodgate, D. Yang, K. Yoshikawa, T. Zhang, 2007: The Arctic Freshwater System: changes and impacts, *Journal of Geophysical Research*, 112, G04S54, doi:10.1029/2006JG000353.

Melling, H., K.K.Falkner, R.A.Woodgate, S.Prinsenberg, A.Muenchow, D.Greenberg, T.Agnew, R.Samelson, C.Lee, B.Petrie, 2008: Freshwater Fluxes via Pacific and Arctic Outflows across the Canadian Polar Shelf, ASOF special volume, Springer-Verlag.

Zhang, J., M. Steele, and R. Woodgate: The role of Pacific water in the dramatic retreat of arctic sea ice during summer 2007, *Journal of Polar Science*, submitted.

Mizobata, K., K. Shimada, R. Woodgate, S.-I. Saitoh, and J. Wang: Estimation of heat flux through the eastern Bering Strait, *Journal of Oceanography*, submitted.

Woodgate, R. A., R. Lindsay, K. Aagaard and T. Weingartner: On the Bering Strait Heat Flux and its influence on Arctic Sea ice, in preparation.

5.3. Website

http://psc.apl.washington.edu/BeringStrait.html
Home page for Bering Strait activities, including links to data access and cruise reports.

5.4. Abstracts/Invited talks

Woodgate, R.A., K.Aagaard, T.Weingartner, T.Whitledge, R.Lindsay: The Pacific Gateway to the Arctic – change and implications of the Bering Strait Throughflow. 2007, invited talk at ONR site visit.

Woodgate, R.A., T. Weingartner, T.Whitledge, I.Lavrenov, K.Aagaard, R.Lindsay: Pacific Gateway to the Arctic: Recent measurements of the Bering Strait Throughflow, invited talk Dec 2007, Moscow.

Woodgate, R.A.: The Changing Arctic Ocean, First in a 3 part UW Alumni Public Lecture Series entitled 'Arctic Adventure: Tales of Currents and Creatures', organized by UW-COFS (College of Ocean and Fisheries Science), February 2008.

Woodgate. R.A., T. Weingartner, R.Lindsay, T.Whitledge: Bering Strait AON project, invited talk at AON meeting at Palisades, New York, April 2008.

Woodgate, R.A.: The Ocean's role in the 2007 Arctic Sea-ice Minimum, invited talk at NY Sea-ice retreat workship, Palisades, New York, April 2008.

Woodgate. R.A., T. Weingartner, R.Lindsay, T.Whitledge, K.Aagaard: Pacific Inflow to the Arctic Ocean – changes in the Bering Strait throughflow, invited talk at NOAA Climate Division Annual System Review, Washington DC, Sept 2-5 2008.

Woodgate R.A.: Bering Strait: Pacific Gateway to the Arctic, invited talk at 2008 ASOF (Arctic Subarctic Ocean Fluxes) meeting in Halifax, 12-14th Nov 2008.

Panteleev, G., T.Kikuchi, D.Nechaev, A.Proshutinsky, R.Woodgate, M.Yaremchuk, J.Zhang, 2008: Toward the reanalysis of the circulation in the Chukchi and East Siberian Seas, abstract AGU 2008.

Hunt, G., P.Stabeno, R. Woodgate, 2008: Advective Processes in the Eastern Bering Sea, invited talk at fall 2008 ESSAS meeting in Nova Scotia.

Woodgate et al: The Pacific Gateway to the Arctic Ocean. Changes in the Bering Strait throughflow. April 2009, NODC Seminar, given over the internet.

Woodgate et al: The Pacific Gateway to the Arctic Ocean. Changes in the Bering Strait throughflow. May 2009, invited speaker at Bering Strait Observatory Planning Workshop in Pac Forest Center, Seattle.

Woodgate et al: The Pacific Gateway to the Arctic Ocean. Changes in the Bering Strait throughflow. June 2009, invited speaker at ESSAS (Ecosystem Studies of Sub-Arctic Seas) Meeting in Seattle.

5.5. Data or databases

Year-round measurements of temperature, salinity and velocity in the Bering Strait.
Data base publicly available via http://psc.apl.washington.edu/BeringStrait.html.
Data also available at NODC and CADIS.

6. CONTRIBUTIONS

6.1. Contributions within Discipline

By providing an improved evaluation of the Bering Strait fluxes, this project will contribute to local, Arctic and global studies.

Most topically, with the startling retreat of the Arctic sea-ice, quantifying the heat flux through the Bering Strait and the impacts of the Bering Strait throughflow on Arctic stratification become urgent issues in the quest to understand causes of Arctic sea-ice retreat.

Within regional oceanography, the work provides vital information for physical, biological and biogeochemical studies within the Bering Strait and Chukchi Sea, since the physical oceanography of the Chukchi Sea is dominated by the properties of the Bering Strait throughflow. Since the Bering Strait is fed from the south, the Bering Strait throughflow is also some indicator of conditions on the Bering Sea shelf, an economically important zone for U.S. fisheries and the focus of the NSF BEST (Bering Ecosystem Study) Program.

The Bering Strait throughflow is also the Pacific input to the Arctic Ocean, which is important for maintaining the Arctic Ocean halocline and providing nutrients for Arctic ecosystems. The Pacific inflow also brings heat into the Arctic. The fate of Pacific waters in the Arctic (especially their ventilation depth) relates to their density which is, to a large extent, set by the time the waters traverse the Bering Strait.

Globally, the Bering Strait throughflow is an important part of the global freshwater budget. Models suggest that an increase in the Bering Strait freshwater flux may weaken the Atlantic meridional overturning circulation. Other modeling studies count the Bering Strait flow as critical for the stability of world climate.

Thus, a better observational estimate of the Bering Strait flow and its variability is critical for a wide range of studies.

6.2. Contributions to Other Disciplines

Bering Strait data have been used in various research areas including non-physical oceanography and areas beyond oceanography, such as biological studies of sea-birds and mammals. Voluntary registration at our data site shows the data is in demand for work ranging from climate modeling to King Crab fishing, including a wide variety of studies covering local, Arctic and global subjects (North Pacific, Gulf of Alaska, Bering Sea, Chukchi Sea, Arctic Ocean, Arctic Ocean outflows, North Atlantic), with topics including ocean circulation; multidisciplinary shelf-basin exchange; eddy processes; benthic-pelagic coupling; ocean sedimentation; hydrology; heat, freshwater and nitrogen budgets; biogeochemistry, including CDOM, POC, and PIC; modeling and observational studies of present-day, future and paleo conditions, including analysis of sediment cores; future climate predictions (including Arctic and Atlantic meridional overturning circulation investigations); present-day and paleo climate stability; recent studies of accelerated retreat of Arctic sea-ice; changes in the fate of Pacific water in the Arctic; and ecosystems and ecosystem change, including effects on algae, plankton, euphasiids, seabirds, grey and bowhead whales.

The moorings also provide a potential logistics platform for other projects. In the past the moorings have carried water sampling devices and various bio-optics systems. We are involved in on-going discussions to include whale acoustic sensors (proposed) and pCO2 sensors (in discussion) on future versions of the moorings.

6.3. Contributions to Human Resource Development

This project is a joint US-Russian collaboration. By joint nationality cruises and meetings, it promotes cultural exchange on scientific and humanitarian topics.

6.4. Contributions to Resources for Research and Education

The results are part of an interdisciplinary graduate course on the Changing Arctic Ocean, being taught by Woodgate and Deming, as a highlight for IPY (International Polar Year) activities. This course is also listed within the University of Washington Program on Climate Change.

6.5. Contributions Beyond Science and Engineering

Through outreach activities, the project has increased community awareness of the Arctic and Arctic research, for example via the University of Washington evening lecture series on the Arctic, and through a Polar Science Weekend at the Pacific Science Center, Seattle's main science museum. The work is part of the Arctic Observing Network and International Polar Year projects.

Cruise Report For Bering Strait Mooring Project 2008, RUSALCA 2008
Russian Vessel Lavrentiev - *Nome, 1st October 2008 – Nome, 10th October 2008*

Rebecca Woodgate[1], Kathleen Crane[2], Mikhail Zhdanov[3], Kevin Wood[4], Vladimir Smolin[5], Terry Whitledge[6]
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[2]NOAA Climate Program Office, Arctic Research Program, Silver Spring MD
[3]Group Alliance, Moscow, Russian Federation
[4] Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle WA
[5]State Research Navigational Hydrographical Institute (SRNHI), Russian Federation
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(Photo by Dan Naber, UAF)

1. PROJECT SUMMARY

As part of the joint US-Russian RUSALCA (Russian US Long-term Census of the Arctic Ocean) Program, a team of US and Russian scientists undertook an oceanographic cruise in October 2008 on board the Russian vessel 'Lavrentiev'.

The major objective of the cruise was mooring work in the Bering Strait region, i.e., the recovery and redeployment of 8 moorings, a joint project by University of Washington (UW) and University of Alaska, Fairbanks (UAF), and the Arctic and Antarctic Research Institute (AARI). The US work is supported by an NSF-IPY grant (PIs: Woodgate, Weingartner, Whitledge and Lindsay). The moorings measure water velocity, temperature, salinity, ice motion, ice thickness (crudely) and some bio-optics.

Despite the expected bad weather and darkness, the moorings were successfully recovered and redeployed during the cruise. Unfortunately, weather prevented the taking of the related high resolution CTD sections, although surface bucket samples were taken for salinity and nutrients at the mooring sites, and some benthic grab work was done opportunistically. Also, underway temperature and pCO2 data was collected for the Bermuda Institute of Ocean Sciences (BIOS). This cruise report concerns the mooring and bucket sample work - for details of other programs, please contact the Chief Scientist.

The cruise started in Anadyr, Russian Federation, at the end of September. The ship arrived in Nome, USA, on the evening of 30th Sept. There, it picked up the US science team and equipment on 1st Oct, and sailed for the Bering Strait that evening. For the 2nd-4th October, high seas and strong southward winds in the Bering Strait prevented mooring operations, and the ship sheltered at the north end of Puoten Bay, just under Cape Dezhneva, on the western side of the strait. A 4-day lull in the weather allowed us to recover and redeploy the moorings on the 5th-8th Oct. On the 9th Oct, the final mooring was deployed, and around midday with a forecast of 12 foot seas and freezing spray, the ship turned for Nome. The ship docked in Nome on the morning of 10th Oct, off-loaded, and left for Anadyr that evening.

2. RUSALCA 2008 MAP OF STATIONS

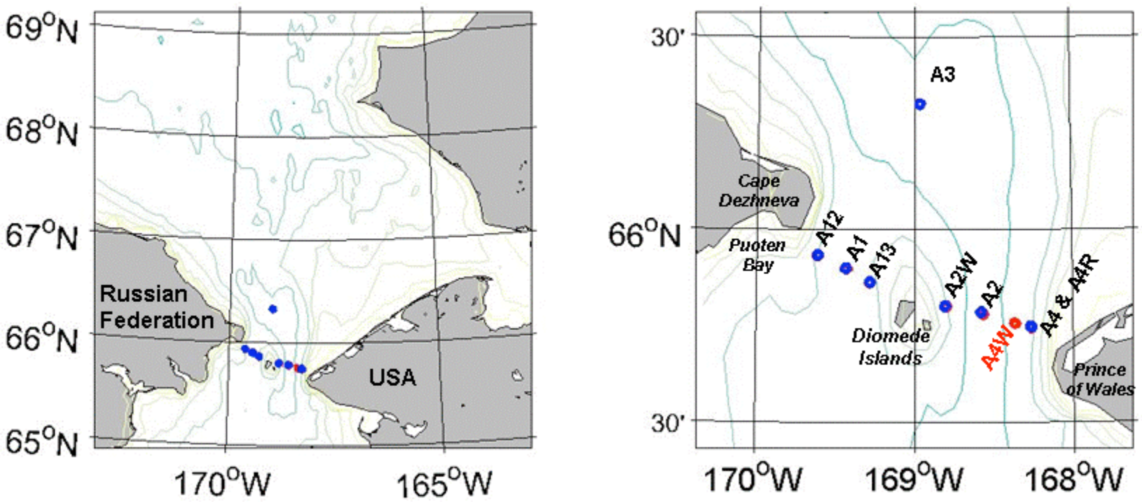


Figure 1. Map of the Bering Strait region (left) and detail of the Strait (right) showing Lavrentiev RUSALCA 2008 mooring locations for the eight moorings deployed in 2008 (A12, A1, A13, A2W, A2, A4, A4R and A3) and the eight moorings recovered in 2008 (A12, A1, A13, A3, A2W, A2, A4W, A4, and A3). Blue dots indicate a site of recovery and deployment. Red dot (A4W) indicates recovery only. Depth contours are every 10m from International Bathymetric Chart of the Arctic Ocean.

3.RUSALCA 2008 CRUISE PARTICIPANTS

- United States:

1. Terry Whitedge (M), UAF, USA – *Chief Scientist, nutrients, moored nutrient sampler*
2. Kathy Crane (F), NOAA – *Program Manager, NOAA; NOAA-Group Alliance Liaison*
3. Kevin Wood (M), NOAA/UW – *Science Liaison*
3. Rebecca Woodgate (F), UW – *Moorings, UW Mooring lead*
4. Wendy Ermold (F), UW – *Moorings*
5. David Leech (M), UAF – *Moorings, UAF Mooring lead*
6. Markus Janout (M), UAF – *Moorings*
7. Jeremy Kasper (M), UAF – *Moorings*
8. Dan Naber (M), UAF – *Mooring, moored nutrient sampler, nutrients*
9. Marlene Jeffries, BIOS – *Underway temperature and pCO2 data, bucket samples*

- Russian (directly part of RUSALCA mooring work):

10. Vladimir Smolin (M), SRNHI, RF – *Expedition Leader, Science Liaison and translator*
11. Vladimir Bakhmutov (M) - *Vladimir's assistant*
12. Alexey Ostrovskiy (M), Group Alliance – *Liaison and translator*
13. Valerian Golavsky (M), Arctic and Antarctic Research Institute (AARI), RF – *Moorings*

- Other Russian Scientists:

Maxim Ivanov, Alexander Kolesnik, Alexander Merezhko, Ildar Dolotkazin, Anatoly Berezka, Petr Vasilyev, Sergey Novoseltsev, Roman Antonov, Denis Benyukh, Lev Pautov, Dmitry Voronov, Renat Shakirov.

4. RUSALCA 2008 CRUISE SCHEDULE

(Aug 2008 – Jim Johnson and Rebecca Woodgate prep gear in Nome for 3 days)

Monday 29th Sept 2008	*mooring team arrive Nome*
Tuesday 30th Sept 2008	*Lavrentiev arrives Nome ~ 1800 local time; US Customs inspections*
Wednesday 1st Oct 2008	*Onload; ship away from dock ~ 1800 local time*
	steam to Bering Strait overnight
Thursday 2nd Oct 2008	*Strong southward winds and high seas – wait out in Puoten Bay*
Friday 3rd Oct 2008	*Strong southward winds and high seas – wait out in Puoten Bay*
Saturday 4th Oct 2008	*Strong southward winds and high seas – wait out in Puoten Bay*
	~ 1700 local, transit into strait, but too rough to work
	Siberian Coastal Current visible (by water colour) along Russian Coast
Sunday 5th Oct 2008	*Winds drop;* Recover A12-07 without hitch
	Recover A11-07 on 2nd dragging attempt
	Recover A13-07 without hitch
	Anchor south of Diomede Islands overnight
Monday 6th Oct 2008	Recover A4-07 without hitch
	Recover A4W-07 without hitch
	Recover A2-07 without hitch
	Recover A2W-07 on 3rd dragging attempt
,	*Benthic work overnight, wait at A3-07 for light*
Tuesday 7th Oct 2008	Recover A3-07 without hitch
	Deploy A3-08 without hitch
	Steam to A4-08
	Deploy bottom half of A4-08, (top half breaks free during deployment)
	Recover drifting part of A4-08
Wednesday 8th Oct 2008	Deploy A2-08 ~ 700m N of usual position due to deployment issues
	Deploy A4R-08 (~200 yards from A4-08) without hitch
	Deploy A2W-08 without hitch
	Deploy A1-08 without hitch
	Deploy A13-08 without hitch
Thursday 9th Oct 2008	Deploy A12-08 without hitch
	Weather worsening and forecast for 12ft seas and freezing spray
	Ship returns to Nome
Friday 10th Oct 2008	*Dock ~ 11am; Offload with shore-based crane (as port side to)*
	Complete off-load around 5pm, all freight to air cargo
	Ship sails late evening

Total: 8.5 days at sea

5. BACKGROUND TO MOORING AND CTD PROGRAM

5.1. Moorings

The moorings serviced on this cruise are part of a multi-year time-series (started in 1990) of measurements of the flow through the Bering Strait. This flow acts as a drain for the Bering Sea shelf, dominates the Chukchi Sea, influences the Arctic Ocean, and can be traced across the Arctic Ocean to the Fram Strait and beyond. The long-term monitoring of the inflow into the Arctic Ocean via the Bering Strait is important for understanding climatic change both locally and in the Arctic. Data from 2001 to 2004 suggest that heat and freshwater fluxes are increasing through the strait [*Woodgate et al.*, 2006]. The work completed this summer should tell us if this is a continuing trend.

An overview of the Bering Strait mooring work (including access to mooring and CTD data) is available at http://psc.apl.washington.edu/BeringStrait.html.

Eight moorings were recovered on this cruise.

These moorings (three in Russian waters – A1-1-07, A1-2-07, A1-3-07, five in US waters – A2W-07, A2-07, A4W-07, A4-07, A3-07) were deployed in another joint US-Russian venture supported by NSF-OPP (*Woodgate, Weingartner, Whitledge, Lindsay, NSF-OPP-ARC-0632154*) and the NOAA-led RUSALCA (Russian-American Long-term Census of the Arctic, http://www.arctic.noaa.gov/aro/russian-american/) program.

Eight moorings were redeployed on this cruise under the same funding. These moorings (three in Russian waters – A11-08, A12-08, A13-08, five in US waters – A2W-08, A2-08, A4-08, A4R-08, A3-08) are almost entirely direct replacements of the recoveries. However, a chain on mooring A4-08 broke on deployment, resulting in only the bottom instrumentation being deployed at that site. Since this is a key, long-term site, a second complete mooring A4R-08 was deployed within ~ 200m of A4-08, and mooring A4W-08 was not deployed in 2008.

This is the 2nd year of the highest resolution array ever deployed in the Bering Strait, (see map above). Three moorings were deployed across the western (Russian) channel of the strait (from west to east - A12-08, A1-08, A13-08). Four moorings were deployed across the eastern (US) channel of the strait (from west to east - A2W-08, A2-08, A4-08, A4R-08). A final 8th mooring (A3-08) was deployed ca. 35 nm north of the strait at a site proposed as a "climate" site, hypothesized to measure a useful average of the flow through both channels [*Woodgate et al.*, 2007]. Testing this hypothesis is a main aim of this work. All moorings (recovered and deployed) measure water velocity, temperature and salinity near bottom (as per historic measurements). Additionally, 6 of the 8 moorings (i.e., all eastern channel moorings, the climate site mooring A3, and the mooring central in the western channel) also carried upward-looking ADCPs (measuring water velocity in 1-2 m bins up to the surface, ice motion, and medium quality ice-thickness) and ISCATS (upper level temperature-salinity-pressure sensors in a trawl resistant housing designed to survive impact by ice keels). Bottom pressure gauges were also deployed on the moorings at the edges of the eastern channel (A2W-08 and A4-08). Two moorings (A2-08, central eastern channel; and A1-2, western part of western channel) also carried ISUS nitrate sensors and optical sensors for fluorescence and turbidity. For a full instrument listing, see the table below.

This coverage should allow us to assess year-round stratification in the strait and also to study the the physics of the Alaskan Coastal Current, a warm, fresh current present seasonally in the eastern channel, and suggested to be a major part of the heat and freshwater fluxes [*Woodgate and Aagaard*, 2005; *Woodgate et al.*, 2006]. The current meters and ADCPs (which give a estimate of ice thickness and ice motion) allow the quantification of the movement of ice and water through the strait. The nutrient sampler, the transmissometer and fluorometer time-series measurements should advance our understanding of the biological systems in the region.

5.2. CTD

The moorings are usually supported by annual CTD sections, with water samples for nutrients. Regretably, the bad weather at the time of year of this cruise precluded running these CTD sections, however surface bucket samples were taken for salinity and nutrients at the mooring sites, and an underway temperature and pCO2 system was logged by the Bermuda Institute of Ocean Science during the cruise.

5.3. International links

Maintaining the time-series measurements in Bering is important to several national and international programs, e.g. the Arctic Observing Network (AON) started as part of the International Polar Year (IPY) effort; NSF's Freshwater Initiative (FWI) and Arctic Ocean Model Intercomparison Project (AOMIP), and the international Arctic SubArctic Ocean Fluxes (ASOF) program. The mooring work also supports regional studies in the area, by providing key boundary conditions for the Chukchi Shelf/Beaufort Sea region; a measure of integrated change in the Bering Sea, and an indicator of the role of Pacific Waters in the Arctic Ocean. Furthermore, the Bering Strait inflow may play a role in Arctic Ocean ice retreat and variability (especially in the freshwater flux) is considered important for the Atlantic overturning circulation and possibly world climate [*Woodgate et al.*, 2005].

6. MOORING OPERATIONS DURING 2008 LAVRENTIEV CRUISE

The RUSALCA 2008 mooring cruise was originally planned for August. When the cruise was moved to October, it was clear there would be substantial challenges with light and weather (and related icing) issues. By October, there is only ~ 12hrs light per day and (as verified by experience) storms are long and intense. However, a break in the weather allowed us to complete the mooring work, if not the CTD sections.

For recoveries, a spectra line was loaded onto the forward winch and fair-led to the block on the forward A-frame, forward of the bridge. The acoustic hydrophone was deployed from the forward lab, just forward of the A-frame (and close to the bowthruster). Once the mooring was released, the ship brought the floating mooring along the starboard side to the forward A-frame, where it was grappled by hook and brought aboard onto the foredeck using the A-frame and winch. An electric-powered pressure washer was successfully connected to the ship's supplies in the forward lab, greatly facilitating the mooring clean-up operation. Deployments were done off the aft-deck, using the ship's trawl wire and stern A-frame for lifting. Most success was obtained with the ship steaming slowly (1.5 knots) into the wind, and the mooring being deployed anchor last from the aft deck. The following issues are noteworthy:

1) The deck height above water is ~12ft, making grappling the mooring with a hook and pole challenging. ***Plan accordingly.***

2) The gangways from the foredeck to the aft-deck are smaller than the floats, and thus floats had to be put back into the ocean and floated around to the stern for deployment and packing/offload. ***Bring extra line for this operation.***

3) Two moorings required dragging. ***Prepare for dragging on all Bering Strait cruises.***

- A11-07 was recovered on the 2nd drag. A possible cause of the release not opening was the cold water making grease on the release mechanism too stiff. This 2nd dragging operation also recovered a mooring anchor (separate from the released mooring). ***Remove grease from release mechanisms.***

- A2W-07 was recovered on the 3rd drag. This mooring carried double releases and a bottom pressure gauge, and the reason for failure to release is not clear. Both releases confirmed release, but one release was jammed shut with small mussels when the mooring finally came on deck. Although the second release was open on final recovery, it is possible it too was jammed with biology and only released when caught by the drag. Another possibility is that the bottom-pressure gauge was jammed in its housing in the anchor, either by geometry, some issue during deployment, or biology. The setup has a fairly tight fit between the gauge and a rubber housing, and there was some evidence of barnacle growth below the housing which could have impeded the gauge being removed from its housing on the anchor. (The identical set up on A4-07 released without hitch, although we note the fouling was less on A4-07 and the currents are usually stronger at A4-07, helping to pull the gauge out from the anchor.) For the redeployments, all releases on all US moorings (which had significantly more fouling than the Russian side moorings) have their ***release mechanisms painted with antifouling paint.*** Additionally, ***the bottom pressure gauges were wrapped in plastic wrap*** (saran-wrap, cling-film), such that the gauge can slip free of this covering on recovery. ***Also, the rubber piping connecting the gauge to the anchor was loosened.***

4) As per last year, two releases were known to require a special deckset, since a manufacturer's error made the acoustic circuits temperature dependent. With this deckset, codes normally starting with 4 can be retuned by changing the initial digit of the code, by trial and error. This was successful and these releases have not been redeployed. It appears that some of the usual decksets can also send these special codes.

5) The ***moorings in the eastern channel and at the northern site showed significantly more biofouling than instrumentation in the western channel.*** This is curious since the accepted wisdom is that the western channel is the most productive. Possibly this reflects the warmer waters. The most fouling was found at site A2W, which also had large collections of sea-birds and whales. This may also relate to the high SeaWifs signal often seen around the island. Barnacles up to 3 cm were common on these moorings – barnacle growth has become the dominant form of biofouling in the strait in recent years. This year, small mussels were also in evidence more than in the past. One mooring also carried a hand-size sea-star. In all cases, salinity cells remained clear, with the possible exception of the iscat, where fouling with small mussels was a big problem.

6) Only 1 of the 6 iscats was recovered, although there is good data on the loggers for all the iscats up to the time of loss. Data show the upper iscats were generally at between 14 and 17m depth. One strong (presumably) storm event in late November has all iscats pulled down to almost 30m, at the same time as strong northward flow. The iscat on A4W became disconnected from its logger at this stage, although the iscat itself remained and is the one iscat to have been recovered. Data from the other 5 iscats ceases in mid February (A3-07 and A1-07), late March (A2-07 and A4-07, within a day of each other) and late April (A2W-07). In all cases, the temperatures are at freezing, suggesting ice damage, although this must be checked against ice-charts. The 2008 deployments have ***put the iscats all at 17m,*** and ***strengthened the plugged link between the iscat and the logger***. We should ***consider making stronger weak links, and revisit the iscat shape in light of pull down information.***

7) The deployments of A4-07 and A2-07 had many issues.

- Firstly, a combination of the ship drifting (rather than towing the mooring), the shortness of the mooring and the location of the anchor on deck, left the ADCP banging against the aft of the ship. This resulted in bending of the "banana" bars holding the viny floats into the frame and loss of 4 vinys. The instrument was recovered and rerigged, but ***the banana bars should be strengthened, and all bars on the frame cotter pinned or screwed.***

- Secondly, when the anchor was dropped, only the steel float of the mooring, the SBE-16 and the bottom pressure gauge went down. It turns out the last link of the chain below the viny ADCP frame broke somehow, possibly due to the rough treatment on deployment, but more likely (given what follows) due to faulty chain. For the remaining deployments, ***at the top of the mooring the chain links were taped***, to keep them straight during deployment.

- Thirdly, on recovery of the Iscat and ADCP that broke off A4-08 on deployment, the iscat tether became hooked underneath the ship. ***Bring grapples to aid in recovery, recover Iscat first, bring extra tether.***

- Fourthly, on the anchor pick for deployment of A2-07, it was noted the bottom link of the chain was cracked and opening. All accessible chain was replaced with chain from recovered moorings. ***Beware all chain on A4-07 and A2-07 on recovery.*** The broken chain carries the marking KX and CCL.

- Fifthly, a combination of the chain issue, plus a tangling issue caused by the ship losing forward way during the deployment, meant A2 has been deployed ~ 700m north of its usual position. (It was not deemed worth the equipment risk to turn the ship while towing the mooring to reposition.) ***In 2009, A2 should be placed in its usual position, not in its 2008 position.***

8) During this cruise, all deck operations (including driving of winches and A-frames) were done by the US science party. Although Russian scientists were likely available to help, it was deemed safer to keep one-common language on deck. ***Ensure the manning of the ship is clear before the cruise.***

Very preliminary analysis of the mooring data show very good data return from all instrumentation. Preliminary plots are given below.

The data show the usual large annual cycle in temperature and salinity. Many of the usual features are present, i.e. high variability in autumn, generally with freshening and cooling; salting (at the freezing point) in the winter; freshening and warming in the spring [*Woodgate et al.*, 2005]. Moorings A4 and A4W sample the Alaskan Coastal Current (ACC), and in general the eastern channel is warmer and fresher than the western channel. The Iscat data also shows more stratification on the eastern side, although there is significant and (interestingly) episodic stratification on the western side. The Iscat data indicate that although the iscats were lost in the winter, the autumn stratification is well caught by these data. The flow fields are strongly barotropic, other than in the ACC, although some velocity shear is evident at other sites also. Also, interestingly, there are hardly any strong southward flow events. It will be informative to integrate flux measurements for these time periods. The flow through the strait is believed to be driven by a sea-level difference between the Pacific and the Arctic, which drives a flow northwards towards the Arctic. Local winds (usually southward in the annual mean) tend to oppose this flow and may reverse it on timescales of days [*Woodgate et al.*, 2005b]. However, the recovered data suggest that reversals have been unusually uncommon this summer, as in last year's data. Since the variability of northward fluxes of heat and freshwater are dominantly dependent on the variability of the volume transport [*Woodgate et al.*, 2006], this may imply further increases in this fluxes, with possible implications for the Arctic and beyond.

Details of mooring positions and instrumentation are given below, along with schematics of the moorings, photos of the mooring fouling and preliminary plots of the data.

7. WATER SAMPLING OPERATIONS DURING 2007 SEVER CRUISE

Bad weather and the large amount of mooring work to be done precluded the taking of CTD sections. However, surface bucket samples were taken for salinity and nutrients at the mooring sites, and at 1 extra site (65º 58.567'N, 169º 47.684'W, in 45m of water, corrected for ship draft) believed (from observation of surface water colour) to be in the Siberian Coastal Current, which on a steam from 65º 57.2'N 169º 39.8'W to 65º 58.6'N 169º 42.2'W appeared as a sharp change in surface colour (lighter brown hear the coast) and extending ~ 3nm from the coast.

These samples will be analysed for nutrients by Terry Whitledge, and for salinity and pCO2 by Bermuda Institute of Ocean Science (BIOS), who also collected underway temperature and pCO2 data from the ship's underway seawater intake.

Table 1. RUSALCA 2008 Bering Strait mooring positions and instrumetation (US GPS).

ID	LATITUDE (N)	LONGITUDE (W)	WATER DEPTH /m (corrected)	INST.
RECOVERIES				
- Russian EEZ				
A1-1-07	65 53.994	169 25.877	52	ISCAT, ADCP, SBE37
A1-2-07	65 56.019	169 36.763	53.3	ISUS, SBE/TF, RCM9T
A1-3-07	65 51.908	169 16.927	49	AARI, RCM9, SBE37
- US EEZ				
A2W-07	65 48.07	168 47.95	52	ISCAT, ADCP, SBE16, BPG
A2-07	65 46.87	168 34.07	56	ISCAT, ADCP, SBE/TF, ISUS
A4W-07	65 45.42	168 21.95	54	ISCAT, ADCP, SBE16
A4-07	65 44.77	168 15.77	50	ISCAT, ADCP, SBE16, BPG
A3-07	66 19.60	168 57.92	58	ISCAT, ADCP, SBE37

DEPLOYMENTS				
- Russian EEZ				
A11-08	65 54.033	169 26.174	52	ISCAT, ADCP, SBE37
A12-08	65 56.060	169 36.738	51	ISUS, SBE/TF, RCM9
A13-08	65 51.897	169 16.907	50	AARI, RCM9, SBE37
- US EEZ				
A2W-08	65 48.124	168 48.371	53	ISCAT, ADCP, SBE16, BPG
A2-08	65 47.195	168 34.691	56	ISCAT, ADCP, SBE/TF, ISUS
A4R-08	65 44.946	168 15.964	50	ISCAT, ADCP, SBE16
A4-08	65 44.882	168 15.761	50	SBE16, BPG
A3-08	66 19.595	168 57.875	58	ISCAT, ADCP, SBE37

AARI = AARI Current meter and CTD
ADCP = RDI Acoustic Doppler Current Profiler
BPG=Seabird Bottom Pressure Gauge
ISCAT = near-surface Seabird TS sensor in trawl resistant housing, with near-bottom data logger
ISUS= Nutrient Analyzer
RCM9= Aanderaa Acoustic Recording Current Meter
RCM9T = Aanderaa Acoustic Recording Current Meter with Turbidity
SBE/TF = Seabird CTD recorder with transmissometer and fluorometer
SBE16 = Seabird CTD recorder
SBE37 = Seabird Microcat CTD recorder

Table 2. RUSALCA 2008 Bering Strait bucket data positions (US GPS).

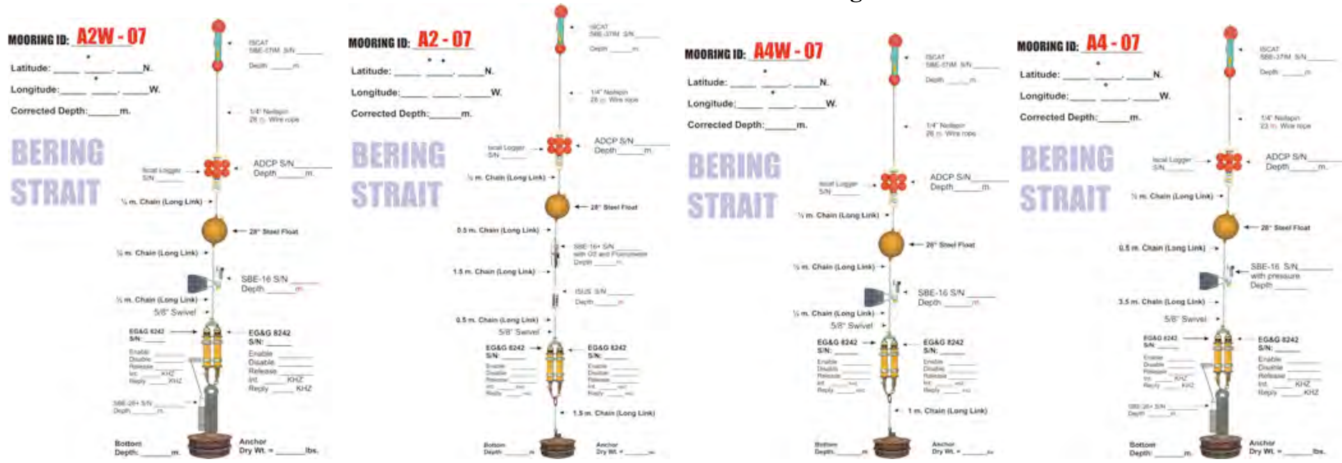
Sample Number	Year	Month	Day	Time Name	Depth (m)	Latitude (N) (deg min)	Longitude (W) (deg min)
1	2008	5	1714	SCC	45	65 58.567	169 47.684
2	2008	5	1751	A12-07	51	65 55.952	169 36.941
3	2008	5	2016	A11-07	52	65 53.992	169 25.88
4	2008	6	0127	A13-07	50	65 51.95	169 16.71
5	2008	6	1720	A4-07	50	65 44.891	168 15.662
6	2008	6	1844	A4W-07	54	65 45.42	168 21.95
7	2008	6	2009	A2-07	56	65 46.891	168 33.886
8	2008	6	2214	A2W-07	53	65 48.11	168 47.351
9	2008	7	1755	A3-07	58	66 19.768	168 58.007
10	2008	8	0246	A4-08	50	65 44.771	168 15.902
11	2008	8	1704	A2-08	56	65 46.901	168 33.524
12	2008	8	2240	A2W-08	53	65 48.034	168 47.28
13	2008	9	0119	nrA11-08	52	65 53.634	169 22.681
14	2008	9	0412	A13-08	50	65 51.901	169 15.038
15	2008	9	1753	-08	51	65 56.033	169 36.87

All dates and times are GMT.
Names are as per nearest mooring location (nrA11 is near A11, not at A11).
Water depths in () are approximate from mooring locations.

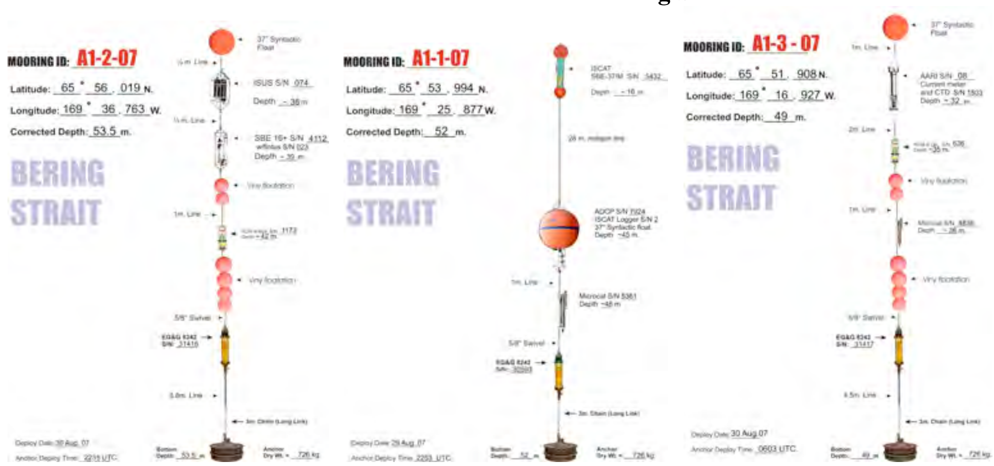
SCC is a non-mooring site, believed (from ship observation of water colour) to lie within the Siberian Coastal Current.

Nutrients and salinity will be analyzed from these samples.

In the eastern channel of the Bering Strait



In the western channel of the Bering Strait



At the climate site, ~ 60km north of the Strait

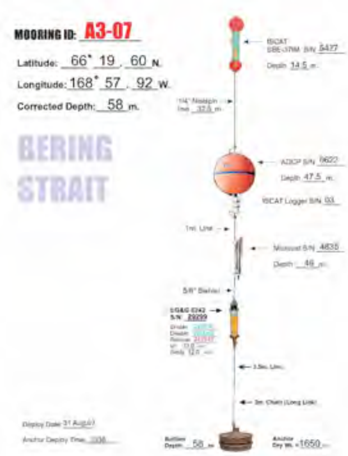
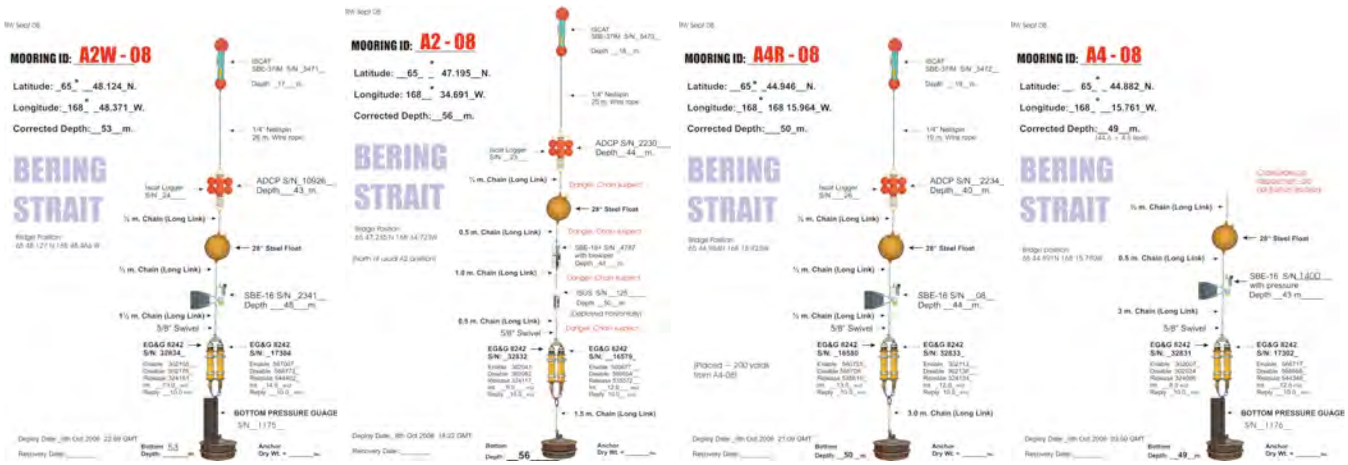
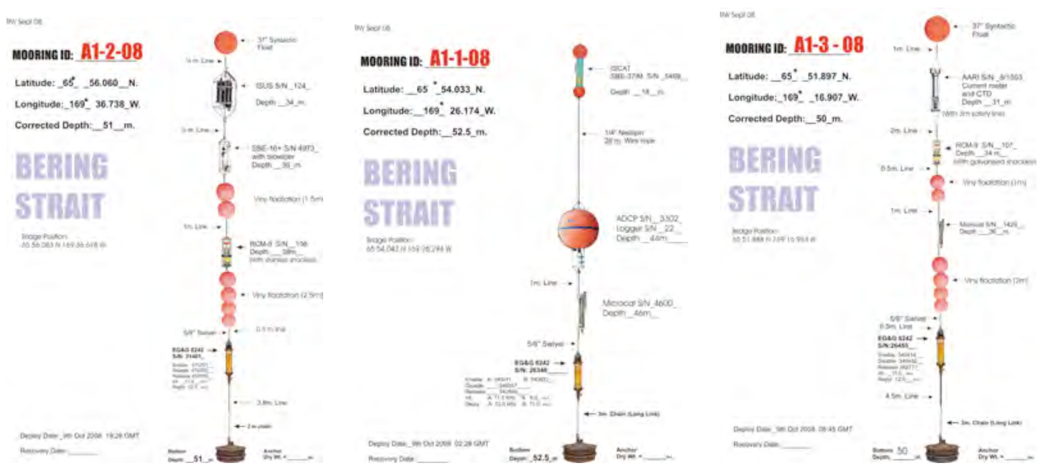


Figure 2. RUSALCA 2008 schematics of mooring recoveries.

In the eastern channel of the Bering Strait



In the western channel of the Bering Strait



At the climate site, ~ 60km north of the Strait

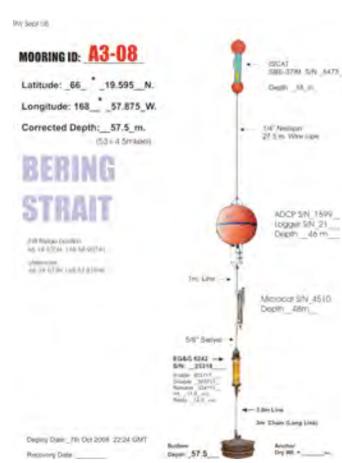
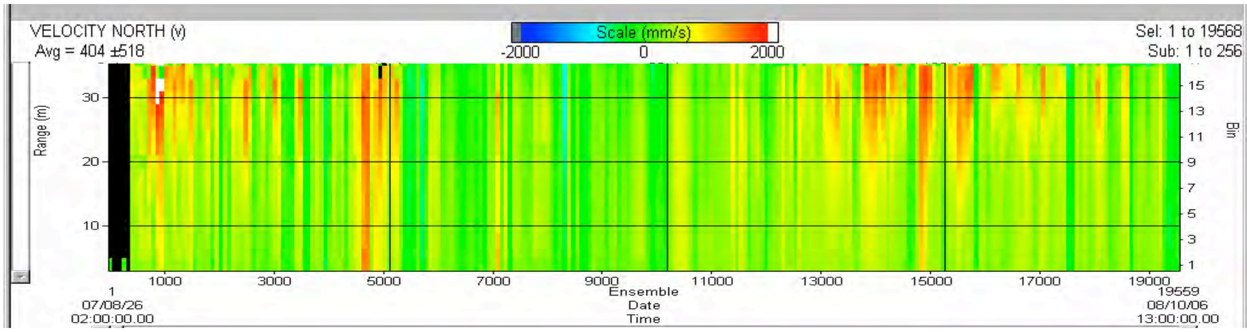
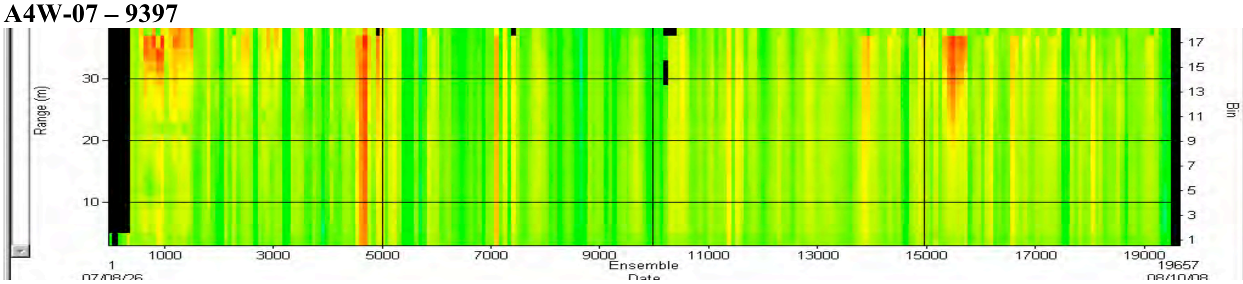


Figure 3. RUSALCA 2008 schematics of mooring Deployments.

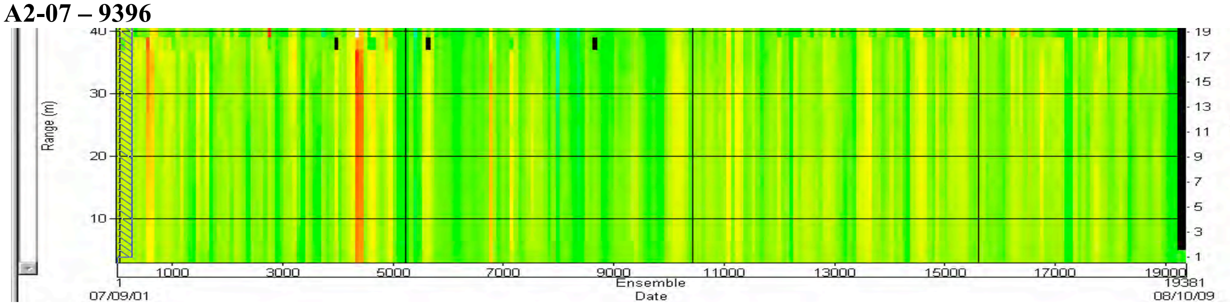
A4-07 - 2270



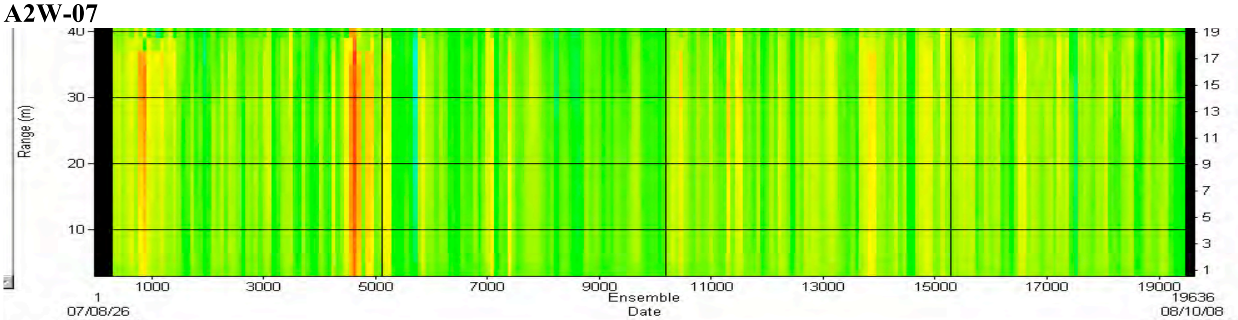
A4W-07 – 9397



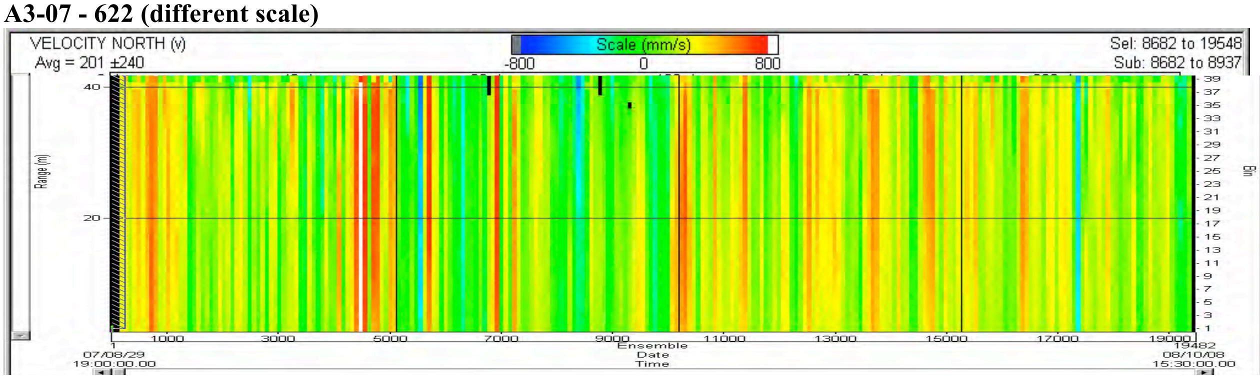
A2-07 – 9396



A2W-07



A3-07 - 622 (different scale)



A2-07 – 9396 northward only

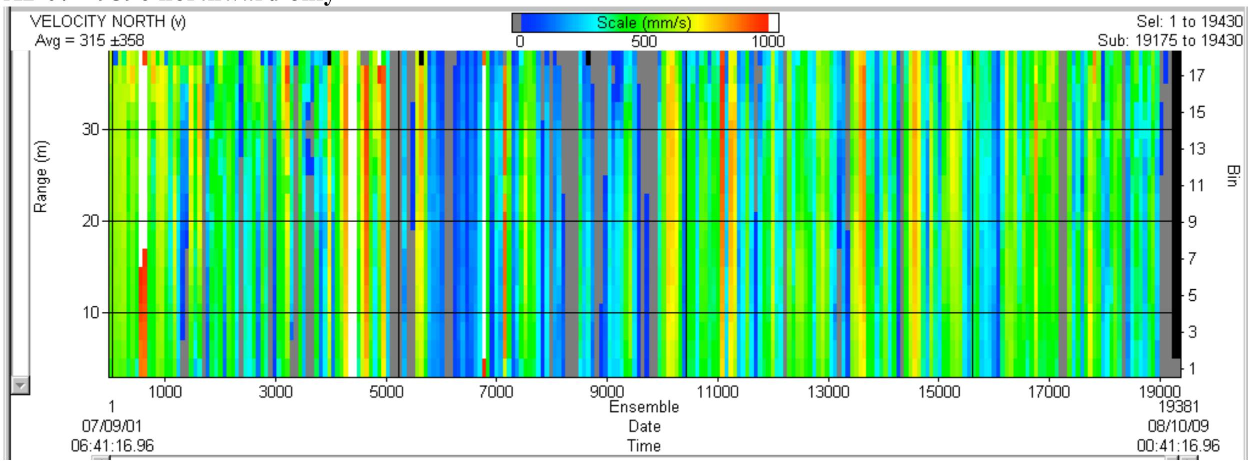


Figure 4. RUSALCA 2008 preliminary ADCP results (A1 data not included).

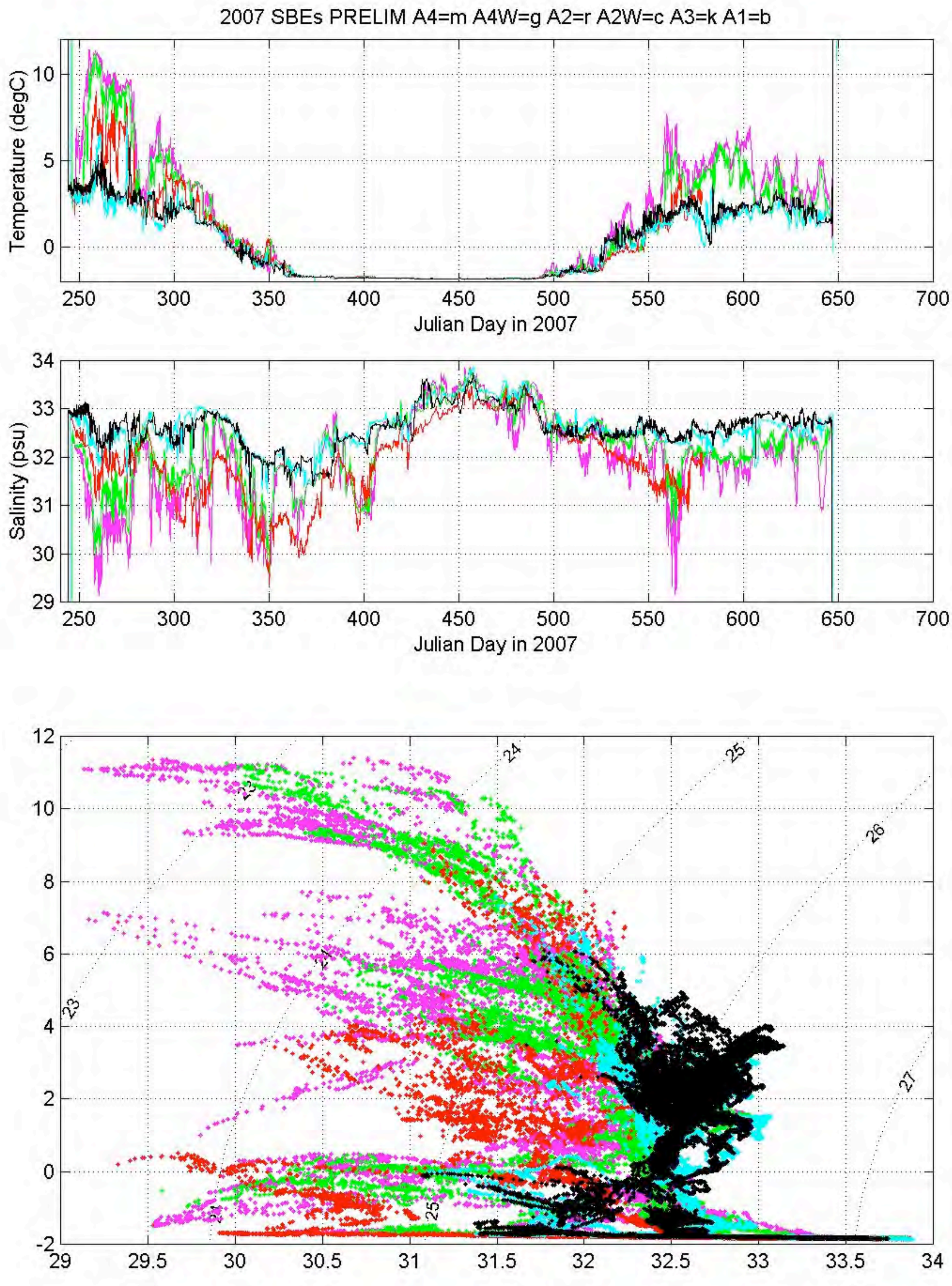


Figure 5. RUSALCA 2008 preliminary SEACAT results (A1, A12, A13 data not included).

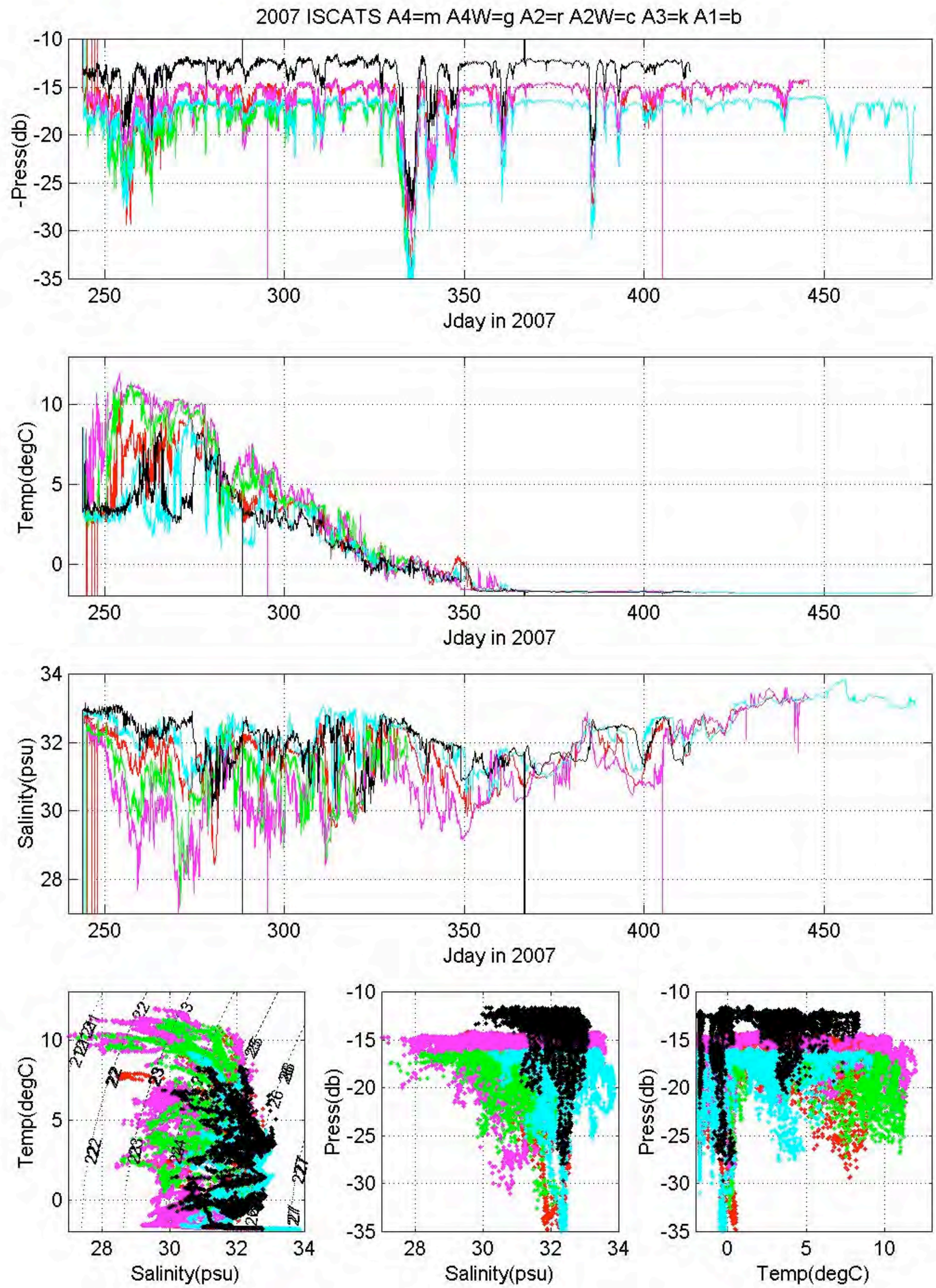


Figure 6. RUSALCA 2008 preliminary ISCAT results (A1 data not included).

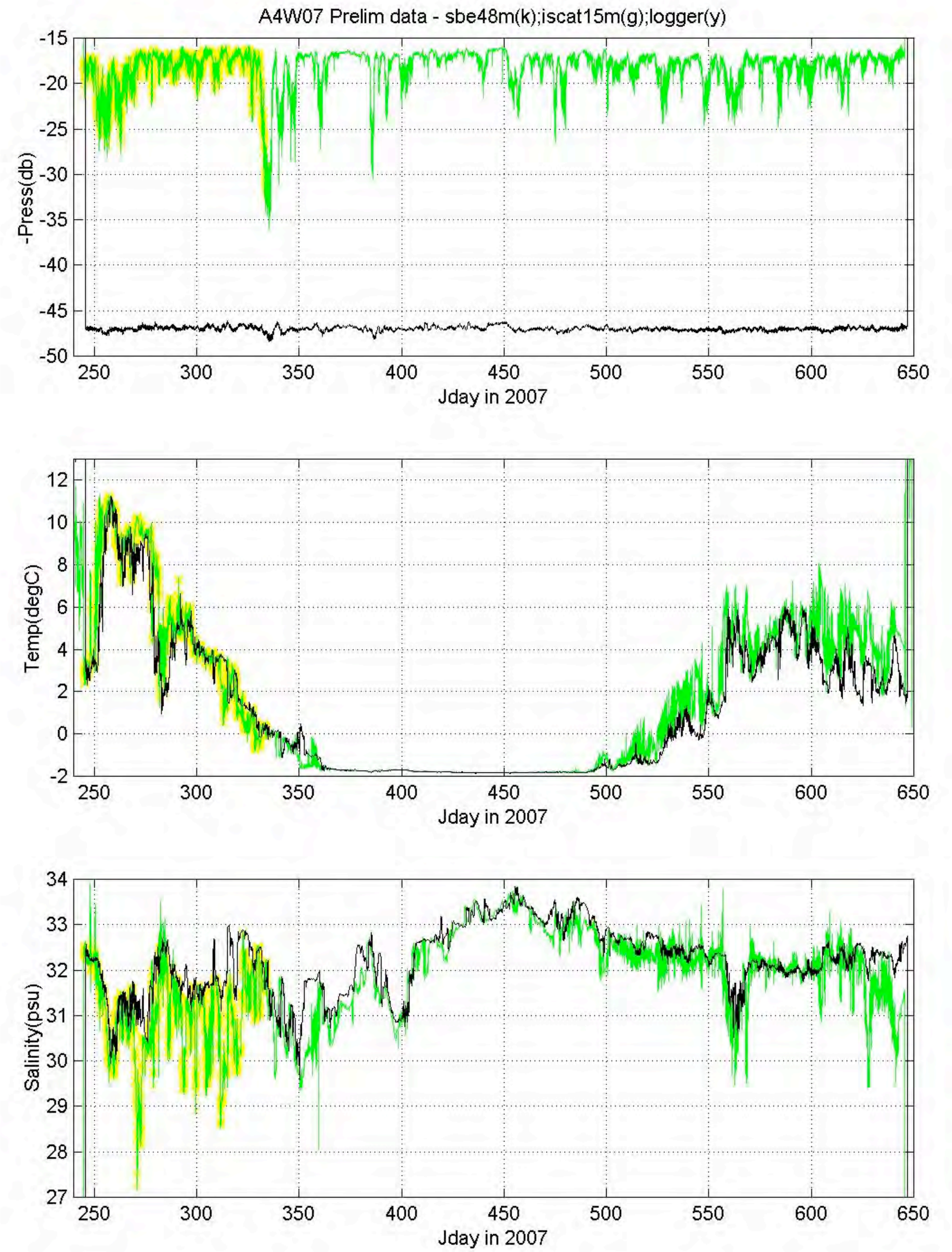


Figure 7. RUSALCA 2008 preliminary ISCAT-SBE comparison – for A4W07 (iscat survived all year).

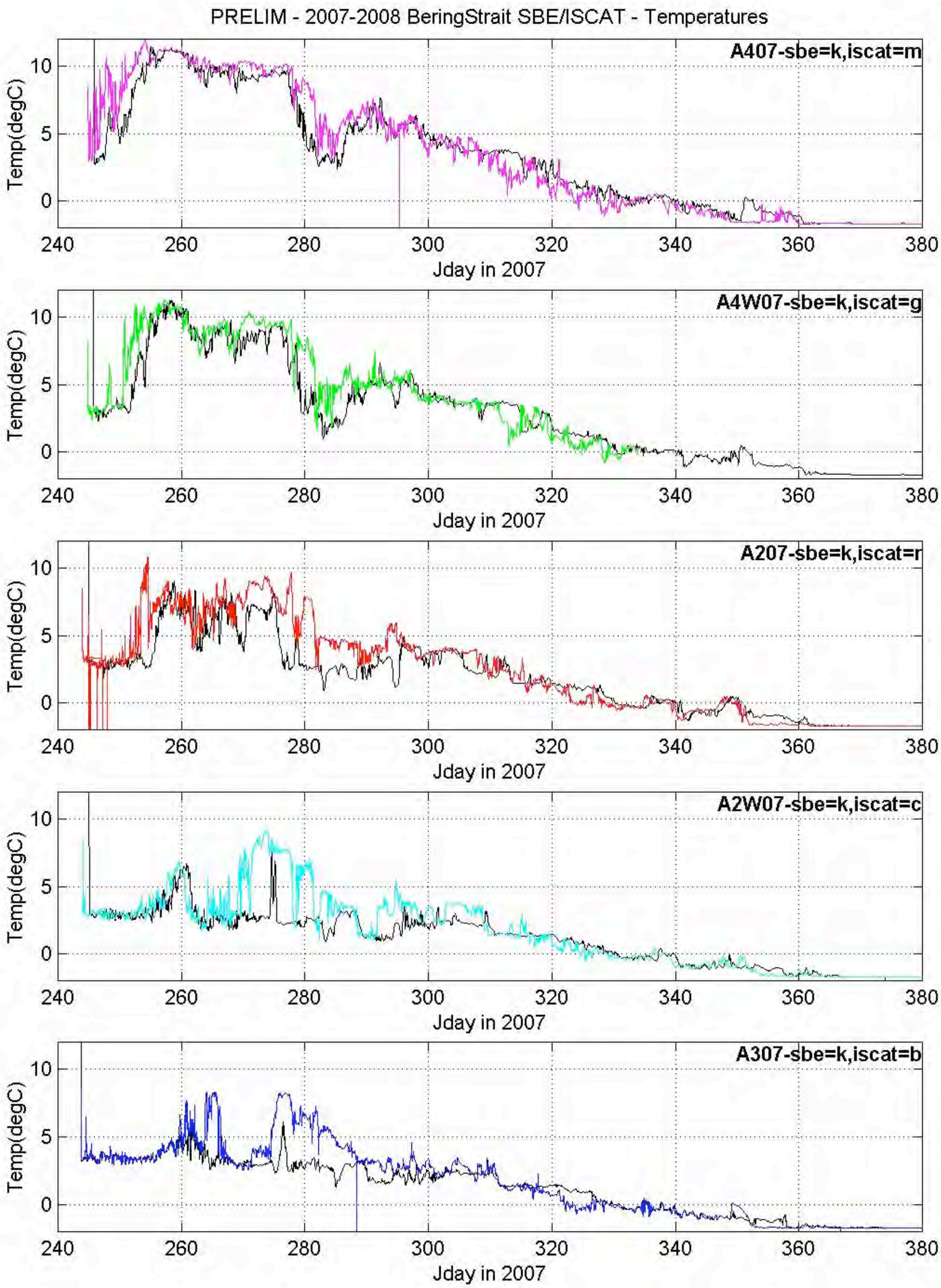


Figure 8. RUSALCA 2008 preliminary ISCAT-SBE comparison all sites - Temperatures (A1 data not included).

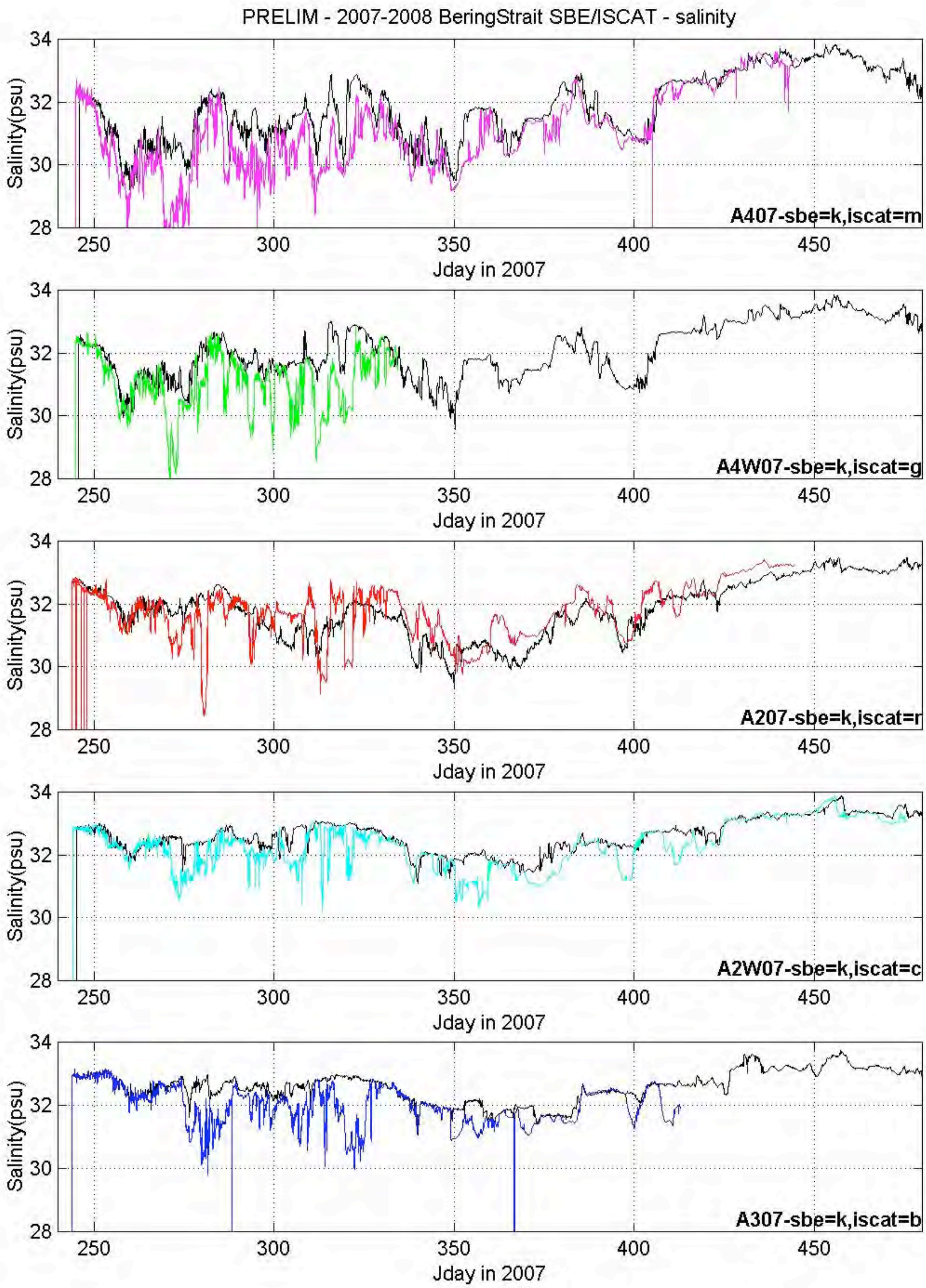


Figure 9. RUSALCA 2008 preliminary ISCAT-SBE comparison all sites – Salinities (A1 data not included. Note likely calibration issue with A207 SBE).

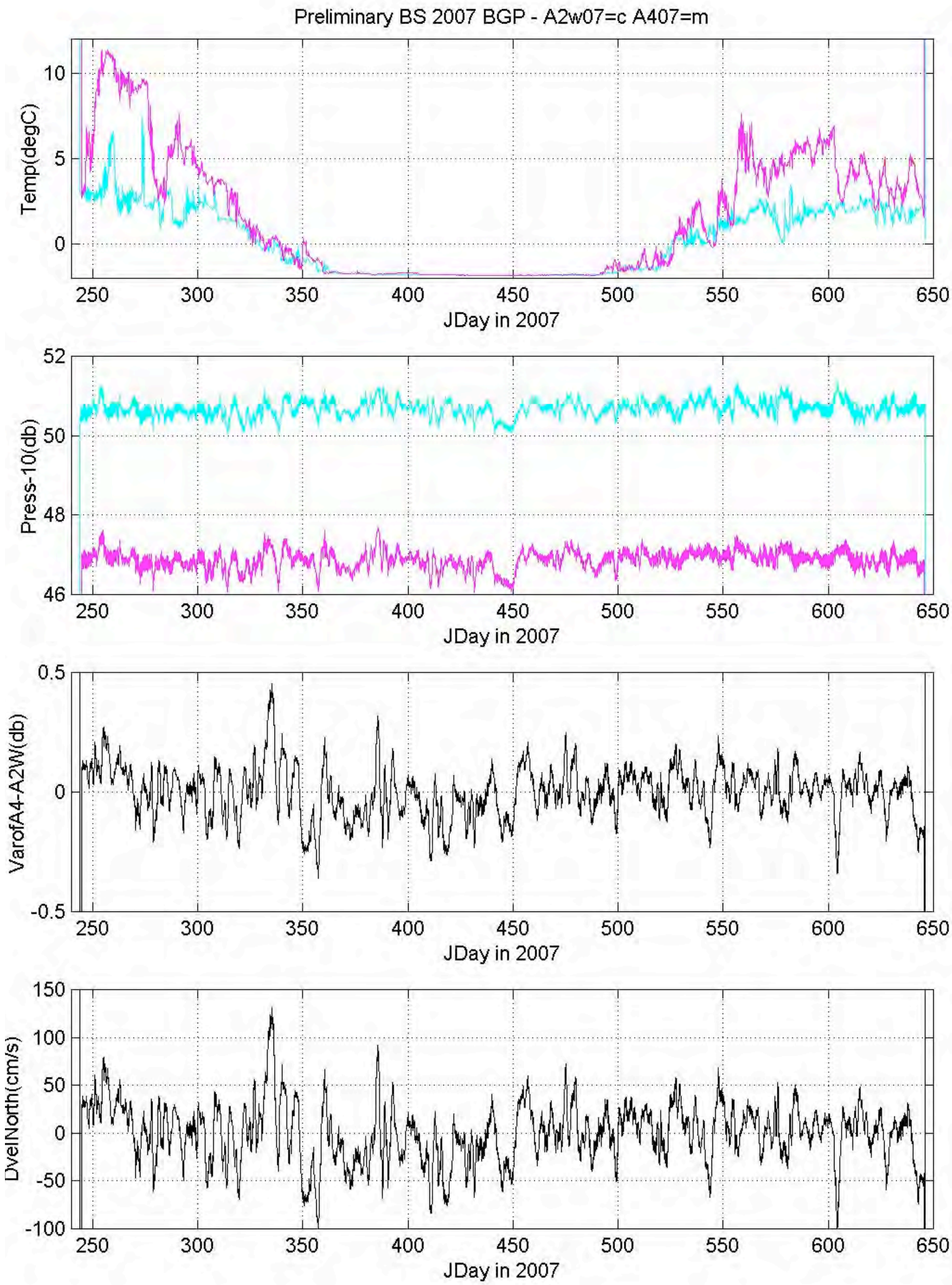


Figure 10. RUSALCA 2008 preliminary Pressure Gauge results**.**

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Woodgate, R. A., K. Aagaard, and T. J. Weingartner (2006), Interannual Changes in the Bering Strait Fluxes of Volume, Heat and Freshwater between 1991 and 2004, *Geophys. Res. Lett.*, *33*, L15609, doi:10.1029/2006GL026931.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner (2007), FIRST STEPS IN CALIBRATING THE BERING STRAIT THROUGHFLOW: Preliminary study of how measurements at a proposed climate site (A3) compare to measurements within the two channels of the strait (A1 and A2). 20 pp, University of Washington.

9. Ocean Analysis and Data Assimilation

a. In Situ and Satellite Sea Surface Temperature (SST) Analyses

b. Development of Global Heat and Freshwater Anomaly Analyses

c. Ocean Heat and Freshwater Content Variability Estimates

d. Evaluating the Ocean Observing System: Performance Measurement for Heat Storage

e. Quarterly Reports on the State of the Ocean: Meridional Heat Transport Variability in the Atlantic Ocean

f. A Fifty-Year Analysis of Global Ocean Surface Heat Flux to Improve the Understanding of the Role of the Ocean in Climate

g. Climate Variability in Ocean Surface Turbulent Fluxes

h. Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses

i. National Water Level Program Support Towards Building A Sustained Ocean Observing System For Climate

j. Evaluating the Ocean Observing System: Surface Currents

k. Global Carbon Data Management and Synthesis Project

l. Optimal Network Design to Detect Spatial Patterns and Variability of Ocean Carbon Sources and Sinks from Underway Surface pCO_2 Measurements

m. Observation-Based Quantification of Seasonal to Interannual Changes in Air-Sea CO_2 Fluxes

n. Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon

o. A Web Site for NCEP's Global Ocean Data Assimilation System (GODAS): Date Link, Data Validation and Global Ocean Monitoring Products

p. Enhanced Ocean Climate Products from NCEP

q. Ocean Data Assimilation Research at GFDL

r. Simulation of the Argo Observing System

s. Observing System Research Studies

In Situ and Satellite Sea Surface Temperature (SST) Analyses

Richard W. Reynolds
NOAA National Climatic Data Center, Asheville NC

1. PROJECT SUMMARY

The purpose of this project is to focus on improvements to the climate-scale sea surface temperature (SST) analyses produced at NOAA. The major effort has been the development of a new daily optimum interpolation analysis, which was designed use multiple satellite data sets as well as in situ data. There are two products. One product uses infrared satellite data from the Advanced Very High Resolution Radiometer (AVHRR). The second product uses AVHRR and microwave satellite data from the Advanced Microwave Scanning Radiometer (AMSR) on the NASA Earth Observing System. The AVHRR-only product now begins in November 1981 and the AMSR+AVHRR product begins in June 2002 when the microwave satellite data became available. Both products include a large-scale adjustment of satellite biases with respect to the in situ (ship and buoy) data. Two products are needed because there is an increase in signal variance when microwave satellite data became available due to its near all-weather coverage.

Additional efforts have been carried out to improve the Extended Reconstruction SST analysis. This analysis presently uses in situ data and begins in 1854. The reconstructions were produced from a low frequency (or decadal-scale component) and from a residual high-frequency component. The high frequency analysis was performed by fitting the observed high frequency anomalies to a set of large-scale spatial-covariance modes. A new version is produced which improves the damping in the late 19th century. However, satellite data which was originally added beginning in 1985 has now been removed because of residual biases which impacted the trend and yearly rankings.

One of the important goals of the Sustained Ocean Observing System for Climate is to improve the SST accuracy over the global ocean. Because of the high coverage of satellite data, in situ data used in the analysis tends to be overwhelmed by satellite data. Thus, the most important role of the in situ data in the analysis is to correct large-scale satellite biases. Simulations with different buoy densities showed the need for at least two buoys on a 10^{o} spatial grid. This will ensure that satellite biases do not exceed 0.5^{o}C. Using this criterion, regions were identified where additional buoys are needed, and a metric was designed to measure the adequacy of the present observing system. Improved bias correction methods now being developed may reduce the needed sampling.

Richard W. Reynolds serves on the Ocean Observation Panel of Climate (OOPC) and the Global Ocean Data and the Assimilation Experiment High Resolution Surface Temperature Pilot Project (GHRSST-PP) Science Team. Members of both groups consist of well-known national and international scientists. All work presented here follows the Global Climate Observing System (GCOS) Ten Climate Monitoring Principles.

2. FY 2006 PROGRESS

2.1. The High-Resolution Daily SST Analyses

During FY2006, two new daily 1/4° SST analyses were developed: the AVHRR-only daily optimum interpolation (OI) from January 1985 to present and the AMSR+AVHRR daily OI from June 2002 to present. During FY2007 a Journal of Climate paper was written to describe the product (see Reynolds et al., 2007). Both analyses use in situ data and use a satellite bias correction. In FY2007 a web server was developed: http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php. The server allows users to get information on how the analyses were generated and to download the data in NetCDF or IEEE binary. The user interface also allows users to generate plots as needed and to generate digital output files in different formats including ASCII.

In FY2008, the daily analysis was upgraded to version 2. These changes primarily consist of additional temporal smoothing. In addition, a preliminary Pathfinder dataset as been prepared using NOAA-7 following Kilpatrick et al. (2001). Using these data, the AVHRR-only daily OI was extended backward in time to November 1, 1981. Complete details of the improvements are given in Appendix A – What's new in version 2. Version 2 is now being run in real-time.

2.2. The Historic ERSST Analysis

In FY2007 changes were made to NOAA's Historical Merged Land-Ocean Surface Temperature Analysis. This version is version 3 and is documented in Smith et al. (2008). The analysis is derived from two independent analyses, a sea surface temperature (SST) analysis, the Extended Reconstruction of SST version 2 (ERSST), and a land surface temperature analysis using the global historical climatology network temperature database.

As explained in the preprint, there are 2 major changes of version 3 over version 2. First, the tuning procedures were improved using simulated data. The result of the change is that data have a stronger influence on the analysis prior to 1930. The second change was the addition of satellite data to the SST analysis beginning in 1985. Although, the satellite data were corrected with respect to the in situ data as described in preprint, there was a residual cold bias that remained as shown in Figure 4 Smith et al. (2008). The bias was strongest in the middle and high latitude Southern Hemisphere were in situ data are sparse. The residual bias led to a modest decrease in the global warming trend and modified global annual temperature rankings. To avoid this problem, the satellite SST data were removed from version 3. To distinguish this change, the latest version is termed version 3b; the version described in the preprint is version 3a.

Version 3b also has one additional change. The most recent ICOADS in situ data were used through 2006 supplemented by GTS after 2006. In addition, the same quality control procedures have been used through out the analysis period. This change was very modest and impacts the global monthly mean values by less than 0.02°C.

There is also a one additional minor change in both version 3a and 3b and described in the preprint. The sea ice data are now processed directly. This change allows the analysis to be made in a more timely fashion. Analyses for the previous month are now available on the third day of the current month.

2.3. Design of an In Situ SST Network to Improve the SST Analysis

During the preceding years, an in situ network to correct "potential satellite bias errors" was determined using simulated biased satellite retrievals and simulated unbiased buoy data. The maximum "potential satellite bias error" was selected to be 2^{o}C as a worse case. Thus, the "potential satellite bias error" would be 2^{o}C if there were no in situ data to correct the bias. The data density of the present in situ network was evaluated to determine where more buoys are needed. These buoys could be either moored or drifting. However, because of the high cost of moored buoys, they will be assumed to be drifters. To reduce the potential satellite bias to below 0.5^{o}C, a buoy density of about 2 buoys/10^{o} grid is required. The present in situ SST observing system was evaluated to define an equivalent buoy density allowing ships to be used along with buoys according to their random errors. These figures are operationally produced seasonally and are used to guide surface drifting buoy deployments. Updated documentation is available in a recent paper by Zhang, et al. (2008).

3. REFERENCES

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Smith, T.M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore, 2008: Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880-2006). *J. Climate,* **21***,* 2283-2296.

Zhang H. M., Reynolds, R.W., Lumpkin, R., Molinari, R., Arzayus, K., Johnson, M., and Smith T.M., 2008: An Integrated Global Ocean Observing System for Sea Surface Temperature Using Satellites and In situ Data: Research-to-Operations. *Bull. Amer. Meteor. Soc.*, **89,** in press.

4. FIGURES

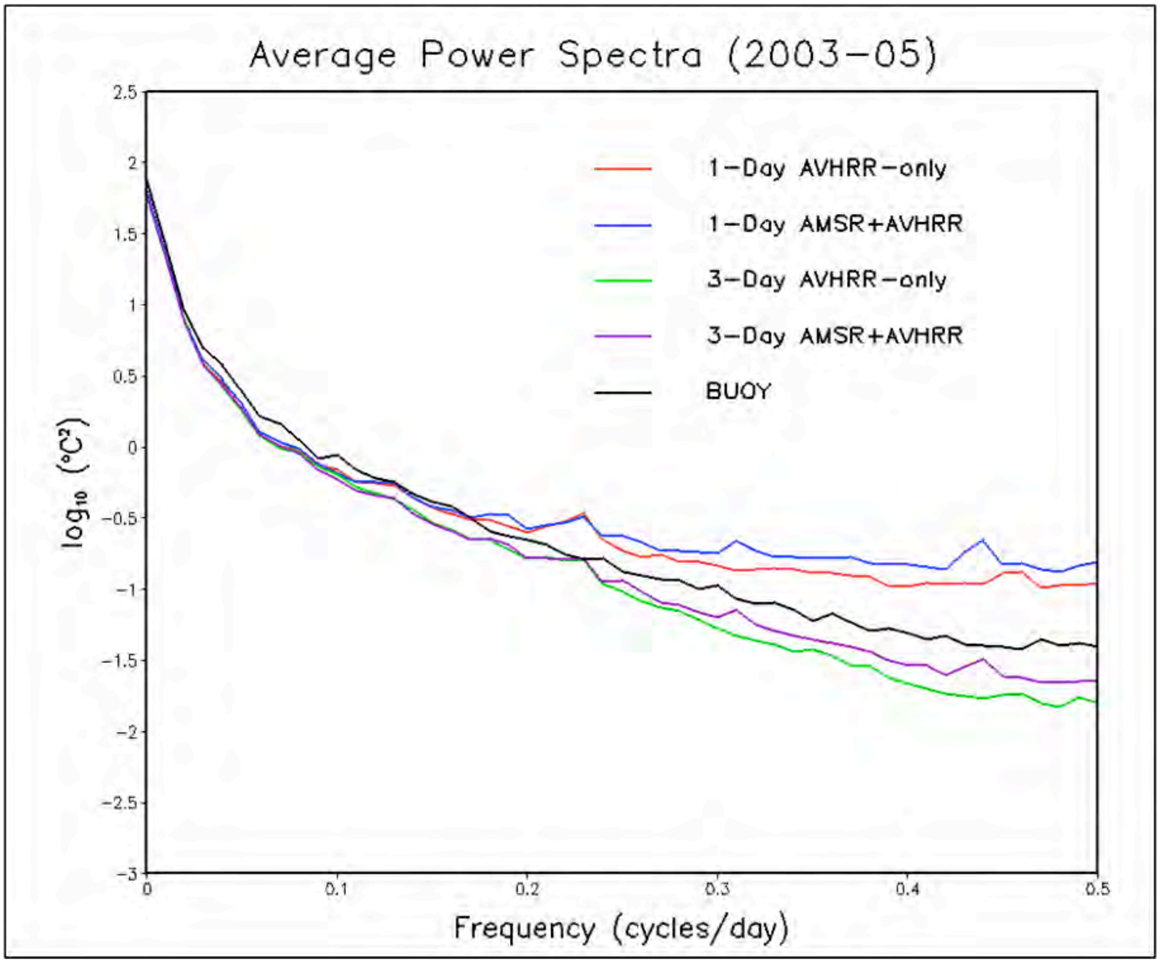

Figure 1. Globally averaged daily spectra for 2003-05 computed at 43 moored buoy locations and averaged. 'AVHRR-only' and 'AMSR+AVHRR' indicate daily OI spectra using either 1-day or 3-days of data. 'Buoy' indicates spectra using daily buoy data.

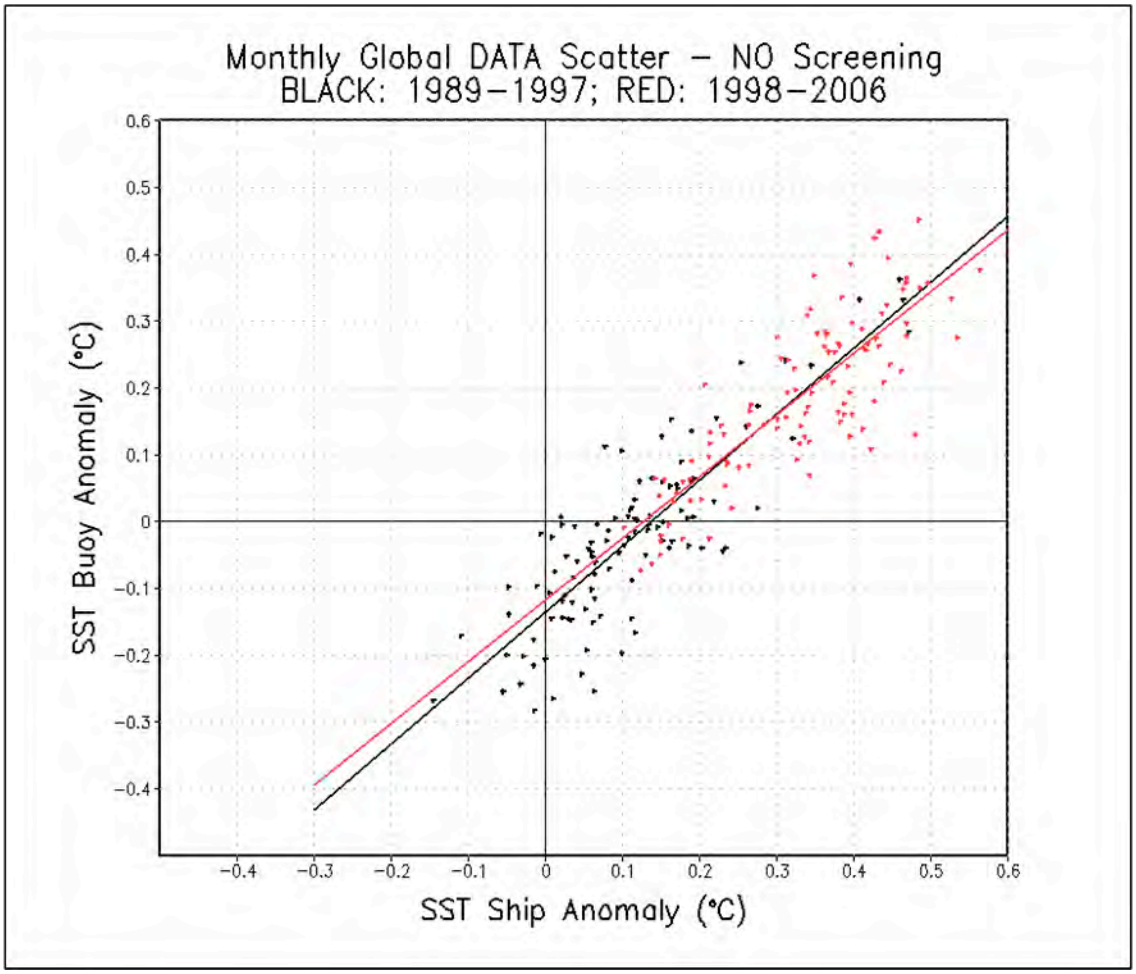

Figure 2. Scatter plot of global collocated average monthly ship vs. buoy anomaly for January 1989 - December 2006. The first 9-years are shown in the black and the second 9-years in red. Least squares linear fits for the two periods are also shown.

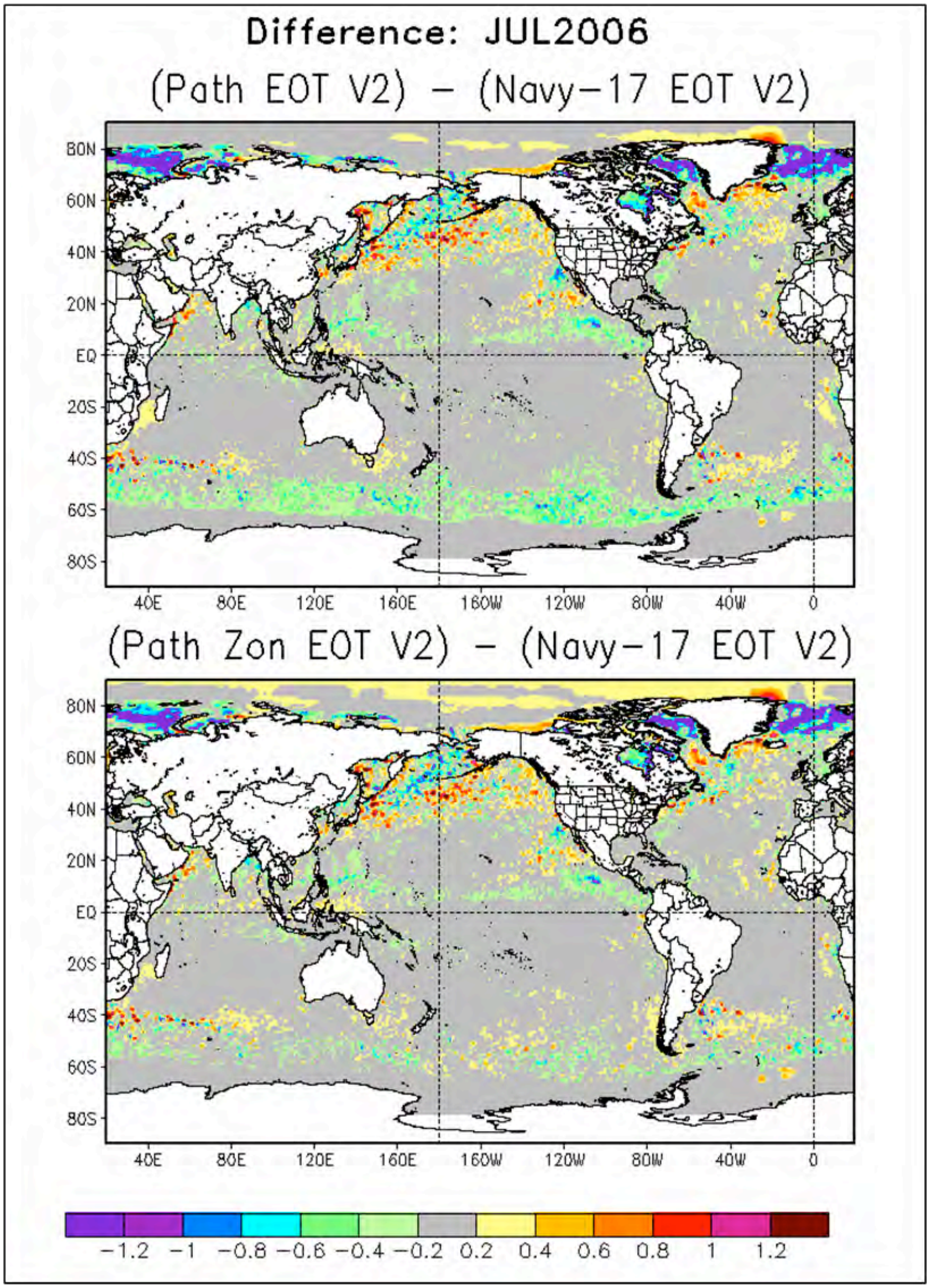

Figure 3. Average July 2006 difference between the daily AVHRR-only OI using Pathfinder NOAA-17 data and Operational Navy NOAA-17 data. All versions use bias corrected satellite data. In the top panel the Pathfinder daily OI uses no preliminary zonal bias correction; in the bottom panel the Pathfinder daily OI uses a preliminary zonal bias correction.

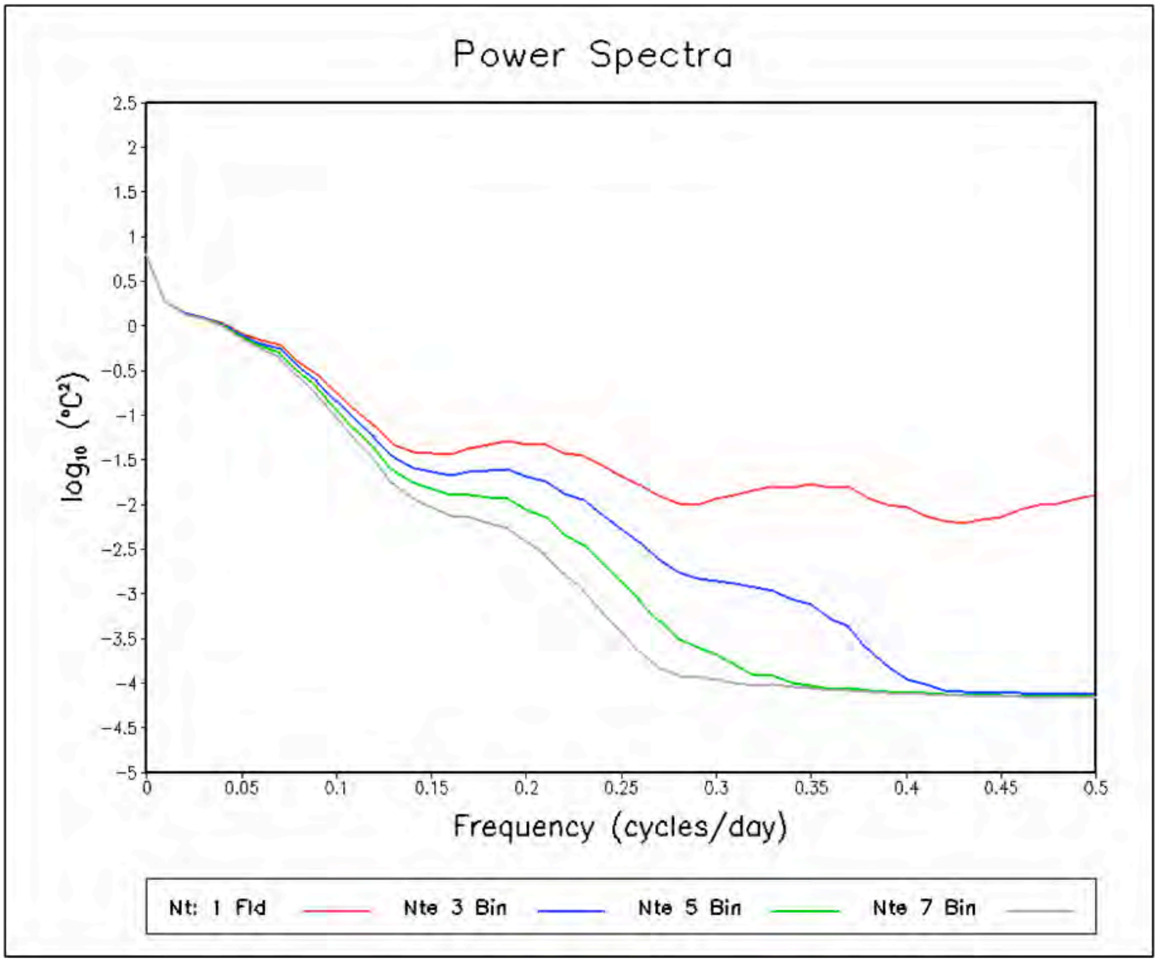

Figure 4. Spatially averaged nighttime AVHRR bias correction spectra for 2000-2005. Binomial 3-point, 5-point and 7-point temporal smoothing are shown; an unsmoothed version is labeled 'Nt 1 Fld'.

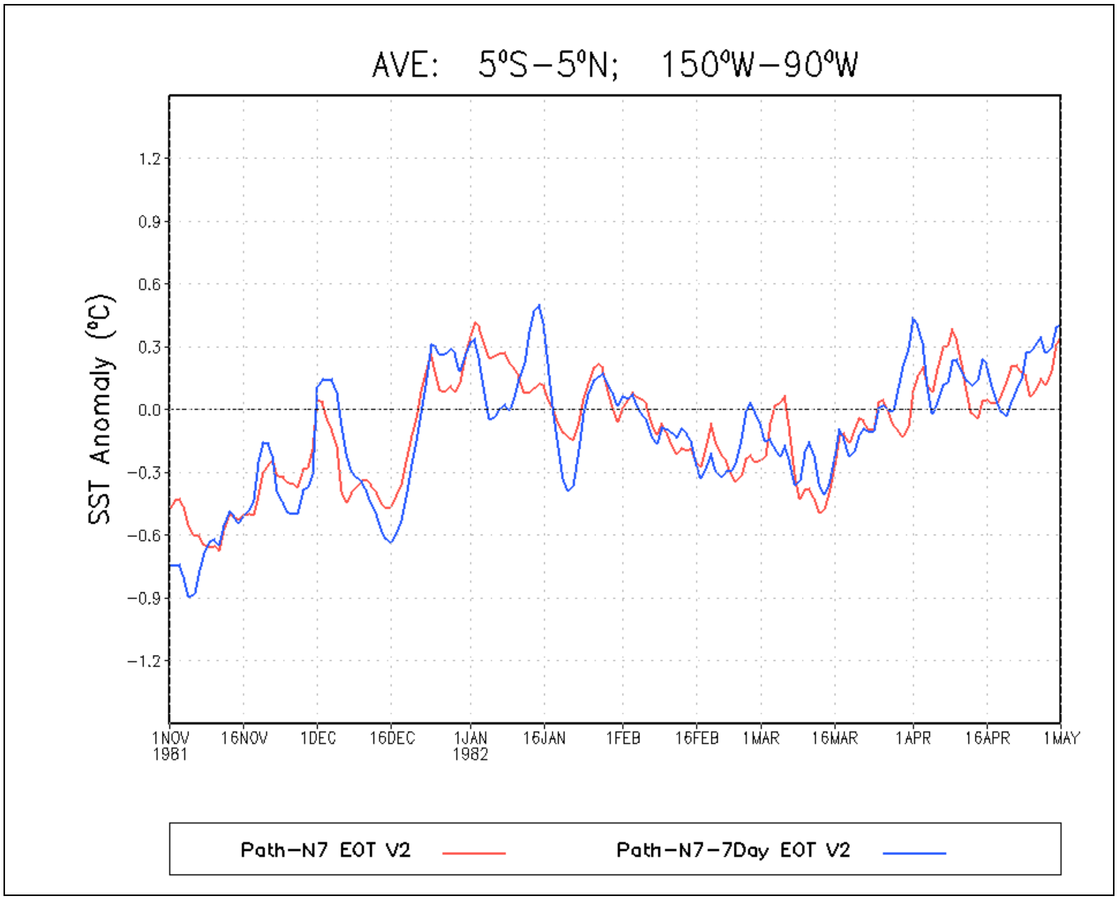

Figure 5. Daily OI Nino-3 anomalies using EOT bias correction with 15 and 7 days of data. 'N-7' indicates that NOAA-7 satellite SST data are used.

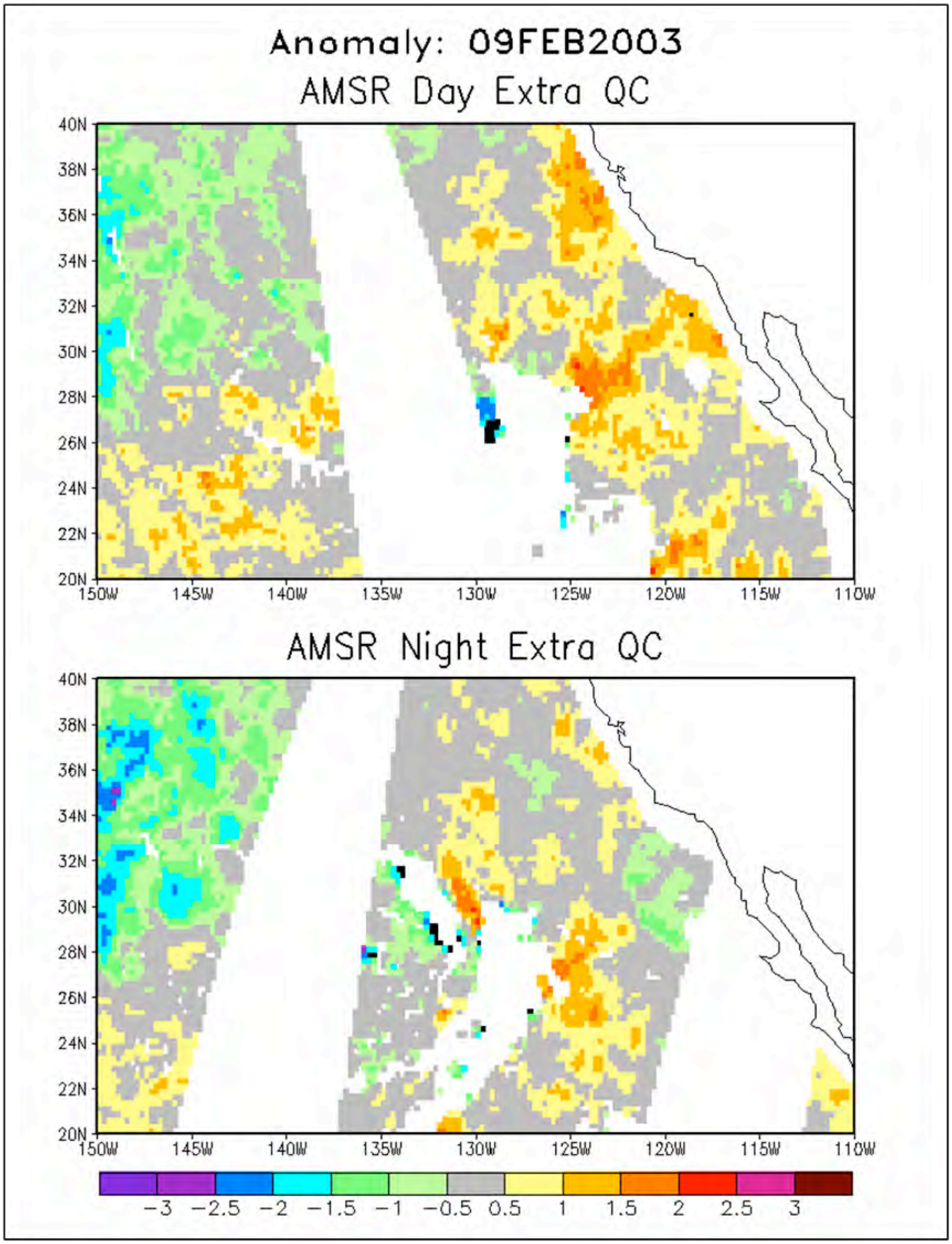

Figure 6. AMSR extra quality controlled SST data anomalies for 9 February 2003. The black regions show where data have been rejected by the extra quality control.

Development of Global Heat and Freshwater Anomaly Analyses

Gregory C. Johnson[1], John M. Lyman[2] and Josh K. Wills[3]
[1]NOAA Pacific Marine Environmental Laboratory, Seattle WA
[2]University of Hawaii/JIMAR, NOAA Marine Environmental Laboratory, Seattle WA
[3]Jet Propulsion Laboratory, Pasadena CA

1. PROJECT SUMMARY

Understanding global climate variability requires knowledge of ocean temperature and salinity fields (or more precisely ocean heat and fresh water content). Accurate estimates of changes in distribution of ocean heat and fresh water content combined with an analysis of how thermohaline (temperature-salinity) anomalies enter, circulate within, and leave the ocean is necessary to monitor and understand interannual to decadal changes in climate. Such fields and analyses help to verify climate models and improve their predictive skill. They help to diagnose the components of sea level change (ocean temperature variations versus ocean mass variations).

This project is developing, updating, and analyzing global analyses of ocean temperature and salinity using quality-controlled compilations of in situ temperature and salinity data from CTD-equipped autonomous profiling floats (Argo), shipboard Conductivity-Temperature-Depth (CTD) instruments, eXpendable Bathy Thermographs (XBTs), moored buoys, and other sources. These data are used to estimate global ocean temperature and salinity fields, hence ocean heat and freshwater content variations, on annual time-scales. Historically, in situ data distributions are relatively sparse, especially before the advent of Argo. However, variations in ocean heat content are closely related to variations in sea-surface height, which has been very well measured since late 1992 by satellite altimeters. By exploiting this close relationship, we are able to quantify sampling errors inherent in estimating a global average of upper ocean heat content from an incomplete data set. We can also exploit the relationship to improve maps of ocean heat content from in situ data by using the altimeter data with local correlation coefficients applied as a first guess at upper ocean heat content in poorly measured regions.

This project, a part of the NOAA Office of Climate Observations Ocean Observing System Team of Experts, by providing analyses of ocean data, helps NOAA to use and assess the effectiveness of the sustained ocean observing system for climate. The work is primarily carried out at NOAA's Pacific Marine Environmental Laboratory by the PMEL and JIMAR investigator, but in very close consultation with the co-investigator at NASA's Jet Propulsion Laboratory.

2. PROJECT ACCOMPLISHMENTS

In FY2008 yearly ocean heat content maps were made by combining in situ temperature profiles with sea surface height anomalies from satellite altimeter data for 1993 through 2007 and reported upon (Johnson et al. 2008). Sea surface salinity maps were also made for 2005 through 2007 and reported upon (Johnson and Lyman, 2008). We wrapped up our study on the effects of sparse historical in situ ocean temperature sampling patterns on global integrals of upper ocean heat content changes (Lyman and Johnson, 2008). Work also continued on quantifying and documenting two sets of instrument errors, XBT fall rate errors and misreported Argo float pressures (Wijffels et al., 2008; Willis et al., 2008).

We updated maps (e.g. Figure 1) of annual upper (0-750 m) ocean heat content primarily for the ice-free portions of the globe from 1993 through 2007 combining in-situ and satellite altimetry data (following Willis et al. 2004) to better resolve smaller (sub-gyre) scale spatial variability over shorter (year-to-year) time-scales for the 2007 State of the Climate Report (Johnson et al., 2008). Prior to making these maps, we removed Argo float profile data with known potential serious pressure biases from our database, and applied the annual fall rate correction estimates for deep and shallow XBT probe data from Wijffels et al. (2008). Johnson et al. (2008) discuss the results.

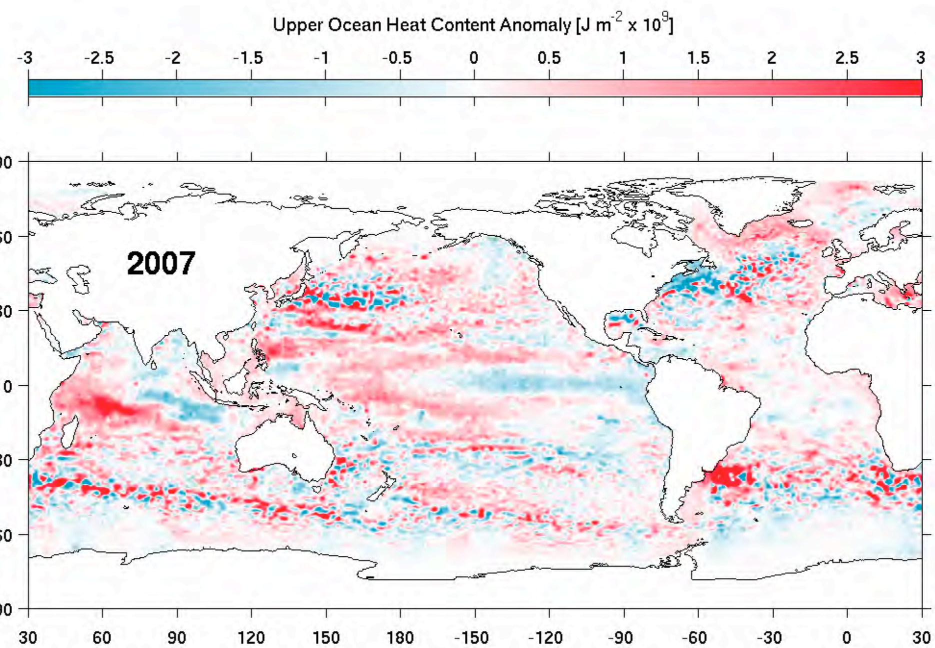

Figure 1. Combined satellite altimeter and in situ ocean temperature data upper (0 – 750 m) ocean heat content anomaly OHCA (J m^{-2}) map for 2007 (top panel) analyzed following Willis et al. (2004), but relative to a 1993 – 2007 baseline. Figure after Johnson et al. (2008).

We continued producing annual average maps of Sea-Surface Salinity (SSS) anomalies with respect to the World Ocean Atlas 2001 Climatology for the 2007 State of the Climate Report (Johnson and Lyman, 2008). These maps (e.g. Figure 2) are only robust for 2005 through 2007, when Argo provided near-global coverage of SSS data. Johnson and Lyman (2008), discuss these results.

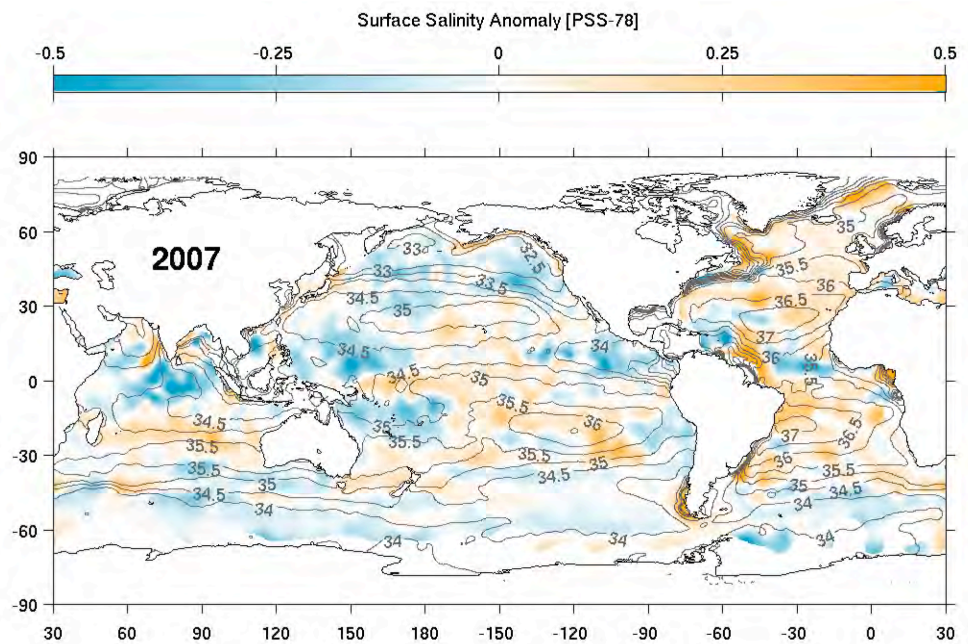

Figure 2. Map of the 2007 annual surface salinity anomaly estimated from Argo data [colors in PSS-78] with respect to a climatological salinity field from WOA 2001 [gray contours at 0.5 PSS-78 intervals]. White areas are either neutral with respect to salinity anomaly or are too data-poor to map. While salinity is often reported in practical salinity units, or PSU, it is actually a dimensionless quantity reported on the 1978 Practical Salinity Scale, or PSS-78. Figure after Johnson and Lyman (2008).

Last year's progress report discussed the effects of sparse in situ temperature profile distributions in pre-Argo years in detail, so that work is not summarized again here. Similarly, the XBT fall rate errors and misreported Argo float pressures were discussed previously and that discussion is not repeated here.

Manuscripts related to this project that were published or submitted for publication in FY2008 are listed below. The project web page is http://oceans.pmel.noaa.gov/.

3. PUBLICATIONS AND REPORTS

Johnson, G. C., and J. M. Lyman, 2008: Global Oceans: Sea Surface Salinity. *In* State of the Climate in 2007, D. H. Levinson and J. H. Lawrimore, Eds., *Bulletin of the American Meteorological Society*, **89**, *7*, S45–S47, doi:10.1175/BAMS-89-7-StateoftheClimate.

Johnson, G. C., J. M. Lyman, and J. K. Willis, 2008: Global Oceans: Ocean Heat Content. *In* State of the Climate in 2007, D. H. Levinson and J. H. Lawrimore, Eds., *Bulletin of the American Meteorological Society*, **89**, *7*, S39–S41, doi: 10.1175/BAMS-89-7-StateoftheClimate.

Lyman, J. M., and G. C. Johnson. 2008a: Equatorial Kelvin Wave influences may reach the Bering Sea during 2002 to 2005. *Geophysical Research Letters*, **35**, L14607, doi:10.1029/2008GL034761.

Lyman, J. M., and G. C. Johnson. 2008b: Estimating global upper ocean heat content despite irregular sampling. *Journal of Climate*, doi:10.1175/2008JCLI2259.1.

Wijffels, S. E., J. Willis, C. M. Domingues, P. Barker, N. J. White, A. Gronell, K. Ridgway, and J. A. Church, 2008: Changing eXpendable Bathythermograph Fall-rates and their Impact on Estimates of Thermosteric Sea Level Rise, *Journal of Climate*, in press, doi:10.1175/2008JCLI2290.1

Willis, J. K., D. P. Chambers, and R. S. Nerem, 2008a: Closing the Globally Averaged Sea Level Budget on Seasonal to Interannual Time Scales. *Journal of Geophysical Research - Oceans*, **113**, C06015, doi:10.1029/2007JC004517.

Willis, J. K., J. M. Lyman, J. M., G. C. Johnson, and J. Gilson, 2008b: In situ data biases and recent ocean heat content variability. *Journal of Atmospheric and Oceanic Technology*, doi:10.1175/2008JTECHO608.1.

Ocean Heat and Freshwater Content Variability Estimates

Sydney Levitus
NOAA National Ocean Data Center, Silver Spring MD

1. PROJECT SUMMARY

When people speak of climate they are often referring to the climate of the atmosphere at the earth's surface. This is where humankind lives and it is only natural to be concerned about the immediate space that humankind inhabits. However, in order to understand the working's of earth's climate system, and to be able to forecast changes in earth's climate system, we need to study all components of earth's climate system including the atmosphere, the world ocean, the cryosphere (earth's ice such as continental ice sheets and mountain glaciers), the lithosphere (earths' continents) and the biosphere. Each of the components of the climate system except for the biosphere can store heat and the ocean, atmosphere, and even the cryosphere can transport heat. Both the storage and transport of heat are important processes that maintain our climate system. The biosphere does not store substantial amounts of heat but it can affect how much heat is stored within each components of earths' climate system.

Rossby (1959) suggested that the world ocean may be the dominant component of the earth's heat balance on interannual- to-decadal- time scales. Rossby did not discuss what we now term "anthropogenic" or "human-induced" warming of earth's climate system. Recent work (Levitus *et al*. 2000, 2001, 2005) has shown Rossby to be correct. Ishii et al. have duplicated these first estimates of the temporal variability of earth's heat content.

During 1955-98 the world ocean (0-3000 m depth) warmed and accounted for more than 80% of the increase in the earth system's heat content. The heat content of the world is now recognized as being a critical variable to describe the earth's climate system. Increasing greenhouse gases will result in an increase of the heat content of the earth system with most of the warming occurring in the world ocean. During 1955-2003 the upper 700 m has warmed but during 2004-2005 this layer of the world ocean cooled.

The NODC Ocean Climate Laboratory (OCL) has provided international leadership in the development of ocean profile databases to provide the data used to make the first estimates of ocean heat content (OHC) during the 1955-present period. Sydney Levitus is Leader of the IOC Global Oceanographic Data Archaeology and Rescue project (Levitus *et al.,* 2004a). This project has resulted in a doubling of historical ocean temperature profiles for the pre-1991 period. Our work is exemplary of the bullet in the Summary of user recommendation for observing system enhancements from the 2004 Annual System Review which is "Build the ocean profile database necessary to compute ocean heat content".

Our work on OHC has attracted considerable attention from the scientific community, Congress, and the media.

Our work has been used in IPCC Assessments most recently in the IPCC 2007 Assessment. The IPCC has received the Nobel Peace Prize for 2007. Our work has also been used in an NRC Report to President Bush.

2. ACCOMPLISHMENTS

During FY08 the P.I. and his colleagues focused on correcting historical and modern data for recently discovered systematic errors in bathythermograph (BT) data. Figure 1 is an example of our most recent work and shows the time series of OHC for the 0-700 m layer of the world ocean through the end of 2007. After reaching a relative maximum in heat content during 2003, world ocean heat content has approximately stayed level. Correction of the biases in BT data results in a reduction of the interdecadal variability.

A major goal of this proposal has been to prepare estimates of ocean heat content every three months and make them available online. This had to be delayed because of the discovery of systematic time-varying errors in the drop rates of XBTs and MBTs and in biases found in profiling floats (PFL). We have corrected for these biases and have begun generating seasonal OHC estimates. Figure 2 shows the time series of seasonal estimates for 1955-2007. These seasonal estimates also appear in Figure 3 with each season plotted separately.

The P.I. was a Lead Author of the IPCC (2007) assessment of earth's climate system. The work published by the P.I. and his colleagues plays a prominent role in Chapter 5 of the IPCC (2007) climate change assessment which was awarded a Nobel Peace Prize.

All of our data are made available within three months of receipt at the NODC Home Page (www.nodc.noaa.gov).

3. PUBLICATIONS AND REPORTS

Levitus, S., J. I. Antonov, T. P. Boyer, 2005: Warming of the World Ocean, 1955-2007. Geophys. Res. Lett., in preparation.

4. FIGURES

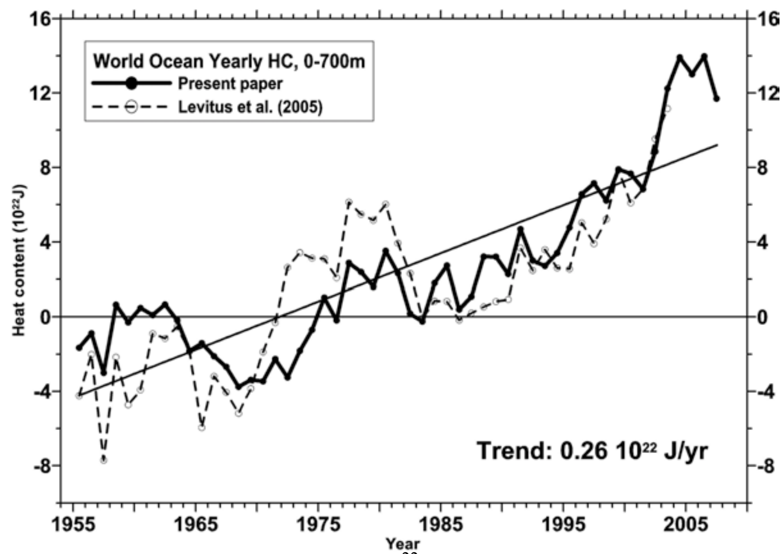

Figure 1. Time series of yearly ocean heat content (10^{22}J) for the 0-700 m layer from this study (solid) and from Levitus *et al.* (2005) (dashed). Each yearly estimate is plotted at the midpoint of the year.

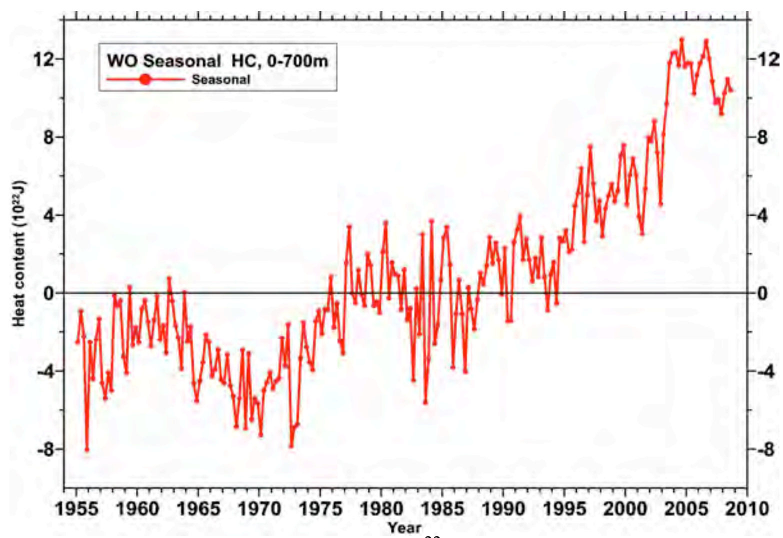

Figure 2. Time series of seasonal ocean heat content (10^{22}J) for 0-700 for 1955-2008.

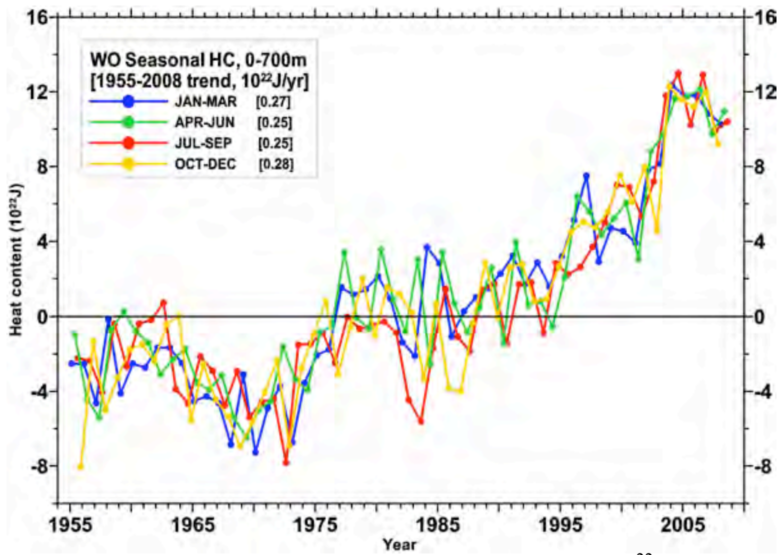

Figure 3. Individual seasonal time series of yearly ocean heat content ($10E^{22}$ J) for the 0-700 m from this study and their trends for 1955-2008.

Evaluating the Ocean Observing System:
Performance Measurement for Heat Storage

Claudia Schmid and Gustavo Goni
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1. PROJECT SUMMARY

The main objective of this project is to provide quarterly reports that evaluate the accuracy of estimates of the global upper ocean heat storage and its time derivative. This product will show (a) locations where upper ocean temperatures were collected in each quarter, (b) how well the observations satisfy the GOOS/GCOS temperature requirements, (c) the locations where future observations are needed to improve the observing system, and (d) how successfully the system reduces the potential bias error. This product will display the performance in terms of these goals since January 1997 and will be used to detect anomalies of the heat storage. The evaluation will incorporate profiles of temperature and salinity from XBTs, CTDs and Argo floats. In addition these estimates will be compared with heat storage estimates from altimetry. The heat storage estimates from altimetry will also be used to extend the heat storage fields into regions where the coverage with in-situ data is poor. An example of a quarterly product is given in Figure 1.

Profiles from XBT, CTD and profiling floats, and data from profiling floats are part of the Global Ocean Observing system. The increasing number of profiles makes an improved estimation of the upper ocean heat storage possible. This parameter is critical for the understanding of the climate system and it has been shown to have a significant impact on the weather over adjacent landmasses and on the strength and frequency of tropical cyclones. Therefore, improving the accuracy of estimates of the upper ocean heat storage and budget is key for climate research.

In this work we estimate the heat storage of the upper ocean on a quarterly basis on a regular grid, both for the mixed layer and for layers of constant depths. To accomplish this, upper ocean temperatures from various sources and instruments (WOD 2001, GTSPP, Argo, XBTs, including high-density lines; thermistor chains; profiling floats; CTDs) are being combined.

All profiles undergo a series of quality control tests to ensure that only profiles of good quality are used in the analysis. For Argo floats these tests are described in a document available on the Internet (http://www.ifremer.fr/coriolis/cdc/argo_rfc.htm - link to ``Argo Real-time Quality Control Tests Procedures"). Similar tests are applied to all non-float profiles. Additionally, quality control tests are performed to detect profiles that deviate significantly (by 10 standard deviations or more) from the NCEP reanalysis and the World Ocean Atlas 2001 or from other profiles collected in the same region and time period. Preparatory work was performed in the Atlantic to ensure that XBT and float profiles can be combined without introduction of artificial climate signals.

The error (potential bias) of the heat storage from in situ observations is derived as based on the statistics and data distribution. The methodology accounts for the error introduced into the estimates by non-uniform spatial and temporal sampling. Firstly, the statistical degrees of freedom of the non-independent observations (e.g. TAO moorings) are homogenized to that of the ARGO array. Weighting factors are computed with the resulting independent observations to quantify their bias with respect to an ideal uniform sampling. The sample standard deviation of the heat storage is computed. Both quantities are derived for a global 5^o by 1.5^o grid. The error of heat storage is computed by weighting the sample standard deviation with the bias factors accounting for non-uniform temporal and spatial sampling.

The currently available upper ocean data set covers the period 1968 to present. The data will be analyzed on a year-by-year basis. For the purpose of this proposal, the quarterly heat storage is being derived for 1992 to present. Once the system is operational an extension into earlier years will also be attempted.

Additionally, comparisons between altimetry- and hydrographic-derived estimates of upper ocean heat storage are conducted. They allow us to investigate the extent in depth of the sea height signal in different regions of all ocean basins. The local changes in upper ocean heat storage are estimated from altimetry-derived sea height anomaly fields, using regressions based on historical in-situ observations. For example, similar estimates of altimetry-derived heat storage are currently used to identify long periodic climate signals, such as the variability of the warm pool in the western Pacific Ocean associated with El Niño.

Of key interest are the dynamical effects that have been shown to be dominant over steric effects in some regions, where a very weak sea surface signal is observed as a compensation of these two components. Altimetry observations will also allow us to complete our estimates in regions where hydrographic data are not available or severely under-sampled in space and time.

2. ACCOMPLISHMENTS

We continued creating the Quarterly Status Report for the heat storage of the mixed layer from in situ observations on a quarterly basis (example in Figure 1). We developed a method to derive the error of this heat storage and extended the time series back to 1992. This product will be used as guidance for the future collection of hydrographic data. It will also achieve the objective required by OCO to identify the locations where anomalies occurred. We created a quarterly report of the heat storage in the upper 750 m using satellite altimetry in conjunction with in situ observations (example in Figure 2). The methodology is described below. The quality of the heat storage estimates from satellite altimetry is quite good in mid and low latitudes. The method can not be used in high latitudes, partly because the coverage with satellite and in situ data is insufficient. Eventually, the estimates based on satellite altimetry may help to optimize the in-situ observation system by increasing the number of collected profiles in regions where the satellite-derived estimates are less reliable. The trend in the top right panel of Figure 2 is due to increases in the satellite-derived sea surface height anomaly. This trend could be, for example, due to ocean warming, haline effects or changes in the geoid.

A web site that reports on various key variables describing the state of the ocean (AOML/SOTO) is available. This site gives an outline of the methodology, links to OCOs web site, and links to a web site that shows monthly estimates of the heat storage rate of the mixed layer in the tropical Atlantic together with the mixed layer properties. Please refer to this site: www.aoml.noaa/gov/phod/soto/.

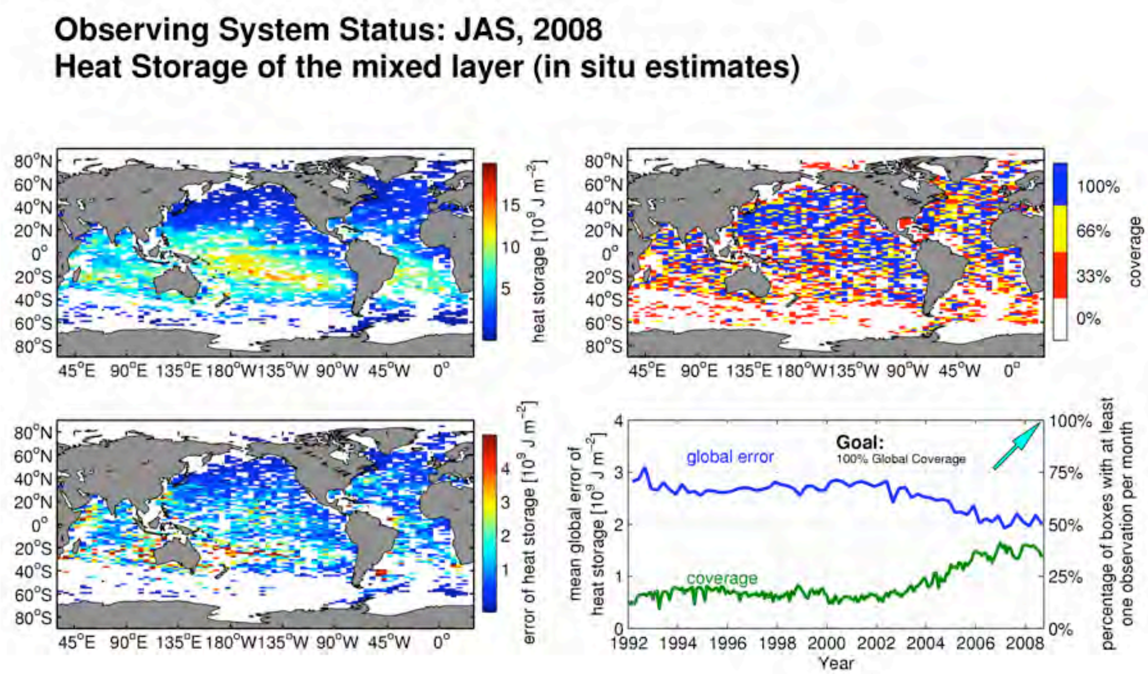

Figure 1. Most recent estimate of Quarterly System Status Report for heat storage of the mixed layer, covering the time period July through September 2008.

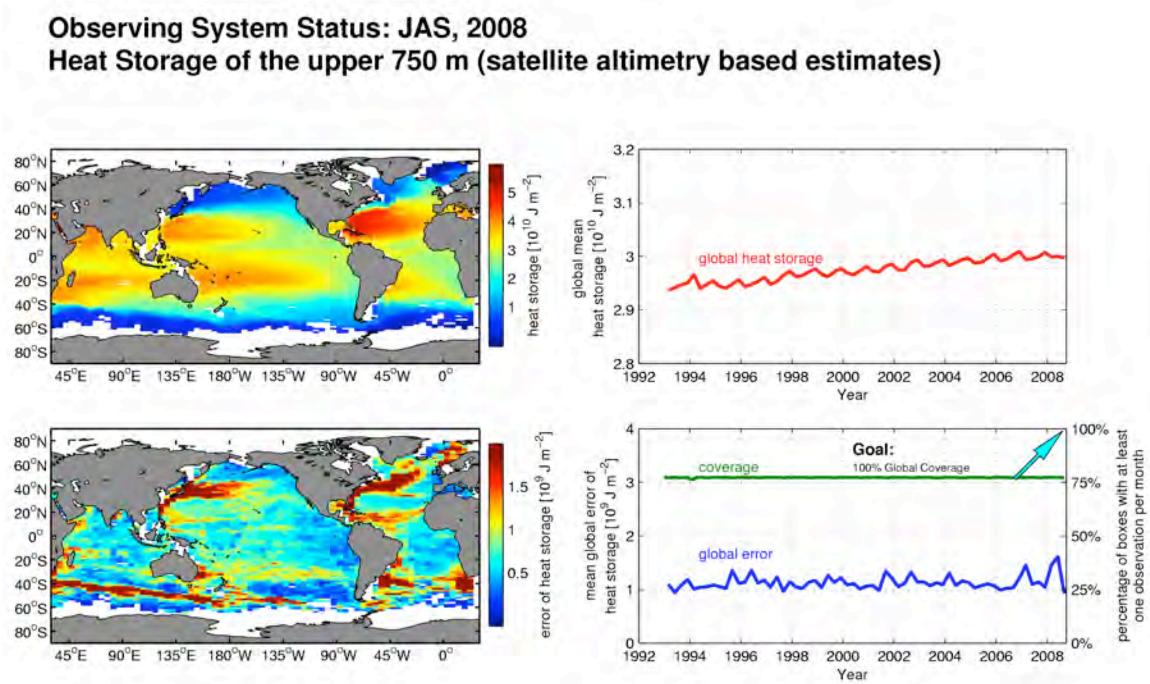

Figure 2. Example of Quarterly System Status Report for heat storage of the upper 750 m, covering the time period July through September 2008. The goal is to generate these quarterly reports regularly.

The correlation coefficient between the sea height anomaly and the oceanic heat storage derived from the hydrographic profiles is computed for different layers (an example is given in Figure 3). The layers are: mixed layer (the mixed layer depth is defined as the depth where the vertical temperature gradient is larger than 0.05ºC/m) and from the surface to selected depths (50m to 1000m, with 50m intervals). In areas where the correlation between sea height anomaly and the oceanic heat storage is good, the altimeter-derived sea height anomalies can be used as a proxy to estimate the upper ocean heat storage. Our results indicate that global correlation coefficients are low (0.5) for the mixed layer and 50m, but that they exceed 0.6 for layer depths of 100m or more.

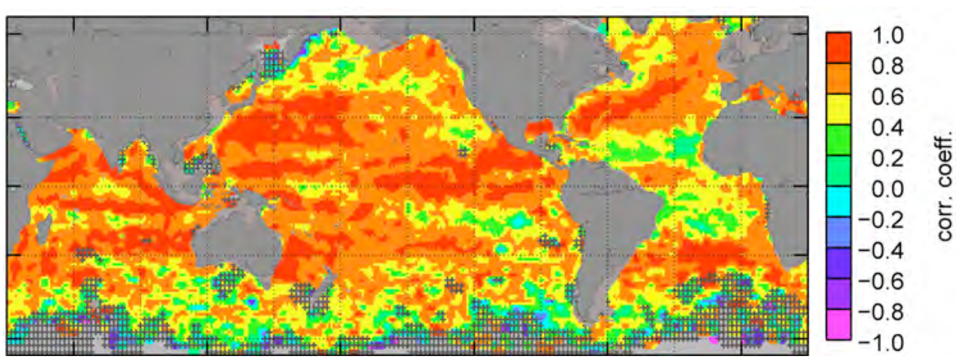

Figure 3. Correlations coefficients between the sea height anomaly and the observed upper ocean heat storage for the upper 750m.

The trend of the heat storage for each layer is derived from the heat storage fields for the 15-year long record (an example is given in Figure 4). In some regions, these trends are related to shifts of currents (e.g. Kuroshio, Gulf Stream). In other regions the changes may be due to heat storage or haline effects.

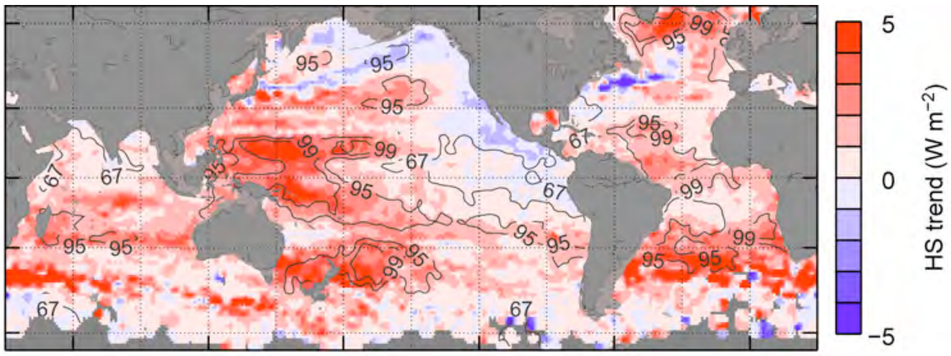

Figure 4. Trend of heat storage for the upper 750m (bottom).

It has to be cautioned, that the magnitudeof the heat storage derived from these observations may be biased due to the fall rate problems of XBTs. Figure 5 shows estimates of the depth dependent biases between Argo floats and XBTs. Figure 6 shows the impact of these biases on the heat storage. Work is currently underway to resolve this issue.

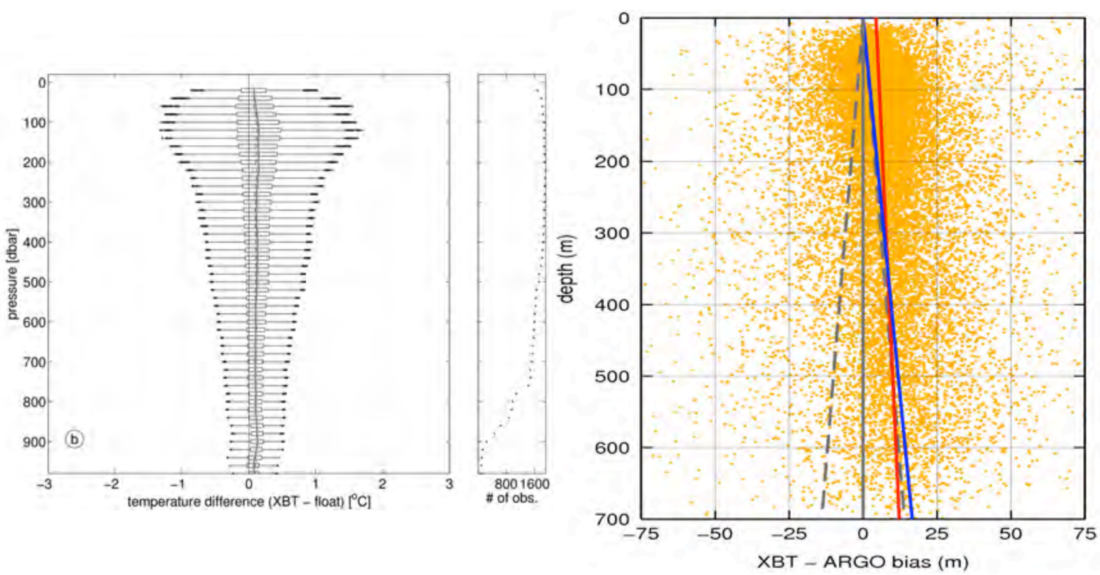

Figure 5. Bias betweeen XBT and Argo profiles. Left: from comparison of nearby profiles. Right: using correlations between satellite altimetry and profiles. Dashed lines are 2% error bounds of the depth specified by the XBT manufacturer. The blue (red) line is a least squares fit of the bias without (with) a 5 m offset at the surface. The blue line is outside of the depth error.

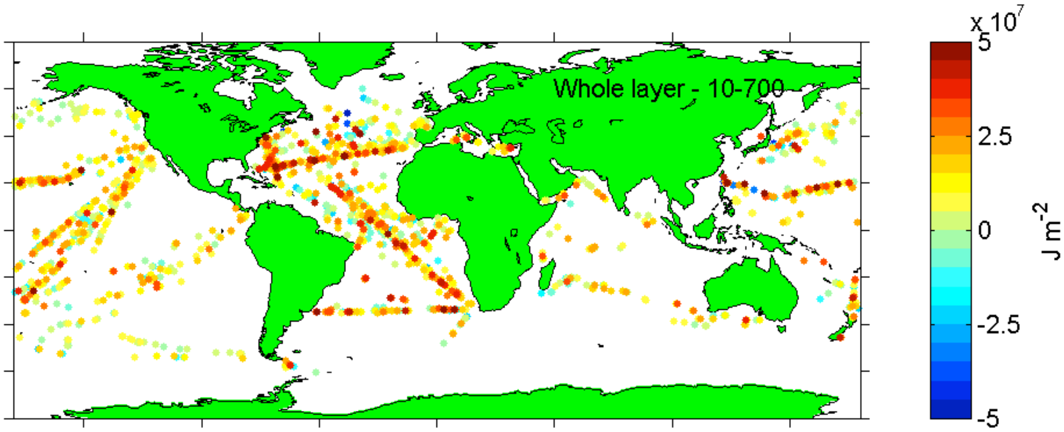

Figure 6. Difference of the heat storage of the upper ocean estimated from floats (including floats with known pressure bin assignment problems in the Atlantic Ocean) and XBTs. Positive values indicate that XBTs overestimate the heat storage. It is obvious that the XBTs yield predominantly larger heat storage estimates than the floats.

Research Highlights.

- Produce status reports of the heat storage of the mixed layer from in situ observations (Figure 1).
- Prepared the first quarterly report of the heat storage in the upper 750 m of the ocean from the combined data set (Figure 2).
- Improved identification of regions where altimetric sea height anomalies are correlated to in-situ observations of heat storage (Figure 3).
- Improved quantification of the error of the altimetry-derived heat storage.
- Develop software to derive trends of the heat storage in the upper 750 m (Figure 4) from the weekly fields derived with the combined data set (altimetry and in situ).

3. PUBLICATIONS

Schmid, C., 2008: Variability of the mixed layer heat budget in tropical Atlantic, in preparation.

Schmid, C., 2008: Comparative analysis of surface heat flux data sets in the Atlantic Ocean. *J. Climate*, submitted.

DiNezio P., G. Goni, C. Schmid, 2008: Identifying and estimating biases between XBT and Argo observations using satellite altimetry, in preparation.

Lentini, C, G. Goni and D. Olson, 2006: Investigation of Brazil Current rings in the Confluence Region. *J. Geophys. Res.,* 111, C06, doi=10.1029/2005JC002988.

Schmid, C., R. L. Molinari, R. Sabina, Y.-H. Daneshzadeh, X. Xia, E. Forteza and H. Yang, 2007: The Real-Time Data Management System for Argo Profiling Float Observations. *J. Atmos. Ocean. Technol*., 24(9), 1608-1628, doi=10.1175/JTECH2070.1.

Schmid, C., 2005: The impact of combining temperature profiles from different instruments on an analysis of mixed layer properties. *J. Atmos. Ocean Technol*., 22(10), 1571-1587, doi=10.1175/JTECH1785.1.

4. MEETINGS

Schmid:
GTSPP Workshop in Hobart, November 12, 2007.
Argo Regional Center Workshop in Hobart, November 13, 2007.
Argo Data Management Meeting in Hobart in November 14 - 16, 2007 (including executive committee on November 12, 2007).
Meeting of the US Argo Panel in Silver Spring, MD, December 12-14, 2007.
XBT fall rate workshop in Miami, March 10-12, 2008.
Office of Climate Observations Review Workshop, Silver Spring, MD, September 3-5, 2008.

Goni:
XBT fall rate workshop in Miami, March 10-12, 2008.
Office of Climate Observations Review Workshop, Silver Spring, MD, September 3-5, 2008.

5. COMMUNITY SERVICE

C. Schmid:
Argo Data Management Team, Executive Committee.
Member of US Argo Panel

G. Goni:
Ocean Surface Topography Science Working Team
WMO/IOC Ship Of Opportunity Program Implementation Panel, Chairman

Quarterly reports on the state of the ocean: Meridional heat transport variability in the Atlantic Ocean

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1. PROJECT SUMMARY

Goal: To contribute to the assessment of the state of the ocean by providing quarterly reports on the meridional heat transport in the Atlantic Ocean. This heat transport is directly related to the role that this basin plays in the meridional overturning circulation (MOC) and is an important benchmark for integrated air-sea fluxes and numerical model performance.

Project Output: "State of the ocean" quarterly estimates of meridional oceanic heat transport in the center of the subtropical gyres in the North and South Atlantic. This project funds the development of a methodology to estimate heat transport variability using data collected along two high density XBT lines operated by AOML, satellite data (altimeter and scatterometer), wind products from the NCEP reanalysis and products from general circulation models. Quarterly reports are posted on the AOML web site.

General Overview: The Atlantic Ocean is the major ocean basin involved in large-scale northward transports of heat typically associated with the meridional overturning circulation (MOC) where warm upper layer water flows northwards, and is compensated for by southward flowing North Atlantic Deep Water. This large-scale circulation is responsible for the northward heat flux through the entire Atlantic Ocean. Historical estimates of the net northward heat flux in the vicinity of its maximum, which occurs in the North Atlantic roughly at the latitude of the center of the subtropical gyre, range from 0.9 PW[1] to 1.6 PW, while estimate in the 30°S to 35°S band are even more uncertain, ranging from negative to more than 1 PW. While much of this variability may be a consequence of the different methods used to estimate the heat transport, natural variability cannot be ruled out. The importance of this heat transport to the world climate together with the possibility of monitoring its variability motivates this project.

AOML collects XBT data on two lines spanning the subtropical oceans: in the North Atlantic since 1995 (quarterly repeats) along AX7 running between Spain and Miami, Florida and in the South Atlantic since 2002 (twice per year until 2004 and quarterly thereafter) along AX18 between Cape Town, South Africa and Buenos Aires, Argentina. These data capture the upper limb of the MOC transport. In the North Atlantic much of the northward transport is confined to a strong boundary current through the Florida Straits, where XBT data can also be usefully augmented with other data from the NOAA/OCO funded Florida Current transport program.

[1] PW is PetaWatt or 10^{15} Watts, a unit of power commonly used for ocean heat transports.

Heat transports have already been successfully computed using XBT data (Roemmich et al, 2001), however the methodology for estimating the transport can be improved. In particular, as density is essential for the flux estimates, results depend on how well salinity profiles can be estimated to complement the XBT data and on how well the profiles can be extended to the bottom of the ocean. Improving these estimates to achieve more accurate fluxes is an essential part of this project, as is a careful quantitative assessment of the accuracy of the resulting fluxes.

Methodology: Northward mass, volume, and heat transport through a vertical plane can be estimated directly from observations. The northward velocity v can be treated as a sum of three terms: (i) a geostrophic contribution (thermal wind equation) relative to a prescribed reference level, (ii) an ageostrophic part modeled as Ekman flow, and (iii) a barotropic part define as the velocity at the reference level. Density ρ can be obtained from XBT data if salinity is accurately estimated and data are extrapolated to the ocean bottom.

$$M = \int\int \rho v \, dxdz \quad [\mathrm{Kg/s}] \qquad V = \int\int v \, dxdz \quad [Sv = 10^6 m^3/s] \qquad H = \int\int \rho c_p \theta v \, dxdz \quad [PW = 10^{15} Watts]$$

Estimates of mass and heat transport have been obtained from temperature profiles collected along AX07 and AX18 high-density lines using Sippican T-7 XBT probes, which typically provide data to 800 m or deeper. Salinity was estimated for each profile by linearly interpolating the closest of Levitus' climatological mean salinity and temperature profiles to the XBT temperature and the climatological profiles were used to extend the data to the bottom. In computing geostrophic velocities, a reference level, based on previous work in the literature and on what is known about the circulation, was prescribed just below the northward flowing Antarctic Intermediate Water (σ_0=27.6 kg m^{-3} in the North Atlantic and σ_0=27.4 kg m^{-3} in the South Atlantic). Within strong flows such as the Florida Current or the Malvinas Current where no level of "no motion" can be found, the transport must be specified (e.g. by the mean value of the Florida Current, etc.). The velocity at the reference level is adjusted so that the net mass transport across the section is zero using a single velocity correction for each section. Typically, values of this correction ranged from 10^{-4} to 10^{-6} m s^{-1}.

2. ACCOMPLISHMENTS

2.1. Products Delivered

Quarterly reports were designed that show the estimated heat transport for each high density XBT section along the AX7 and AX18 lines (Figure 1 and 2) and are posted quarterly on AOML's state of the ocean web site at http://www.aoml.noaa.gov/phod/soto/mht/index.php. Each figure shows: the position of the most recent XBT transect (red) and the position of the all the transects completed to date (blue) (Top left panel); the temperature section corresponding to the last section (top right panel); the time series of the obtained values for the different components of the heat transport (bottom left) and the annual cycle of the heat transport components (bottom right).

Values of heat transport are given in PW (1 PW = 10^{15}W). One PW is equivalent to the amount of electricity produced by *one million* of the largest nuclear power plants in existence today (the largest nuclear plants produce about 1 gigaWatt of electrical power).

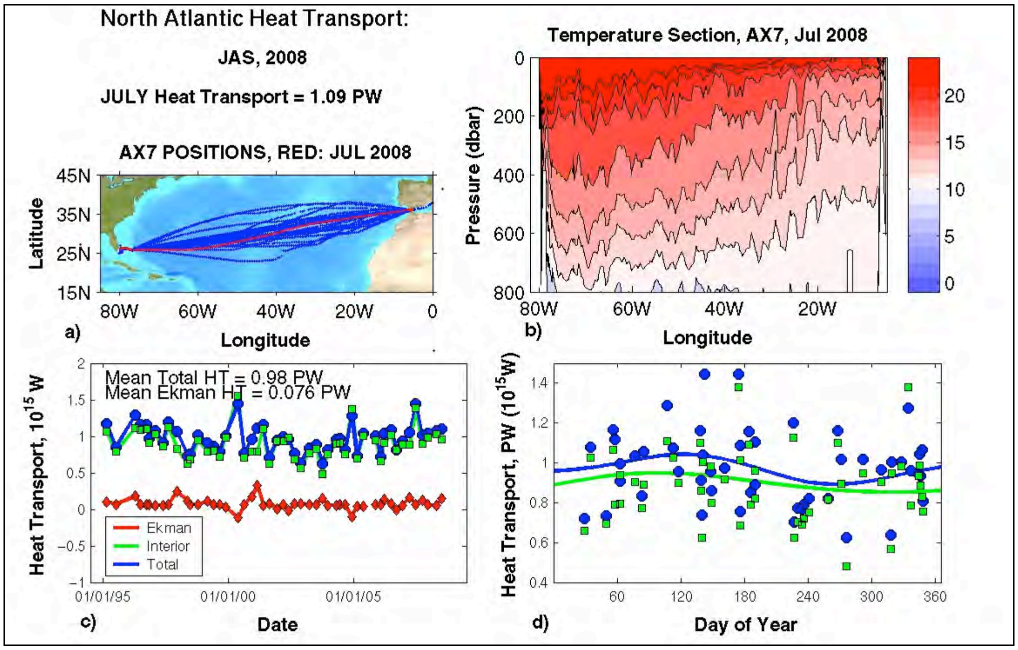

Figure 1: Report for the July-August-September quarter of 2007 for North Atlantic Meridional Heat transport along the AX7 high density XBT line. Transport results based on July 2008 XBT section (positions shown in top left, temperature section shown in top right). Heat transport estimates were decomposed into the geostrophic (interior) and Ekman components and their total (lower left).

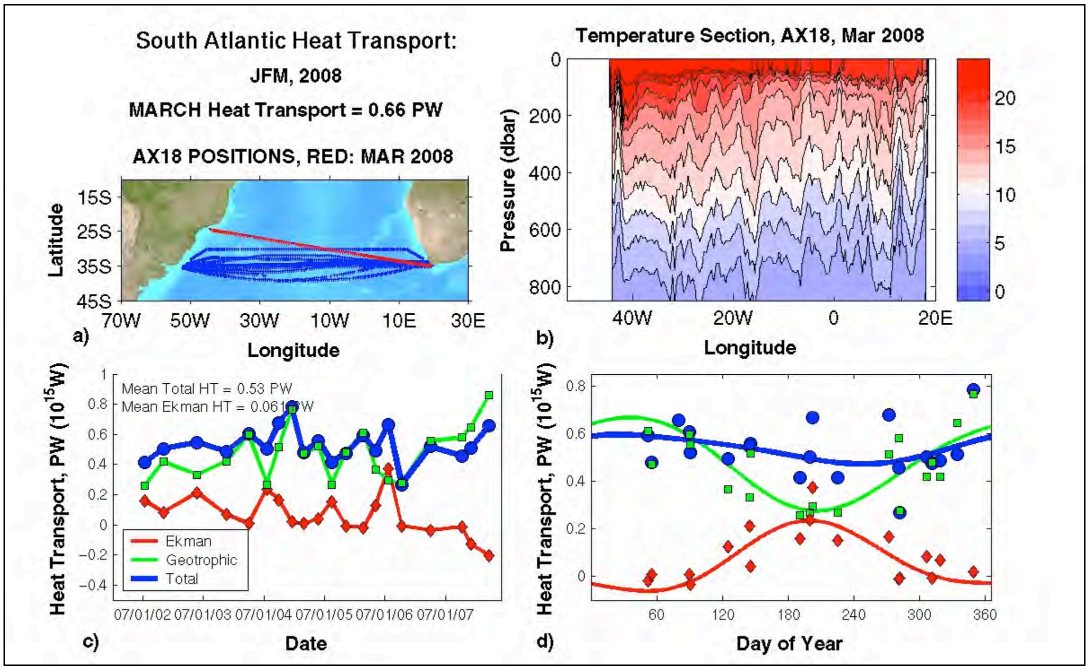

Figure 2: Report for the January-February-March quarter of 2008 for South Atlantic Meridional Heat transport along the AX18 high density XBT line. Transport results based on March 2007 AX18 XBT section (positions shown in top left, temperature section shown in top right). Heat transports were estimated using a shallow (green squares) and deep (red diamonds) reference level (lower left). Total heat transports demonstrate no significant seasonal signal because the seasonal signal in the Ekman layer is directly out of phase with the geostrophic signal (lower right).

2.2. Scientific Findings

South Atlantic:

The methodology described above was applied to the South Atlantic data and an intensive study of the errors was completed (Baringer and Garzoli, 2007). Garzoli and Baringer (2007) applied this method to the fourteen high-density XBT AX18 sections collected between July 2002 and May 2006 to compute the meridional heat transport in the South Atlantic. The integrated volume transport yields a mean value for the total transport east of the Walvis ridge of 28 Sv, 19 Sv for the Brazil Current (between 0 and 800 m) and -9 Sv for the DWBC (2500 to 6000). These values are agreement with the previous calculations obtained from direct observations. The net flow in the center of the basin ranges from 0 to 30 Sv depending on the structure of the wind. The values obtained for the heat transport ranged from 0.40 to 0.81 PW with a mean value of 0.54 PW and a standard deviation of 0.11 PW. The total heat transport does not show any significant change with time (Figure 4). The variability in heat transport may be a consequence of the natural physics of the system or may be related to the difference in cruise track (sampling different physical regimes). The variability of the transports as a function of the mean latitude suggests that there is no obvious relationship between the geostrophic transport (what is actually measured) and the latitude. Therefore, the long-term interannual variability (on the order of 0.4 PW peak to peak) is not convincingly driven by aliasing of the sections in space and is probably best described as 'natural variability'.

Since the paper was published seven additional cruises were conducted. Currently, the container line that was used to conduct the XBT transects, altered there shipping route. Until a new ship company that operates between Cape Town (South Africa) and Buenos Aires (Argentina) can be find to conduct the cruises, the transects are conducted between Cape Town and Santos (Brazil).

The mean results of the 20 realizations are given in Table 1.

Table 1. Results for the total heat transport calculated by Garzoli and Baringer, (2007) (line 1), from the 3 transects conducted between Cape Town and Santos (line 2) and as an average of the 20 realizations (line 3).

Mean Heat transport (14 realizations CT-BA) = 0.53 PW (*Garzoli and Baringer, 2007*)	**Std = ±0.11 PW**
Mean Heat transport (3 transect CT-R) = 0.54 PW	**Std= ± 0.10 PW.**
Mean Heat transport (20 realizations) = 0.53 PW	**Std = ± 0.12 PW**

The variability with time is shown in Figure 3. Different colors represents the different components of the heat transport: geostrophic, Ekman component and total heat transport, the later estimated as the sum of the previous two. The last 3 points (indicated as yellow) correspond to the last 3 cruises conducted along a slightly different route.

The total transport obtained from the last 3 realizations that follows a different route (0.54 PW) doer not differ significantly than the one obtained from the results from Garzoli and Baringer (14 realizations, 0.53 PW). The mean transport from the total 20 cruises is 0.53 ± 0.12 PW.

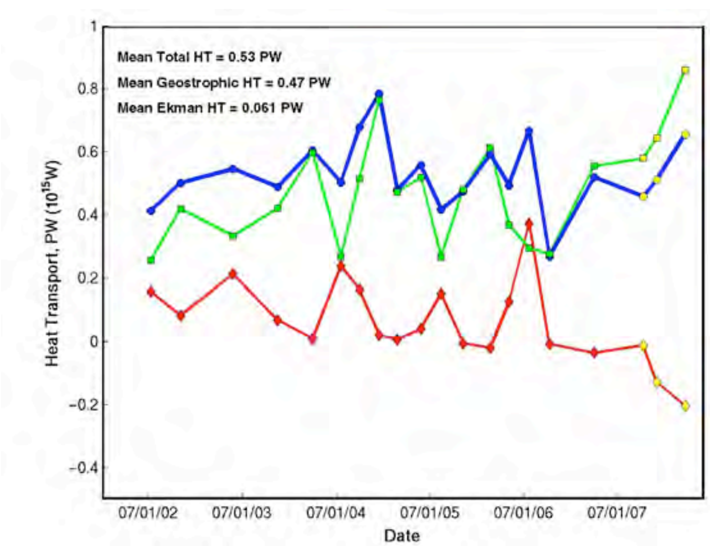

Figure 3. Variability with time of the total (blue), geostrophic (green) and Ekman (red) fluxes. The last three points corresponds to the route Cape Town to Santos.

It is interesting to note that at the end of the record (Figure 3) the geostrophic component has increased while the Ekman component decreased. As a result the total heat transport remains the same. To illustrate why this happens, Figure 4 shows the time series of the Ekman heat transport integrated across the basin as a function of latitude. Dots indicate mean latitude of each cruise. The last 3 cruises (Cape Town to Santos) were conducted at latitude located in the mean further north than the previous transects and in a region where during that time of the year (southern hemisphere summer) the Ekman fluxes are negative. Also during the southern hemisphere summer, the Brazil Current reached its southern-most extension.

As reported by Garzoli and Baringer (2007) the total heat transport shows apparent interannual variability, but does not show a strong indication of seasonality. However the Ekman and geostrophic components of the heat flux (Figure 5) show indications of an annual cycle that explains 80% of the total variance. The cycles are out of phase and therefore the total heat flux does not show any significant seasonality.

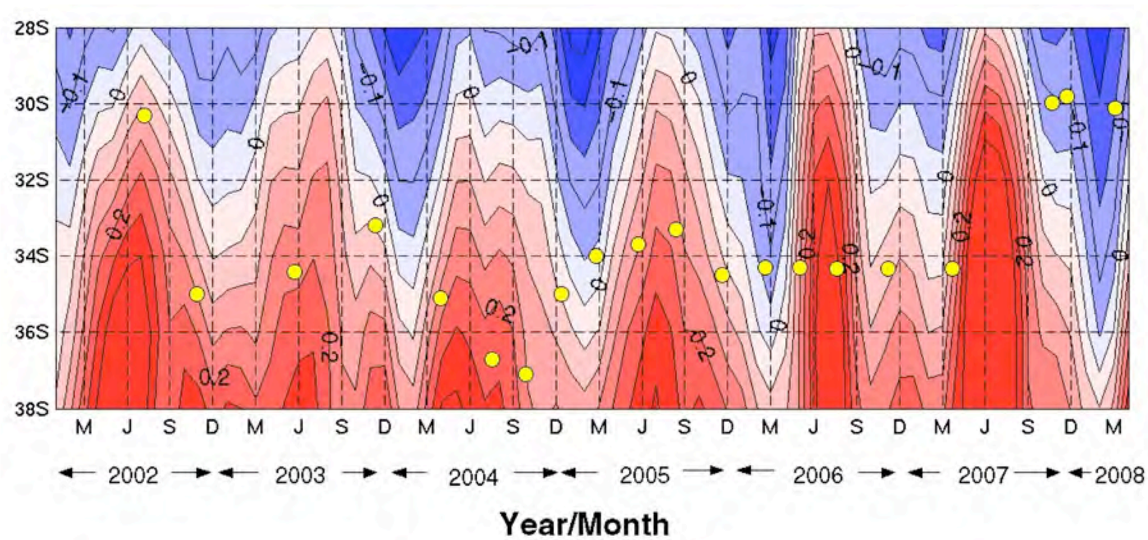

Figure 4. Time series of the Ekman Heat transport integrated across the basin as a function of latitude. Dots indicate mean latitude of each cruise.

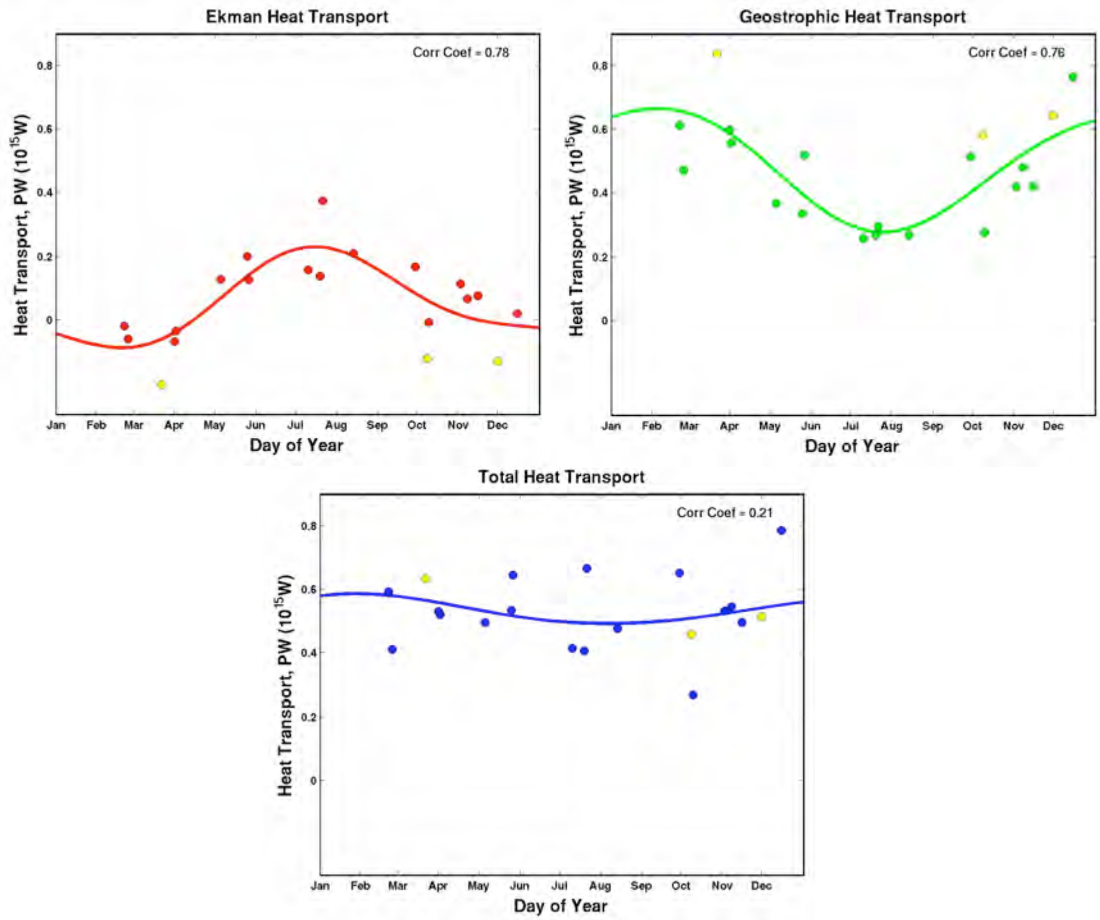

Figure 5. Annual cycle of Ekman and geostrophic components (top), and total heat transport (bottom) across the AX18 20 realizations. Results from the 3 lines occupied from Cape Town to Rio are shown in a different color (yellow).

North Atlantic:

The heat transport was found to vary on inter-annual time scales from 0.8 ± 0.2 PW at in 2003 to 1.2 ± 0.2 PW in 1996 and the present with instantaneous estimates ranging from 0.6 to 1.6 PW (Figure 6 and Figure 1). Heat transport due to Ekman layer flow computed from annual Hellerman winds was relatively small (only 0.1 PW). This variability is entirely driven by changes in the interior density field; the barotropic Florida Current transport was kept fixed (32 Sv[3]). At low frequencies, North Atlantic heat transport variations were found to correlate with the Atlantic Multidecadal Oscillation (AMO) as shown in Figure 6.

[3] Sv is a Sverdrup or 10^6 m^3/s, a unit commonly used for ocean volume transports.

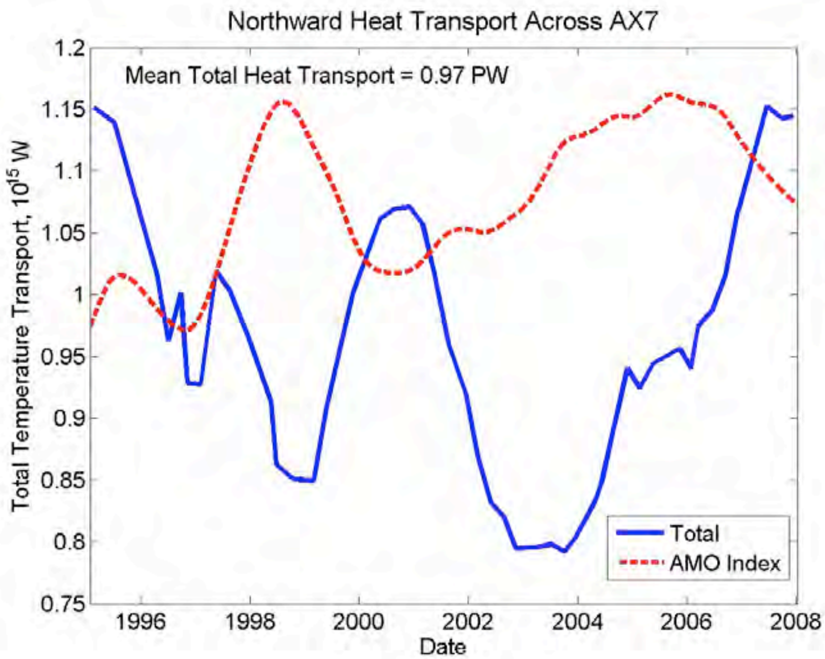

Figure 6. Time series of total heat transport in the center of the subtropical gyre in the North Atlantic Ocean along the XBT lined designated AX7. In the North Atlantic, there has been an oscillation in heat transport over the past 12 years (solid blue). The apparent trend through 2005 has ended with increasing northward heat transport in following years. Heat transport appears to be loosely inversely related to the Atlantic Multidecadal Oscillation (AMO) Index (red dashed).

2.3. Analysis of wind products

The heat transport is composed of two terms, the geostrophic component and the Ekman component, the last one estimated from wind products. As reported in the Plan for FY08, a comprehensive study of the wind products (climatology, reanalysis and satellite) was started to determine which is the most appropriate for each region and to estimate the errors incurred due to the use of different products. Up to date, the following was accomplished: The Ekman flux and the resulting total heat transport were obtained from three different wind products Hellerman, NCEP and ECMWF.

In the North Atlantic, Ekman heat flux (as opposed to temperature transport in the surface Ekman layer) is computed as the difference between the Ekman temperature transport in the surface mixed layer (defined using XBT observations for each month) and the mass-balancing transport of the vertically averaged ocean temperatures (defined as the areal averaged T from each XBT section). Results are shown in Figure 7. The Ekman fluxes differ by less that 0.03 PW, hence the Hellerman Ekman fluxes were used.

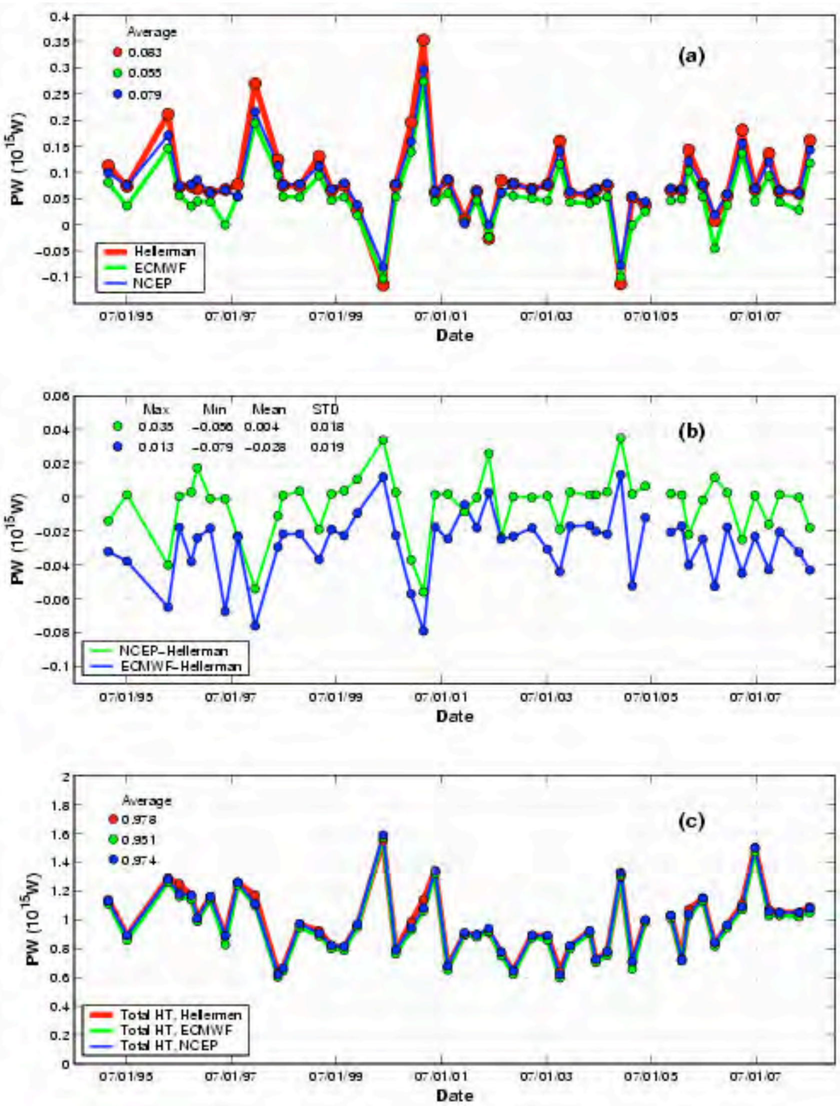

Figure 7. a) The Ekman flux is determined from the Hellerman annual mean climatology, the ECMWF monthly values and the NCEP monthly values. The Ekman fluxes differ by less that 0.03 PW. b) Differences between the Ekman fluxes above. The ECMWF fluxes are typically lower that the Hellerman or NCEP fluxes. c) The total heat transport using the three different Ekman flux estimates.

In the South Atlantic, the Ekman heat flux is computed as above: namely the total Ekman heat flux is defined as the difference between the Ekman temperature transport (in the Ekman layer) and the section average Temperature times the Ekman mass flux (so that the Ekman transport is mass-balanced). However several different areal Temperature averages were compared (defined as ‘cases’ below). Results are shown in Figure 8. The different average of total heat transport is less than 0.06 PW, however there are interesting variations over time linked to mesoscale variability in the region, Brazil Current meandering etc that the NCEP winds were used for the heat transport estimates.

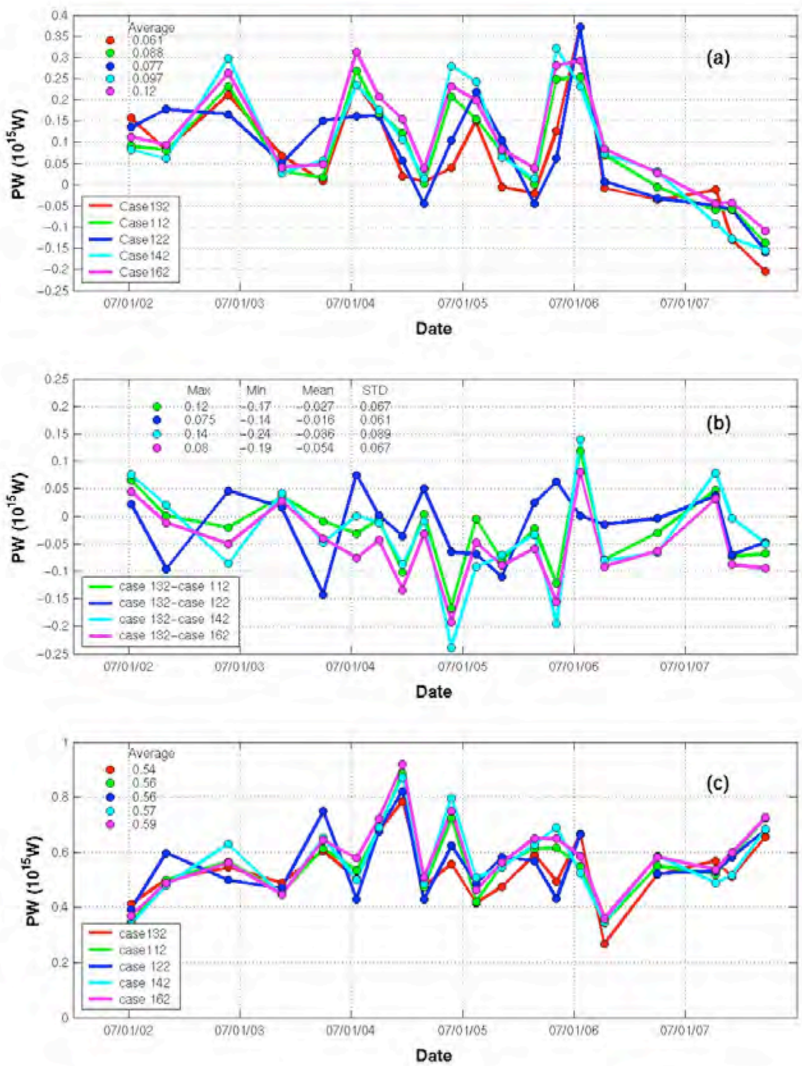

Figure 8. a) The Ekman flux is determined from wind stress values. The Ekman fluxes differ by less that 0.06 PW. b) Differences between the Ekman fluxes above. The case 132 fluxes are typically lower than other cases c) total heat transport using the five different Ekman flux estimates. 'Cases' are defined in Table 2.

Table 2. The Ekman heat fluxes shown in Figure 8 were computed from the 'cases' listed above. The temperature field used was either from the Levitus climatology alone or a combination of the XBT observations (0- 850 meters) and Levistu data (below 850 meters).

Case	Wind Product	Average Temperature from
case 132	NCEP monthly	Levitus temperature field.
case 112	NCEP monthly climatology	XBT-Levitus temperature field.
case 122	NCEP monthly	XBT-Levitus temperature field.
case 142	Hellerman annual mean	XBT-Levitus temperature field.
case 162	ECMWF monthly	XBT-Levitus temperature field.

A fifty-year analysis of global ocean surface heat flux to improve the understanding of the role of the ocean in climate

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1. PROJECT SUMMARY

The ocean and the atmosphere exchange heat at their interface via a number of processes: solar radiation, longwave radiation, sensible heat transfer by conduction and convection, and latent heat transfer by evaporation of sea surface water. The amount of heat being exchanged is called heat flux. The distribution of heat flux over the global oceans is a key element for climate studies, as it is required to establish air-sea feedback mechanisms, to provide guidance and motivation for modeling studies, to verify individual or coupled atmosphere-ocean general circulation model simulations, and to serve as forcing functions for ocean model exercises. However, direct flux measurements are sparse. Our present knowledge of the global air-sea heat flux distribution stems primarily from the bulk parameterizations of air-sea fluxes as functions of surface meteorological variables (e.g., wind speed, temperature, humidity, cloud cover, etc). The source of observations for those flux-related variables include marine surface weather reports from Voluntary Observing Ships (VOS) collected by Comprehensive Ocean-Atmosphere Data Set (COADS) and satellite remote sensing from various platforms. Atmospheric reanalyses from numerical weather prediction (NWP) centers such as National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasts (ECMWF) provide additional model-based database. Nonetheless, none of the three data sources are perfect as each suffers from at least one of the four deficiencies: (1) incomplete global coverage, (2) relatively short time series, (3) systematic bias, and (4) random error.

While improving the quality of each data source is a necessary step toward improving the estimates of surface heat fluxes, this project takes an alternative approach, i.e., to improve the quality of the flux estimates through objectively synthesizing the advantages of the three data sources. The synthesis approach has been applied successfully to generate gridded products of surface vector wind, SST, and precipitation. This project, which is termed “Objectively Analyzed air-sea heat Fluxes (OAFlux)”, develops an equivalent global synthesis product for surface heat fluxes by utilizing the methodology developed and experience learned from a previous pilot study for the Atlantic Ocean.

The project has two main objectives. The first objective is to produce a 50-year (from the mid 1950s onward) analysis of surface latent, sensible, net shortwave and net longwave radiation fluxes over the global oceans with improved accuracy. This will be achieved by an appropriate combination of COADS data, NWP reanalysis output, and satellite retrievals using advanced objective analysis. The target resolution is 1° longitude by 1° latitude and monthly. Daily flux fields are produced when satellite data are available. The second objective is to use the data to study the heat flux variability on seasonal, annual, interannual, decadal and longer timescales and their relation to global climate change. The scientific investigation helps to assess the quality and reliability of the dataset in depicting the multi-decade climate record since the 1950s and to provide physical insights into the dataset.

Global analysis of global air-sea latent and sensible heat fluxes, ocean evaporation, and related surface meteorological variables has been completed for the years 1958–2006 with monthly and daily resolutions. The datasets are freely available to the community via the project website (http://oaflux.whoi.edu). The proposed study contributes to the CLIVAR programs including CLIVAR Atlantic, Pacific and PACS, and benefits the CLIVAR and other research communities on studies of climate variability and predictability.

2. ACCOMPLISHMENTS

The major tasks that have been carried out in FY2008 include:

2.1. Public release of OAFlux analysis of ocean evaporation, air-sea latent and sensible heat fluxes, and related surface meteorological variables from 1958 to 2006

The OAFlux project announced the release of the third version of OAFlux products in early 2008. The version consists of a global analysis of ocean evaporation, air-sea latent and sensible heat fluxes, and related surface meteorological variables from 1958 to 2006 on 1-degree resolution, with monthly datasets available for the entire 49-year period and daily datasets from 1985 onward (Figure 1). The project has made two releases before: one was in March 2004 for the Atlantic Ocean basin analysis (1988-1999) and the other was in December 2005 for the global ocean analysis (1981-2002).

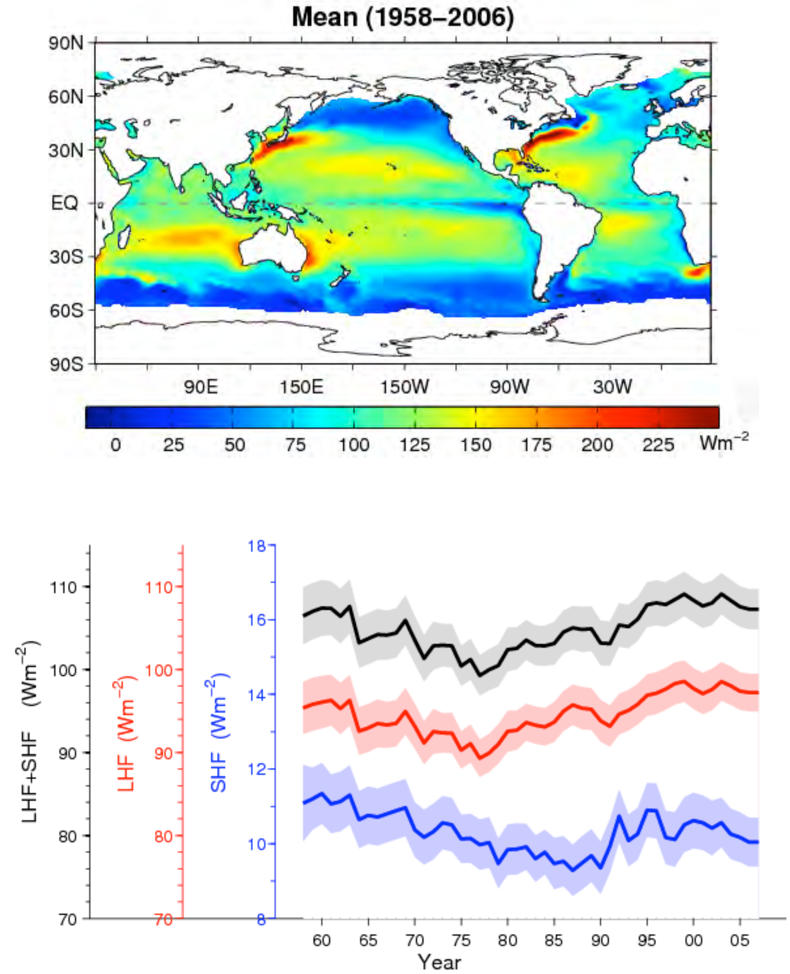


Figure 1. (top) Mean global latent and sensible heat fluxes averaged over the period from 1958 to 2006. (bottom) Variability of yearly-mean global averages of latent hear flux (red line), sensible heat flux (blue line), and latent plus sensible heat fluxes (black line). The shaded area on both sides of the line represents the lower and upper bounds of the error bars.

The OAFlux products are constructed not from a single data source, but from an optimal blending of a total of 22 daily input fields originating from three NWP reanalyses (ERA40, MCEP1, NCEP2) and multiple satellite platforms (AVHRR, SSM/I, QuikSCAT, AMSR-E). These optimally estimated daily surface meteorological fields were then input into the COARE bulk flux algorithm 3.0 to compute daily flux fields. Methodology, strategy, and procedure of the synthesis were detailed in a technical report ([1] Yu et al. 2008). Also discussed in the report is the accuracy of the flux estimates. The OAFlux daily time series were compared with in situ flux time series measurements at 107 locations (105 buoys plus 2 ships) over the global basin to assess the accuracy of the estimates. The comparison shows that daily latent plus sensible heat flux estimates are unbiased and have the smallest mean error: the mean OAFlux-buoy difference is of 1.0 Wm^{-2} and the mean OAFlux-buoy difference in absolute measure is of 7.4 Wm^{-2}. Based on the buoy comparisons, error estimation for daily global flux field was derived through post analysis (Figure 2).

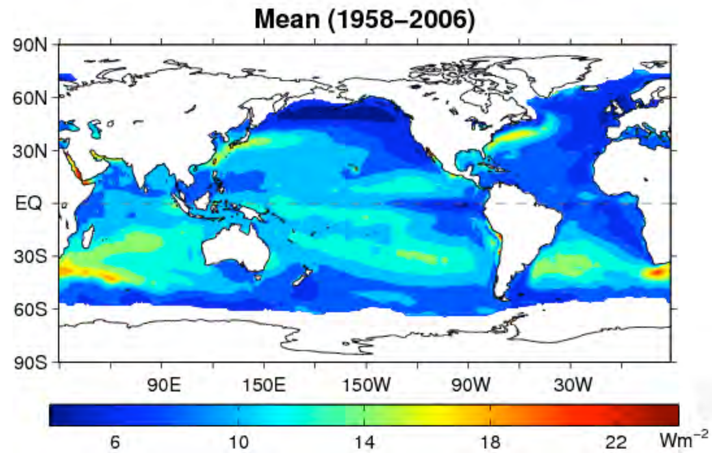


Figure 2. Estimated errors for latent plus sensible heat fluxes averaged from 1958-2006.

The datasets are freely available to interested users for non-commercial scientific research through the project website at http://oaflux.whoi.edu/. The data are also archived at two data centers outside WHOI: one is the Asia-Pacific DATA-Research Center (ADPRC) at the University of Hawaii (http://apdrc.soest.hawaii.edu/w_data/air-sea3.htm), and the other is the Data Support Section (DSS) at NCAR (http://dss.ucar.edu/datasets/ds260.1/).

2.2. Construction of flux validation database that constitutes flux buoy time series measurements at 100+ locations

In situ air-sea time series measurements from surface moored buoys have been a useful reference for validating flux estimates derived from ship reports, satellite observations, and NWP models. They are regarded as ground-truth and can help identify system biases in gridded flux products and quantify error and uncertainty. Recognizing the important role of flux buoy measurements in developing improved global flux products, efforts have been made to collect all available air-sea time series measurements from flux buoys over the global basins and to compile them all to establish a flux validation database. A total of 105 flux buoys was collected (Figure 3), among which only 62 locations were equipped with pyranometers (downward shortwave measurements) and 24 locations with pyrgeometers (downward longwave measurements) at 24 buoy locations. The database is a key validation tool in developing OAFlux products ([2] Yu et al. 2008).

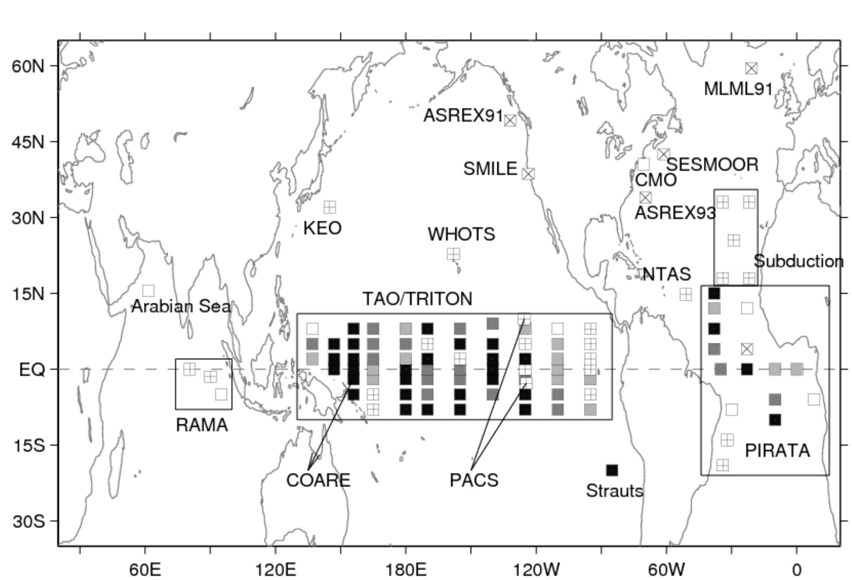


Figure 3. Name, location, and duration of the 105 buoys that were used to establish flux validation database.

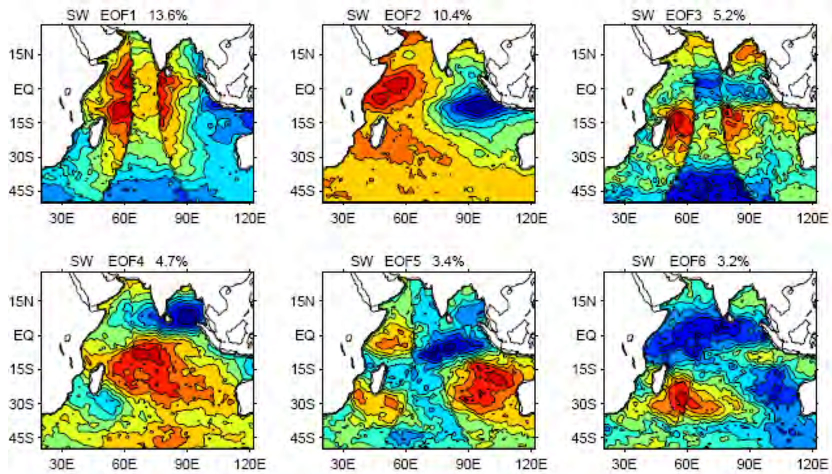
2.3. Experimenting optimal approaches to improve estimates of shortwave and longwave radiation at the ocean surface

Incoming solar radiation (Q_{SW}) is the only significant external heat source at the ocean surface. Its balance with ocean heat loss processes (e.g. longwave radiation (Q_{LW}), latent heat (Q_{LH}) and sensible heat (Q_{SH}) losses) drives the ocean meridional heat transport and attenuates temperature contrasts between equator and poles. To understand and explain past and current climate conditions and to predict future climate conditions, we need to know how solar and longwave radiation components have been changing, how the change affects the net heat balance (i.e., $Q_{net} = Q_{SW} - Q_{LW} - Q_{LH} - Q_{SH}$), and how Q_{net} is related to the warming of global oceans.

After completion of the ~50-year global analysis of air-sea latent and sensible heat fluxes, the technical focus of the OAFlux project has moved on to improving radiation estimates at the ocean surface. Two data sets are used, one is the International Satellite Cloud Climatological Project (ISCCP) and the other is from the NASA/GEWEX Surface Radiation Budget (SRB). Extensive comparison with in situ flux buoy measurements has been conducted, from which three major biases/errors in these two products are identified. The first one is the so-called “Indian Ocean Gap” (Figure 4), due to the lack of coverage from geostationary satellites over an area centered on 70°E for all of the July 1983 - June 1998 time period. The gap was eliminated after June 1998 when Meteosat-5 was moved over the region. The second is the large overestimation of ISCCP incoming solar radiation in the equatorial oceans. ISCCP is severely biased, with the largest bias (>30Wm^{-2}) over the western tropical Pacific and eastern Indian warm water regions. SRB also overestimates solar radiation but with lesser degree. The third problem is the spurious jumps in the time series of global averaged longwave radiation in ISCCP datasets, caused by spuriousness in atmospheric temperature products from the NOAA operational TOVS. These three biases/errors are so fundamental that they impede the use of the existing products in climate analysis.

Reducing or eliminating the three errors is a difficult task, because the errors come from many sources. Effort in the past year has focused on reducing the gap effect on short and longwave radiation estimates in the Indian Ocean and a linear smoothing technique was selected based on the error characteristics. EOF analysis was performed to check the signals before and after smoothing (Figures 4-5). It is clear that the smoothing effectively removed the gap and meanwhile does not alter the signals.

Before (SRB Original)



After (SRB smoothed)

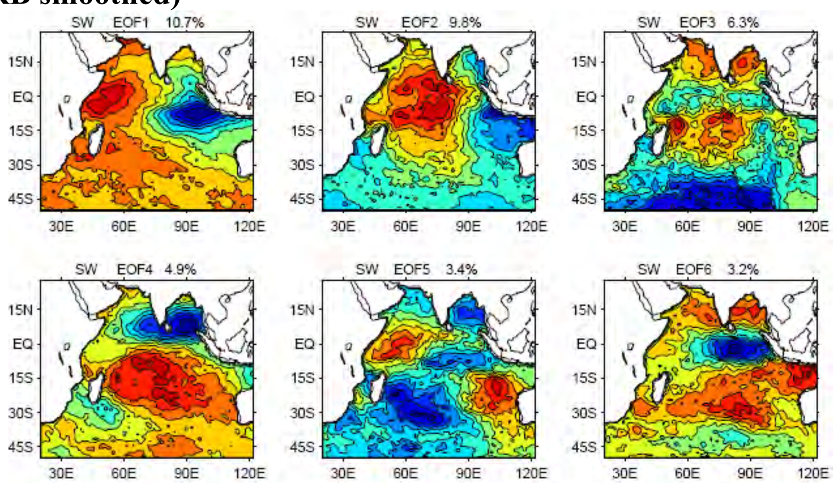


Figure 4. First 6 EOF patterns for solar radiation before (upper 6 panels) and after linear smoothing was applied (lower 6 panels).

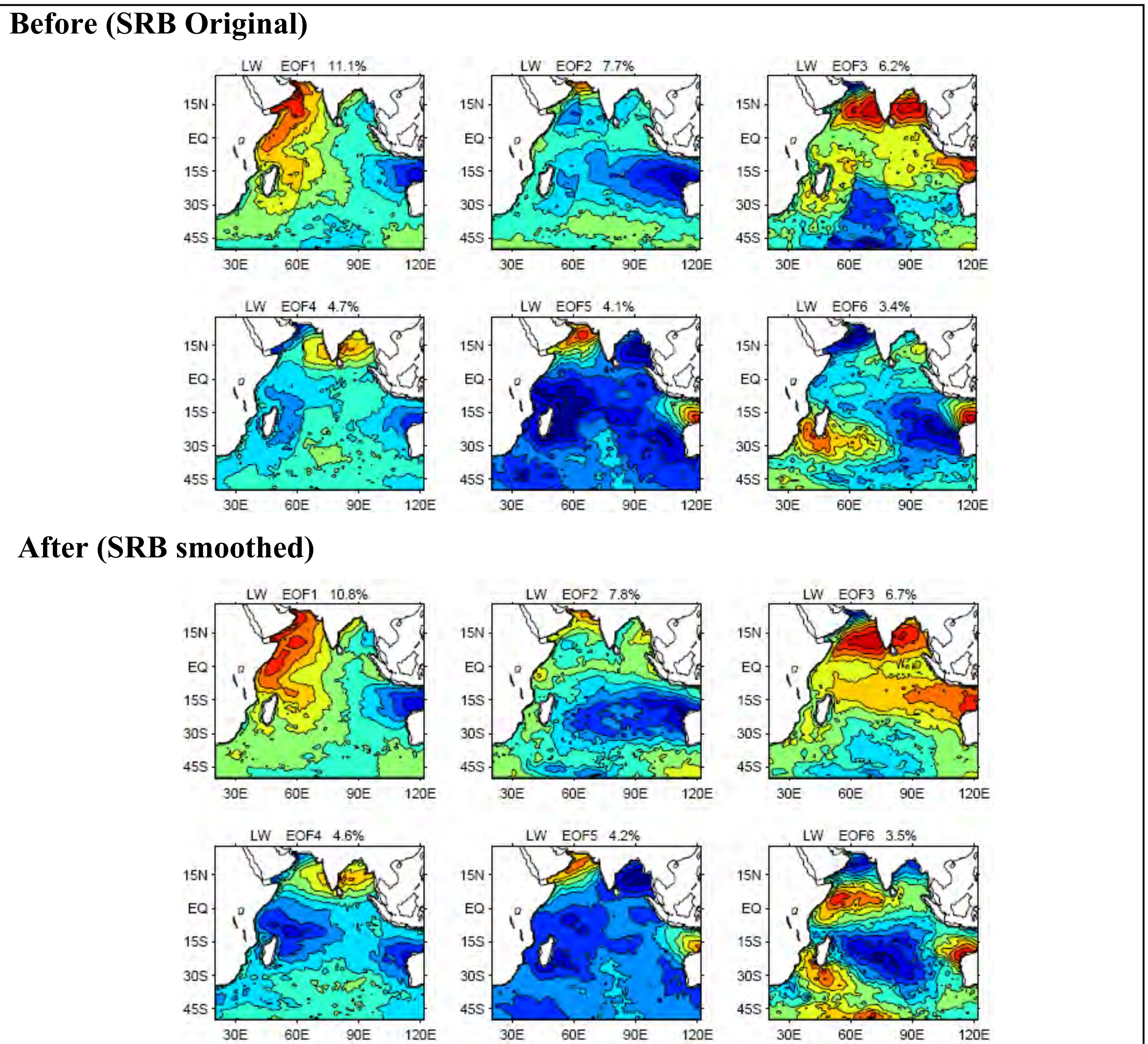


Figure 5. First 6 EOF patterns for longwave radiation before (upper 6 panels) and after linear smoothing was applied (lower 6 panels).

2.4. Connecting OAFlux evaporation product to precipitation products to study the change of global water cycle in past decades

The evaporation rate (E) is linked to latent heat flux (Q_{LH}) following the relation: $E = Q_{LH}/(\rho L_e)$, where ρ is the density of seawater and L_e the latent heat of vaporization. The relation is based on the fact that evaporation releases not only latent heat but also water vapor to the atmosphere. The relation also allows the global ocean evaporation to be computed by capitalizing on the availability of the ~50 year global analysis of latent heat flux. Thus, time series of monthly and daily analysis of ocean evaporation from 1958 to 2006 is developed and released online as a supplement to existing ocean heat flux products.

The OAFlux evaporation production provides the climate community the needed component in studying global water cycle. Precipitation estimates form 1979 to present are available from two groups, the NASA GPCP (Global Precipitation Climatology Project) and

NOAA CMAP (CPC Merged Analysis of Precipitation by Xie and Arkin). Hence, in addition to developing the evaporation dataset, the effort in the past year has made to link the OAFlux evaporation with GPCP and CMAP precipitation, and to analyze and understand changes in global water cycle from 1980 to the present, the period that precipitation datasets are available.

The OAFlux evaporation shows that global evaporation has been increasing steadily since the early 1980s (Figure 6a, red line), indicative of a changing global water cycle ([3] Yu 2007). Time series of global-averaged ocean precipitation from CMAP and GPCP do show precipitation has also been changing, but CMAP projects a downward trend opposite to the upward trend mapped by GPCP (Figure 6a, gray and dark black lines). The two different projections of the change of precipitation give different trends of evaporation-minus-precipitation (E-P, Figure 6.b). On one hand, $E_{OAFlux} - P_{GPCP}$ suggests that global freshwater fluxes have increased only slightly, though both components show a large increase and thus an enhanced water cycle. On the other hand, $E_{OAFlux} - P_{CMAP}$ suggests that precipitation has decreased with evaporation increasing, resulting in a large increase of freshwater fluxes to the atmosphere. The cause of the differences in the precipitation products is being investigated.

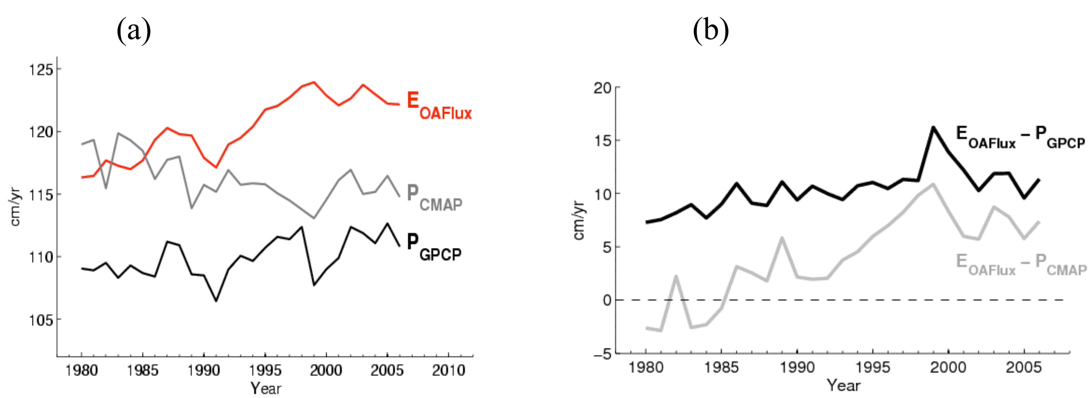


Figure 6. (a) Yearly-mean time series of global-averaged ocean evaporation from OAFlux (red), precipitation from CMAP (gray), precipitation from GPCP (black); (b) yearly-mean time series of global-averaged $E_{OAFlux} - P_{GPCP}$ (black) and $E_{OAFlux} - P_{CMAP}$ (gray).

In summary, we have accomplished the following five major tasks in the past year:

(i) Public release of OAFlux analysis of ocean evaporation, air-sea latent and sensible heat fluxes, and related surface meteorological variables from 1958 to 2006.
(ii) Construction of a flux validation database that constitutes flux buoy time series measurements at 100+ locations.
(iii) Experimenting optimal approaches to improve estimates of shortwave and longwave radiation at the ocean surface.
(iv) Connecting OAFlux evaporation product to precipitation products to study the change of global water cycle in past decades.
(v) Lead and co-authored 10 referred manuscripts and 1 technical report.

3. PUBLICATIONS AND REPORTS

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Contributors to Levinson, D.H., J.H. Lawrimore, et al., 2008: State of the Climate in 2007. *Bulletin of the American Meteorological Society*, 89, S1–S179.

Climate Variability in Ocean Surface Turbulent Fluxes

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1. PROJECT SUMMARY

FSU produces fields of surface turbulent air-sea fluxes and the flux related variables (winds, SST, near surface air temperature, near surface humidity, and surface pressure) for use in global climate studies. Surface fluxes are by definition rates of exchange, per unit surface area, between the ocean and the atmosphere. Stress is the flux of horizontal momentum (imparted by the wind on the ocean). The evaporative moisture flux would be the rate, per unit area, at which moisture is transferred from the ocean to the air. The latent heat flux (LHF) is related to the moisture flux: it is the rate (per unit area) at which energy associated with the phase change of water is transferred from the ocean to the atmosphere. Similarly, the sensible heat flux (SHF) is the rate at which thermal energy (associated with heating, but without a phase change) is transferred from the ocean to the atmosphere. In the tropics, the latent heat flux is typically an order of magnitude greater than the sensible heat flux; however, in the polar regions the SHF can dominate.

The FSU activity is motivated by a need to better understand interactions between the ocean and atmosphere on weekly to interdecadal time scales. Air-sea exchanges (fluxes) are sensitive indicators of changes in the climate, with links to floods and droughts[1] and East Coast storm intensity and storm tracks[2]. On smaller spatial and temporal scales they can be related to the storm surge, and tropical storm intensity. On longer temporal scales, several well-known climate variations (e.g., El Niño/Southern Oscillation (ENSO); North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO)) have been identified as having direct impact on the U.S. economy and its citizens. Improved predictions of ENSO phase and associated impact on regional weather patterns could be extremely useful to the agricultural community. Agricultural decisions in the southeast U.S. sector based on ENSO predictions could benefit the U.S. economy by over $100 million annually[3]. A similar, more recent estimate for the entire U.S. agricultural production suggests economic value of non-perfect ENSO predictions to be over $240 million annually[4]. These impacts could easily be extended to other economic sectors, adding further economic value. Moreover, similar economic value could be foreseen in other world economies, making the present study valuable to the global meteorological community.

ENSO, PDO, and NAO (AO) each have atmospheric and oceanic components that are linked through the surface of the ocean. Changes in the upper ocean circulation result in modifications

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to the SST and near surface wind patterns. Variations in SSTs can be related to ENSO and other climate patterns; however, it is the fluxes of heat and radiation near the ocean surface that transfer energy across the air-sea interface. It is an improved understanding of these turbulent fluxes and their variability that motivates our research (radiative fluxes are difficult to accurately estimate from in situ data; however, satellite-based estimates are available). By constructing high quality fields of surface fluxes we provide the research community the improved capabilities to investigate the energy exchange at the ocean surface.

FSU produces both monthly in-situ based (the FSU3) and hybrid satellite/numerical weather prediction (NWP) fields of fluxes and the flux-related variables. Our long-term monthly fields are well suited for seasonal to decadal studies, and our hybrid satellite/NWP fields are ideal for daily to annual variability and quality assessment of the monthly products. The flux-related variables are useful for ocean forcing in models, testing coupled ocean/atmospheric models, and for understanding climate related variability (e,g., the monthly Atlantic surface pressure is a good indicator of extreme monthly air temperatures over Florida).

The flux project at FSU targets the data assimilation milestones within the Program Plan. Our assimilation efforts combine ocean surface data from multiple Ocean Observing System networks (e.g., VOS, moored and drifting buoys, and satellites). One set of performance measures targeted in the Program Plan is the air-sea exchange of heat, momentum, and fresh water. When the FSU products are combined with ocean models (either at FSU or other institutes), performance measures relating to surface circulation and ocean transports can be addressed. The FSU flux project also focuses on the task of evaluating operational assimilation systems (e.g., NCEP and ECMWF reanalyses) and continues to provide timely data products that are used for a wide range of ENSO forecast systems. All products are distributed in a free and open manner at: http://www.coaps.fsu.edu/RVSMDC/FSUFluxes/.

2. ACCOMPLISHMENTS

An analysis of nine flux products (including the FSU Fluxes) has been completed, and it has revealed a vast difference between these products. We have updated this analysis, and improved our understanding of key differences among these products. We have nearly completed production of research-quality, in-situ monthly flux fields for the tropical and North Pacific Ocean (1978 to 2004). In the previous year, we identified some problems that result in unrealistic fields around the TAO moorings (a similar problem was identified in many of the comparison products); this year we solved this problem in our FSU3 product. The product release of the Pacific product has been delayed until we can complete the editing of the winds, which are key components in the fluxes.

We also continued our operational production of monthly quick-look wind fields for the tropical Pacific and Indian Oceans. These are based on our older techniques.

Global and Regional satellite wind and stress products have continued to improve through minor improvements in our variational technique. We have greatly lengthened the time series of this data set. We have also examined the biases in fluxes due to ignoring sub-monthly variability, and found these to be physically important >5 Wm^{-2} over the vast majority of the world's oceans, including the tropics! In high-latitude winters, monthly averaged biases often exceeded 30Wm^{-2}. In most cases, these biases were associated with the passage of atmospheric fronts, and the highly correlated changes in air temperature, atmospheric humidity, and wind speed. Our gridding technique for the monthly in situ data handles these issues very well for stress, but does not do so for heat fluxes (nor could any similarly derived monthly average). We had hoped to use NWP air temperature and humidity, combined with satellite winds to solve this problem; however, we found that temperature and humidity changes associated with frontal passages were not well resolved in NWP products, making useful bias adjustments very difficult if not impossible. Unfunded work with collaborators suggests that air temperatures and humidities estimated from satellite observations could do better, but it is not clear if the sampling is sufficient to reduce the biases below a few Wm^{-2}.

The effective reduction in funding (level funding combined with increasing costs) has prevented us from working on the error analysis for our fields. We view this work as very important, but we lack the resources to continue that effort with our current budget. We are participating on other efforts that will help address key questions about the noise and practical resolution. That will be very helpful, but a spatially varying assessment is desired.

Deliverables for FY 2008 included:

1. Update Atlantic, Indian, and Pacific Oceans using new ICOADS releases (if available).
2. Complete Equatorial and North Pacific 1˚ winds and fluxes.
3. Begin operational production and distribution of quick-look, 1˚ in situ fluxes for the Atlantic, Indian, and Pacific Oceans.
4. Publish comparisons of FSU3 fluxes to other available in-situ, satellite, and blended flux products.
    - Subtask1: Report results at national and international meetings.
5. Objective estimation of uncertainty in flux fields and related variables.
    - Subtask1: First complete uncertainties for wind vector components.
6. Production of satellite and NWP hybrid fluxes.
    - Subtask1: Estimate biases in NWP near surface temperatures and humidities.
    - Subtask2: Assess the importance of height adjustment algorithms for humidity (preliminary results indicate that this can be a large difference).
    - Subtask3: Assess biases associated with ignoring short-term variability contributing to surface fluxes.

2.1. Update products using new ICOADS releases [Deliverable 1]

No updates for ICOADS were made available in FY 2008; therefore, we did not complete any updates or extensions to our products past 2004. We anticipate an ICOADS update to be released in 2009, so this task will be pushed forward.

2.2. Complete Equatorial and North Pacific 1˚ in-situ fluxes [Deliverable 2]

In FY 2008, we nearly completed the automated and visual data quality evaluation for the tropical and North Pacific Ocean fluxes for the period 1990-2004. We completed the scalar input fields (wind speed, air temperature, and atmospheric humidity) for 1978 to 2004, and have edited the wind vectors for 1982 through 2004 (leaving on 1978 through 1981 to be completed). The 1˚ wind and flux products (the FSU3) for the Pacific Ocean revealed a problem with our handling of moored buoys (especially in the tropics) which resulted in the mooring chains being evident in the objective flux fields. The problem is due to the sparse longitudinal sampling of the TAO buoys, and to small but widespread and seasonally varying biases relative to the ship observations. The treatment of buoy data has been modified to remove this problem in a manner that retains most of the value of the buoy data. In 2007, we found that many ship observations had been misclassified (in ICOADS) as moored buoys. We have developed an automated technique for removing the vast majority of such misclassified data, and found a small positive impact to the flux fields, and more substantial reduction in the questionable data removed in the editing process.

2.3. Production of in-situ quick-look products [Deliverable 3]

Although we were unable to implement quick-look versions of the 1˚ objective FSU fluxes, we continue to create an older version (the FSU2) 2˚ tropical Pacific Ocean wind (pseudo-stress) fields based on near-real time in-situ data. Quick-look 2˚ gridded pseudo-stress fields are produced at the beginning of each month using the previous month's GTS-transmitted data. In addition to the Pacific, COAPS continues to produce one-degree pseudo-stress fields for the tropical Indian Ocean using the method of Legler et al.[5]. Related research quality products exist through 2004 for the Pacific and 2003 for the Indian Ocean. We have not updated the FSU2 and Legler research products as we had anticipated switching to the near real time version of the FSU3 technique. This switch was delayed by the desire of the flux community to have an assessment of multiple flux products (including the FSU3), and the data quality and sampling issues we had to solve. We will push the quick-look FSU3 product forward to FY 2009. Both two-degree fields for the Pacific Ocean and one-degree fields for the Indian Ocean FSU winds are available at http://www.coaps.fsu.edu/ RVSMDC/SAC/index.shtml.

As part of our continued production of the FSU2 for the tropical Pacific Ocean, we now produce additional monthly graphics for inclusion into the on-line version of the NOAA Climate Diagnostics Bulletin (http://www.cpc.ncep.noaa.gov/products/CDB/).

2.4. Publish comparisons of FSU3 fluxes to other available in-situ, satellite, and blended flux products [Deliverable 4]

The research for this comparison is done. We have a draft of the paper, and are improving it prior to submission. The subtask of presenting the information at national and international meetings was completed. The discussions from these presentations indicate that most flux product users know very little about the qualities of the flux products they choose to use. It is clear that a well written comparison of the strengths and weaknesses of products would be of great service to a wide range of communities.

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[5] Legler, D. M, I. M. Navon, and J.J. O'Brien, 1989: Objective analysis of pseudostress over the Indian Ocean using a direct-minimization approach. *Mon. Wea. Rev*., **117,** 709-720.

2.5. Objective estimation of uncertainty in flux fields and related variables [Deliverable 5]

While we have completed key coding improvements, we have not found sufficient time to make much progress on this problem. The effective reduction in funding (level funding combined with increasing costs) has prevented us from working on the error analysis for our fields. We view this work as very important, but we lack the resources to continue that effort with our current budget. We are participating on other efforts that will help address key questions about the noise and practical resolution. That will be very helpful, but a spatially varying assessment is desired.

2.6. Production of satellite and NWP hybrid fluxes [Deliverable 6]

We produce equivalent neutral pseudostress fields, which can easily be used to determine surface stress. For isolated projects we produce hybrid NWP and satellite fluxes; however, we (in 2007) believed that there are substantial errors in the heat fluxes that should be addressed prior to public release of these products. In 2008, we investigated these biases, and found them to vary in space and time in a manner that would be difficult to correct and would cause large biases in even monthly averaged fluxes (subtask 1). We have investigated the importance of height adjustment and parameterization choice of the humidity values (subtask 2), and found that both considerations have physically significant impacts on the resulting fluxes. Mean differences due to parameterizations could be tens of Wm^{-2} for even mild conditions. We have also found that the differences due to the height adjustments have non-Gaussian distributions[6], which further complicates error analysis. In particular, we found that the biases associated with errors in episodic events (such as passage of atmospheric fronts; subtask 3) are quite large, even when considered as part of a monthly averaged flux. We therefore conclude that satellite and NWP hybrid result in biased fluxes, with the biases changing regionally and seasonally in a manner that is difficult or impossible to correct sufficiently for many applications. We have explored the possibility of combining observations of air temperature and humidity derived from satellite, and found some promise and the need for much more detailed assessment.

[6] Kara, A. B., A. J. Wallcraft, and **M. A. Bourassa**, 2008: Air-Sea Stability Effects on the 10m Winds Over the Global Ocean: Evaluations of Air-Sea Flux Algorithms. *J. Geophys. Res.,* **113**, C04009, doi:10.1029/2007JC004324.

3. PUBLICATIONS AND REPORTS

3.1.Refereed

Arguez, A. J. J. O'Brien, and S. R. Smith, 2008: Air Temperature Impacts over Eastern North America and Europe Associated with North Atlantic SST Variability. *International Journal of Climatology*, doi:10.1002/joc.1700, in press.

Kara, A. B., A. J. Wallcraft, C. N. Barron, E. J. Metzger, H. E. Hurlburt, and M. A. Bourassa, 2008: Accuracy of 10 m Wind Speeds from Satellites and NWP Products Near Land-Sea Boundaries. *Journal of Geophysical Research - Oceans*, *113*, C04009, doi:doi:10.1029/2007JC004324.

Morey, S. L., D. S. Dukhovskoy, and M. A. Bourassa, 2007: Connectivity between variability of the Apalachicola River flow and the biophysical oceanic properties of the northern West Florida Shelf. *Continental Shelf Research*, in press.

3.2. Technical reports and other publications

Moroni, D.F., 2008: A global and regional diagnostic comparison of air-sea flux parameterizations during episodic events, M.S. Thesis, 65 pp., Florida State University, Tallahassee, Florida, USA.

Smith, S. R., R. N. Maue, and M. A. Bourassa, 2008: 'Global Winds', State of the Climate in 2007, *Bulletin of the American Meteorological Society*, D. H. Levinson and J. H. Lawrimore, A. Arguez, H. J. Diamond, F. Fetterer, A. Horvitz, J. M. Levy, S32-S34, American Meteorological Society.

Bourassa, M. A., P. J Hughes and S. R. Smith, 2008: Surface Turbulent Flux Product Comparison, *FLUX NEWS*, *5*, 22-24.

Bourassa, M. A., D. Dukhovskoy, S. L. Morey, and J, J. O'Brien, 2007: Innovations in Modeling Gulf of Mexico Surface Turbulent Fluxes, *FLUX NEWS*, *3*, 9.

3.3. Conference proceedings/presentations

Bourassa, M. A., 2008: Remote Sensing of Ocean Surface Winds: Concepts and Applications, Univ. South Carolina, Feb., Columbia, South Carolina. *(Invited)*

Bourassa. M. A., 2007: Measuring surface turbulent stress from space. *2nd Oceanography Student Symposium*. Nov., Tallahassee, Florida. *(Invited)*

Morey, S. L, D. S. Dukhovskoy, and M. A. Bourassa, 2007: Connectivity between variability of the Apalachicola river flow and the biophysical oceanic properties of the Northern West Florida shelf . *2nd Oceanography Student Symposium*. Nov., Tallahassee, Florida. *(Invited)*

Moroni, D. F., and M. A. Bourassa, 2007: A global and regional comparison of air-sea flux parameterizations. Pacific Ocean Distributed Active Archive Center (PO.DAAC), Jet Propulsion Lab., Nov., Pasadena, CA. *(Invited)*

Bourassa, M. A., P. J. Hughes, S. R. Smith, and J. Rolph, 2008: Recent Air/Sea Flux Activities and FSU. *NOAA Climate Observations Division 6th Annual Review*, Sept., Silver Spring, MD.

Bourassa, M. A., L. Bucci, C. A. Clayson, C. Forgue, M. Onderlinde and B. Roberts, 2008: The Influences of Differing Temperature and Moisture Roughness Length Parameterizations on Height Adjustment and Turbulent Surface Fluxes. *Third JCOMM Workshop on Advances in Marine Climatology*, May, Gdynia, Poland.

Bourassa, M. A., L. Bucci, C. A. Clayson, C. Forgue, M. Onderlinde and B. Roberts, 2008: The Influences of Differing Temperature and Moisture Roughness Length Parameterizations on Height Adjustment and Turbulent Surface Fluxes. *2nd Joint GOSUD/SAMOS Workshop*, June, Seattle, Washington.

Hughes, P. J., M. A. Bourassa, S. R. Smith, 2008: Regional comparison of surface turbulent flux products. *Ocean Sciences 2008*, American Geophysical Union, March, Orlando, FL.

Hughes, P. J., M. A. Bourassa, S. R. Smith, 2008: Regional Comparison of Surface Turbulent Flux Products. *Third JCOMM Workshop on Advances in Marine Climatology*, May, Gdynia, Poland.

Morey, S. L., D. S. Dukhovskoy, and M. A. Bourassa, 2008: connectivity between variability of the Apalachicola River flow and the biophysical oceanic properties of the northern West Florida Shelf. *Ocean Sciences 2008*, American Geophysical Union, March, Orlando, FL.

Morey, S. L., D. S. Dukhovskoy, and M. A. Bourassa, 2008: Connectivity between variability of the Apalachicola River flow, episodic wind forcing, and the biophysical oceanic properties of the northern West Florida Shelf, *NOAA Climate Observations Division 6th Annual Review*, Sept., Silver Spring, MD.

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Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses

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1. PROJECT SUMMARY

Oceanic Fresh water flux is an essential component of the global water cycle and plays an important role in forcing the oceanic circulation. However, its mean state, short-term variability and long-term changes are poorly monitored and documented due to undesirable qualities of the data sets for its two primary components, precipitation (P) and evaporation (E). Two major factors restricting the quality of existing oceanic fresh water flux data sets are 1) the lack of an extensive and continuous network of in-situ observations for calibrating and verifying each component, and 2) insufficient efforts to synthesize analyses for E and P. The availability of many new observation-based and model-produced data sets, especially precipitation, surface air temperature, sea surface temperature, humidity, and wind, makes it possible to quantitatively calibrate, verify and refine the existing P and E products.

In the past decade, two sets of satellite-based precipitation products have been developed at NOAA's Climate Prediction Center (CPC) that are used to monitor precipitation variations over global oceans. The CPC Merged Analysis of Precipitation (CMAP, Xie and Arkin 1997) is defined by merging individual products of satellite estimates derived from infrared (IR) and microwave (MW) observations. The CMAP data sets are created on a 2.5^{o}lat/lon grid over the globe and on monthly and pentad (5-day) time resolution for a 30-year period from January 1979 to the present. The other CPC oceanic precipitation analysis is that generated by the CPC Morphing Technique (CMORPH, Joyce et al. 2004) for high temporal / spatial applications. Cloud/precipitation movement vectors are first computed from high-resolution infrared image data in 30-min intervals observed by geostationary satellites. These movement vectors are then used to separately 'propagate' precipitation systems observed (by more-physically-based but less frequently sampled PMW observations) both forward/backward in time from "past"/"future" PMW scans to get the analyzed fields of precipitation at the targeted times. By weighting the forward and backward propagated rainfall estimates by the inverse of their respective temporal distance from scan time, these separate propagations are then morphed. The CMOPRH precipitation analysis is produced on an 8kmx8km grid over the globe from 60^{o}S to 60^{o}N and on 30-min intervals from December 2002. Both CMAP and CMORPH have been widely used by scientists around the world to a variety of applications including monitoring and assessment of global climate, model verifications and studies on global water budget/flux.

Further refinements of the CMAP and CMORPH are needed to improve their capacity to quantitatively document the precipitation variations and fresh water flux over the global oceans. The objectives of this project are to improve the CMAP and CMORPH precipitation analyses over ocean and to examine the fresh water flux as seen in the existing observations and in the NCEP Global Oceanic Data Assimilation System (GODAS). Specifically, we will

1) Provide the CMAP and CMORPH gridded analyses of oceanic precipitation, *together with estimates of uncertainty*, for a range of spatial and temporal scales consistent with data availability. Each product will be accompanied by a historical set of analyses of varying duration. The products will be updated and made available to the various communities of interest as promptly as the availability of input data permit, with lags ranging from less than one day to 3 months.

2) Monitor and assess the global oceanic fresh water flux using our precipitation analyses several of the available oceanic evaporation products and compare them with that generated by the NCEP operational Global Oceanic Data Assimilation System (GODAS). As part of this activity, we will examine the uncertainty of the fresh water flux derived from the current generation of observed precipitation and evaporation analyses to get insight into to what extent the differences between the flux in GODAS and observation are attributable to problems of the model.

3) Perform a set of modular research and development tasks to address critical shortcomings of the current precipitation analyses and to improve the existing products.

2. ACCOMPLISHMENTS

2.1. CMORPH Global Precipitation Analyses

The overall goal of this part of our project is to improve the CMORPH and to apply the technique to produce high-resolution oceanic precipitation for an extended period from 1998 to the present. Many recent studies (e.g. Ebert et al. 2007, Xie et al. 2007) have demonstrated that CMORPH provides high-resolution global precipitation satellite estimates with the best quantitative accuracy among similar products. The objectives of this part of our project are to further improve the CMORPH technique, to extend its record and to adjust the CMORPH for applications for quantitative monitoring of oceanic precipitation variability.

a) Development of next generation algorithm for the CMORPH

While the current version of the CMORPH algorithm is capable of producing global precipitation analysis in very high resolution (30min in time and 8kmx8km in space) and with high quality, it does not take full advantage of precipitation estimates from all available satellites, especially in the sense that information from IR derived rainfall estimates should be used for large temporal gap occasions between Microwave (MW) scans. Adopting the Kalman Filter technique enables us to utilize instantaneous precipitation estimates from all MW satellite observations available around the target time, and to a lesser degree IR derived rainfall, to optimally combine into a complete global field.

The basic idea of the Kalman Filter approach is to 'propagate' the instantaneous MW observations from their individual observation times to a target time using the cloud advection vectors derived from IR images and then to combine the propagated MW estimates with weights inversely proportional to the error variances. One important step in applying the Kalman Filter technique is to define error statistics (correlation) for the individual input MW precipitation estimates as a function of the time difference between the target global field and the MW observations. To this end, we compared propagated MW estimates against surface radar observations over the conterminous United States for each available satellite. As expected, the correlation decreases and the error increase with the propagation time (Figure 1). The correlation between the propagated satellite MW estimates and the ground truth (radar) is higher than 0.5 for concurrent observations but decreases to less than 0.2 when the MW estimates are propagated for 2.5 hours in each temporal direction or longer (or 5 hour combined period). MW estimates from different instruments present different error statistics. Overall, MW precipitation estimates from the TRMM TMI/AMSU exhibit the best/poorer performance in representing precipitation throughout the propagation time period examined. These statistics suggest that in addition to the MW observations, IR derived rainfall estimation is useful in filling temporal gaps larger than three hours between MW scans.

The satellite error functions are then utilized to define the global precipitation analysis from the propagated MW estimates through the Kalman Filter. Quantitative assessments are performed for the precipitation analysis generated by the Kalman Filter-based and the results showed significant improvements in the performance of the analysis in representing the spatial variations and temporal change of precipitation (red line Figure 2). Further work is underway to fine-tune the error statistics for various seasons and for different regions and to include information from additional new satellites to achieve the best possible performance. Temporally/spatially coincident MW rainfall estimation from the under-flying TRMM (and GPM for 2013 and beyond) relative to precipitation from each sun-synchronous MW equipped obiter will be used to determine the regional/seasonal skill/error characteristics needed to optimally combine the rainfall for the entire globe.

The results of this part of the work have been reported at couple scientific meetings and will be summarized into a journal paper once the entire process is completed.

b) Extending the CMORPH period of record back beyond December 2002

Currently, CMORPH high resolution precipitation estimates are available for a period from December 2002 to the present. As an important part of this project, we are in process of extending the CMORPH data record back for the period to November 1998. This will generate a 10-year complete record of high-resolution precipitation over the global land and ocean.

The backward extension of the CMORPH has been delayed due to the transition of the computer systems at the NOAA Climate Prediction Center (CPC). However, we were able to finish the collection of all the satellite data necessary for the backward extension, develop, test, and benchmark the retrospective analysis system on the new computer system, and start the backward extension. As of the end of the FY2008, we have finished the backward extension from December 2002 to September 2002 and the extension is undergoing at a pace of 4 months of data reprocessing in a month. We expect the backward extension of the CMORPH analysis for the entire data period will be complete in the next fiscal year. The CMORPH satellite precipitation estimates for the extended period are being made available through the CPC ftp server upon the completion of final check. Shown in Figure 3 is an example of the CMORPH precipitation for 00Z, October 13, 2002. CMORPH is capable of depicting large-scale distribution as well as fine structures of global oceanic precipitation with high quantitative quality.

Preliminary results of this CMORPH backward extension has been reported at the Annual AGU assembly.

c) Adjusting the CMORPH against a long-term data record

Construction of the CMORPH global high-resolution precipitation analysis enables a variety of applications in monitoring, documenting and diagnosing oceanic precipitation. Its data record (from 1998), however, is insufficient for the creation of a robust climatology, making it difficult to define anomaly. To overcome this limitation, we have taken a straightforward and effective approach to adjust the high-resolution CMORPH precipitation analysis for recent years to a long-term record with a coarser resolution so that anomaly patterns can be defined for the adjusted CMORPH against the climatology of the long-term record.

The GPCP pentad precipitation analysis of Xie et al. (2003) is used as the reference long-term precipitation data against which the high resolution CMORPH precipitation estimates are adjusted. The GPCP pentad (5-day) precipitation analysis is constructed on a 2.5^{o}lat/lon grid over the global by merging information from multiple satellite observations and in situ measurements. The analysis starts from January 1979 and is updated on a real-time basis at NOAA Climate Prediction Center.

Ratio between the original CMORPH and the GPCP pentad analysis is computed for each 0.25^{o}lat/lon grid box and for each day by comparing the accumulated precipitation amount over a 2.5^{o}lat/lon GPCP grid box covering the target grid and over a 15-day period ending at the target date. The ratio is then multiplied to the original CMORPH. The adjusted CMORPH presents overall quantitative consistency with the GPCP pentad analysis (Figure 4) while retains the high-resolution information in the original CMORPH (Figure 5). To facilitate the definition of anomaly for the adjusted CMORPH, GPCP pentad precipitation climatology for 1979 – 1995 (CPC official base period for satellite observations) is desegregated into daily and 0.25^{o}lat/lon resolution using the adjusted CMORPH mean precipitation fields for recent years, enabling quantitatively assess and monitor the oceanic precipitation on a very high resolution. Further work is underway to apply this method for real-time applications. Once completed, the adjusted CMORPH high-resolution oceanic precipitation analysis will be provided to CPC ocean group for monthly global ocean monitoring.

2.2. CMAP Global Precipitation Analyses

This part of our research project involves two components: 1) documentation of the global oceanic fresh water flux using the CMAP and other observation-based data sets of precipitation and evaporation; and 2) Continuous updates and improvements of the current CMAP for better quantitative applications over ocean.

a) Documentation of the global oceanic fresh water flux

Majority of the work on this topic has been done during FY2007, including the examination of the mean climatology and seasonal variations of fresh water flux as depicted by observations and how they are reproduced by several NCEP model-based products. In FY2008, we continued our efforts to examine the interannual variation patterns of oceanic precipitation and evaporation patterns associated with large-scale patterns including ENSO, PNA, and MJO. As shown in Figures 6 and 7, in general the magnitude of the evaporation anomaly associated with ENSO is much smaller (~1/5) than that of precipitation. All of the NCEP model-based products (CDAS1, CDAS2, CFS, and GDAS) are capable of reproducing the ENSO-induced large-scale patterns, especially for precipitation. The evaporation anomaly pattern generated by the NCEP Climate Forecast System (CFS), however, presents relatively poor agreements with that of the observations. These results have been reported at the 3rd International Conference on Reanalysis and a paper describing our work on the examination of oceanic fresh water flux in the NCEP model-based products has been almost completed, pending submission to the special issue of the reanalysis conference (to be announced by the organizers).

b) Updates and improvements of the oceanic precipitation data sets

The CMAP precipitation analysis has been updated routinely and made available to the science community and general public through the CPC ftp server (ftp.cpc.ncep.noaa.gov/precip). As of October, 2008, the CMAP data set is available for a 30-year period from January 1979 to August 2008.

One major shortcoming of the current generation global oceanic precipitation analyses, including those of GPCP, CMAP, and TRMM, is its uncertain magnitude which is crucial in many applications such as the examination of oceanic fresh water flux and energy budget. While efforts have been made by many satellite algorithm developers to improve the quantitative accuracy of satellite retrievals over ocean, it is necessary to include the information of direct measurements of precipitation from in situ platforms. During FY2008, we performed comprehensive examinations of the biases in the satellite precipitation estimates and developed a prototype algorithm to remove the satellite bias through matching the probability density function (PDF) of the satellite estimates against that of the co-located in situ measurements. Matching pairs of the gauge and satellite data are collected over grid boxes with at least one gauge over a spatial domain of 10^{o}lat/lon centering at the target grid box and over a time period of 30-days ending at the target date. Cumulative PDF functions are then defined for the satellite and gauge data, respectively. Bias in the satellite estimates is finally identified and removed by matching the cumulative PDF of the satellite estimates with that of the gauge analysis.

Satellite observation and in situ measurements of precipitation over China are used for our experiments. The relatively dense gauge network there provided us with test cases to examine the sensitivity of the bias correction results to the gauge network density. Cross-validation is performed for the PDF matching technique and results showed successful correction of the bias over regions with reasonable in situ gauge networks (Table 1).

The results of this work have been presented at several scientific meetings. Further work is underway to examine the impact of the gauge network with inadequate distribution density and configuration to the effectiveness of the bias correction.

3. PUBLICATIONS

3.1. Journal Papers

Joyce, R. J., Pingping Xie, Yelena Yarosh, John E. Janowiak and Phillip A. Arkin, 2008: The use of TRMM data in the CMORPH suite of precipitation analyses, Special Issue on Precipitation Measurements from Space, *J. Meteor. Soc. of Jpn.*

Joyce, R. J. Pingping Xie, Yelena Yarosh, John E. Janowiak and Phillip A. Arkin, 2009: CMORPH: A ‘Morphing’ Approach for High Resolution Precipitation Product Generation, Book Chapter for Springer Book Volume on 'Satellite Applications for Surface Hydrology' planned for publication in 2009.

Xie, P., W. Wang, J.E. Janowiak, M. Chen, C.L. Shie, and L. Chiu, 2009: Examining fresh water flux over global oceans in the NCEP CDAS, CDAS2, GDAS, GFS and CFS. To be submitted to the special issue for the 3rd *WCRP International Conference on Reanalysis*.

3.2. Conference Presentations

Joyce, R. and P. Xi e, 2007: Kalman filter approach to CMORPH: a skill and error assessment of instantaneous and propagated passive microwave estimated rainfall, *Pilot Evaluation of High Resolution Precipitation Produc*ts (PEHRPP) workshop, 3-5 December, 2007, Geneva.

Joyce, R., and P. Xie, 2008: A Kalman Filter Approach to CMORPH Passive Microwave Rainfall Estimation, *IGARSS meeting*, Boston, MA, 6-11 July 2008.

Joyce, R. and P. Xie, 2008: A Kalman filter approach to blend various satellite estimates in CMORPH. *4th International Precipitation Working Group Meeting*, Oct. 13 0 17, 2008, Beijing, China.

Xie, P., W. Wang, J.E. Janowiak, M. Chen, C.L. Shie, and L. Chiu, 2008: Examining fresh water flux over global oceans in the NCEP CDAS, CDAS2, GDAS, GFS and CFS.

Third WCRP International Conference on Reanalysis. Tokyo, Japan, Jan. 28 – Feb.1, 2008.

Xiong. A.Y., P. Xie, J.-Y. Liang, Y. Shen, J.E.. Janowiak, M. Chen, and P.A. Arkin, 2008: Merging gauge observations and satellite estimates of daily precipitation over China. *4th International Precipitation Working Group Meeting*, Oct. 13 0 17, 2008, Beijing, China.

Yarosh, Y., P. Xie, and R. Joyce, 2008: Retrospective CMORPH Reprocessing Efforts, *Spring AGU Joint Sessions*, 26 – 30 May, 2008 Fort Lauderdale, FL.

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climatology. *J. Climate*, **12**, 2850 – 2880.

Xie, P., and P.A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Amer. Meteor. Soc.*, **78**, 2539 – 2558.

Xie, P., J.E. Janowiak, P.A. Arkin, R. Adler, A. Gruber, R. Ferraro, G.J. Huffman, and S. Curtis, 2003: GPCP pentad precipitation analyses: An experimental data set based on gauge observations and satellite estimates. *J. Clim.*, **16**, 2,197 – 2,214.

Xie, P., M. Chen, A. Yatagai, T. Hayasaka, Y. Fukushima, and S. Yang, 2007: A gauge-based analysis of daily precipitation over East Asia. *J. Hydrometeor.*, **8**, 607 – 626.

5. FIGURES

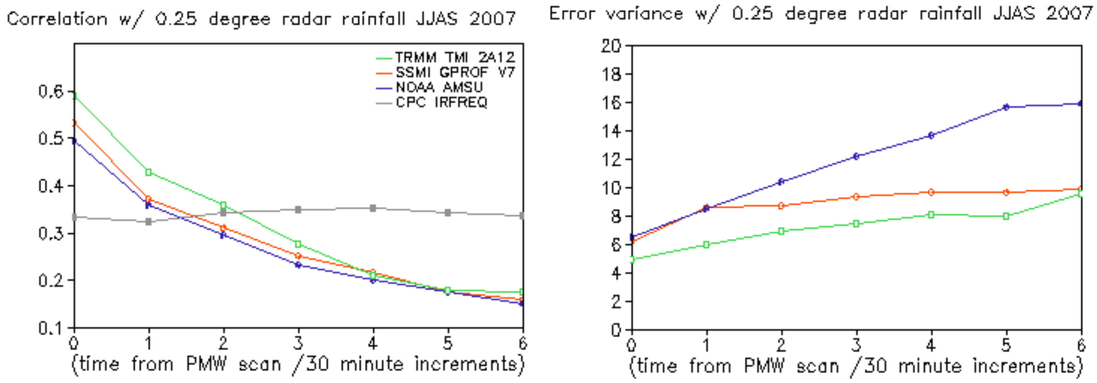

Figure 1. Correlation (left) and error variance (right) of forward propagated PMW rainfall relative to hourly 0.25 degree Stage II radar for JJAS 2007, x-axis = temporal distance to PMW scan time.

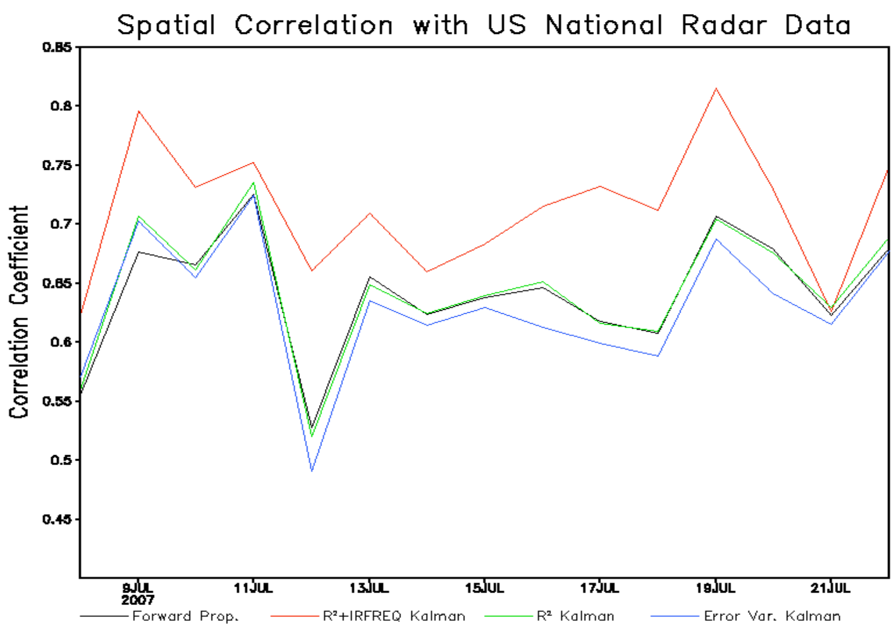

Figure 2. Validation results (correlation) for the operational and experiment versions of CMORPH over CONUS.

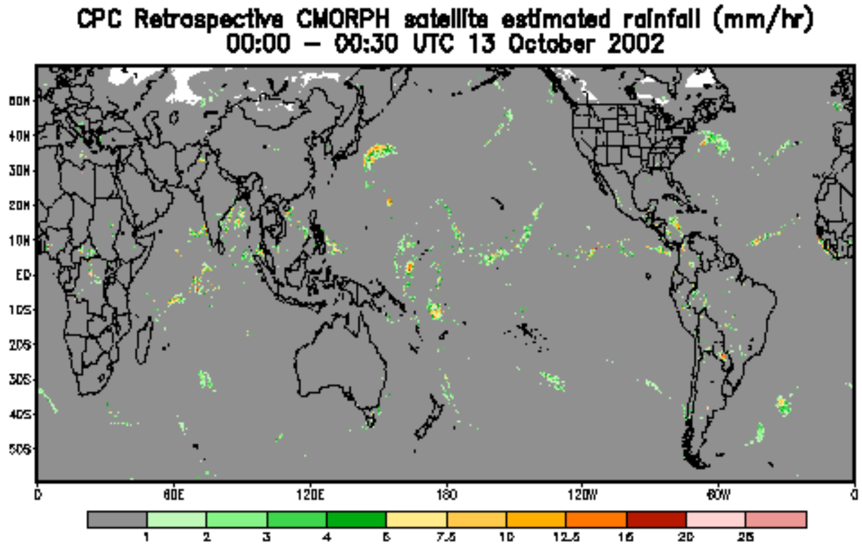

Figure 3. Sample CMORPH 30-min precipitation distribution for 00:00-00:30Z, 13 October, 2002.

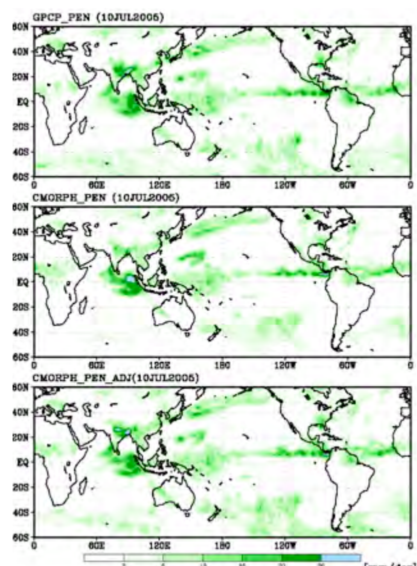

Figure 4. Spatial distribution of pentad precipitation of GPCP (top), original CMORPH (middle), and adjusted CMORPH for the 39th pentad (July 10-14) of 2005 (mm/day).

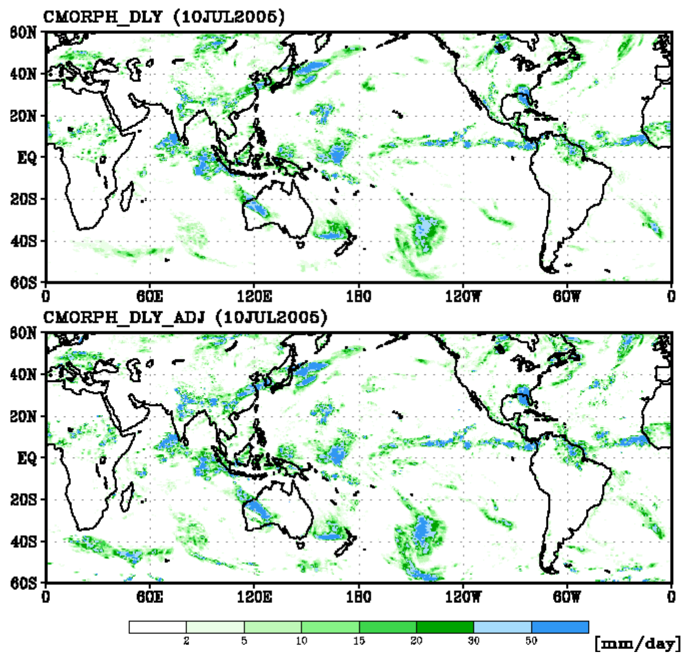

Figure 5. Spatial distribution of daily precipitation of original CMORPH (upper) and adjusted CMORPH for July 10, 2005 (mm/day).

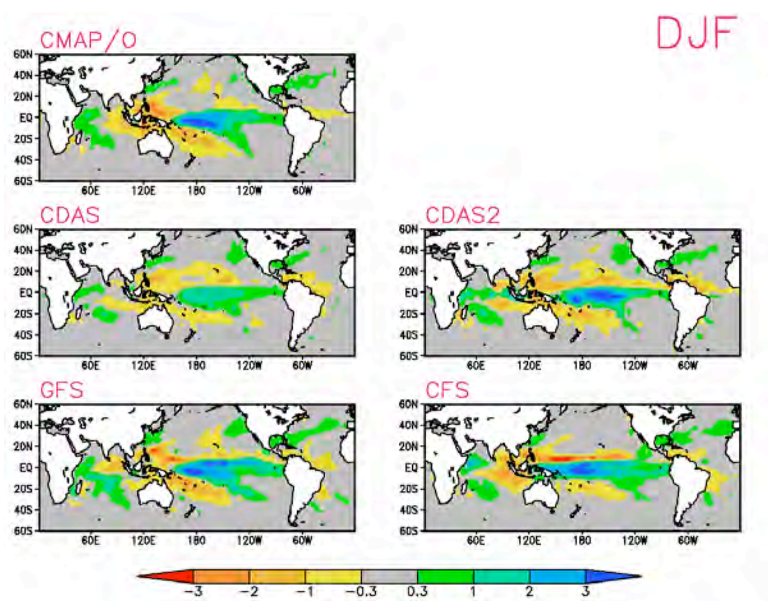

Figure 6. Regressional coefficients of December-January-February (DJF) precipitation anomaly (mm/day) against the NINO3.4 index for precipitation generated by the observation (CMAP), NCEP Reanalysis 1 (CDAS), NCEP Reanalysis 2 (CDAS2), NCEP Global Forecast System (GFS) AMIP simulations, and NCEP Climate Forecast System (CFS) CMIP simulations.

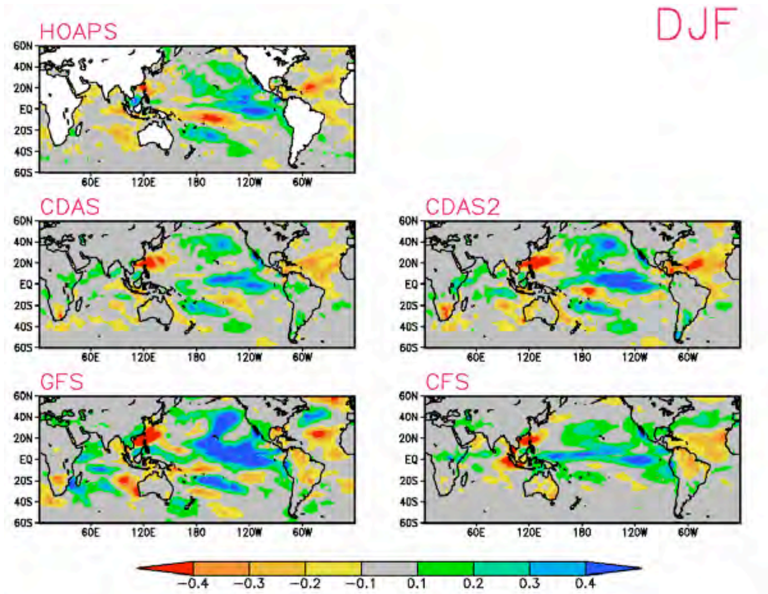

Figure 7. Regressional coefficients of December-January-February (DJF) evaporation anomaly (mm/day) against the NINO3.4 index for precipitation generated by the observation (HOAPS), NCEP Reanalysis 1 (CDAS), NCEP Reanalysis 2 (CDAS2), NCEP Global Forecast System (GFS) AMIP simulations, and NCEP Climate Forecast System (CFS) CMIP simulations.

Table 1. Cross-Validation Statistics for the original and bias-corrected CMORPH.

CMORPH	**Bias (%)**	**Correlation**
Original	**-9.7%**	**0.706**
Bias-Corrected	**-0.0%**	**0.785**

National Water Level Program Support Towards Building A Sustained Ocean Observing System For Climate

Allison Allen, Stephen Gill, Chris Zervas, Carolyn Lindley, and Lori Fenstermacher
NOAA National Ocean Service, Silver Spring MD

1. PROJECT SUMMARY

The objective of this project by the NOAA National Ocean Service (NOS) Center for Operation Oceanographic Products and Services (CO-OPS) is to develop and implement a routine annual sea level and extreme event analysis reporting capability that meets the requirements of the Climate Observation Program

The fundamental URL's are:

http://tidesandcurrents.noaa.gov for access to all programs, raw and verified data products, standards and procedures, and data analysis reports and special reports.

http://opendap.co-ops.nos.noaa.gov/content/ for access to data through an IOOS web portal.

http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml for access to the latest NWLON sea level trends and monthly mean sea level anomalies.

http://tidesandcurrents.noaa.gov/sltrends/sltrends_global.shtml for access to the latest sea level trends and monthly mean sea level anomalies for a set of global sea level reference stations.

The Climate Operating Monitoring Principles employed by the Climate Program Office are very similar to those used by NOAA's National Water Level Program (NWLP). NWLP's backbone observation system is the National Water Level Observation Network (NWLON) is a long-term continuous operational oceanographic network which meets several of NOAA's mission needs for tides and water levels. The NWLP is an end-to-end program that is planned, managed, and operated to provide products that meet user-driven needs. The program is also comprised of continuous quality control, data base management, operational readiness, continuous developments in technology, and fully open web-site for data delivery. These data and associated sea level products are made available over the web-site for use by PSMSL, UHSLC, and the WOCE communities. $100k was provided in last year's (FY2008) budget request to accomplish the task described below.

Task One - Routine Sea Level Analysis Reports

62 water level stations were identified in the International Sea Level Workshop Report (1997) as a core global subset for long-term sea level trends. The Climate Observations Program Plan calls these climate "reference stations" and includes the following performance measures for the reference stations:

1. Routinely deliver an annual report of the variations in relative annual mean sea level for the

entire length of the instrumental record.

2. Routinely deliver an annual report of the monthly mean sea level trend for the past 100 years with 95% confidence interval.

The CO-OPS technical report on sea level trends (Zervas, 2001) has been used as a starting template for an annual report. In addition to the analysis of long-term sea level trends and monthly mean sea level analyses, a new product is being developed to present summaries of the exceedance probabilities at selected stations.

In 2006, CO-OPS completed the development component of the routine analyses of the aforementioned 62 reference stations, including 18 NWLON stations and 44 non-NOAA global stations. The monthly mean sea level data for the non-NOAA stations were obtained from the Permanent Service for Mean Sea Level (PSMSL) website. The data set obtained was their Revised Local Reference (RLR) data which has been carefully quality-controlled for datum continuity.

http://tidesandcurrents.noaa.gov/sltrends/sltrends_global.shtml

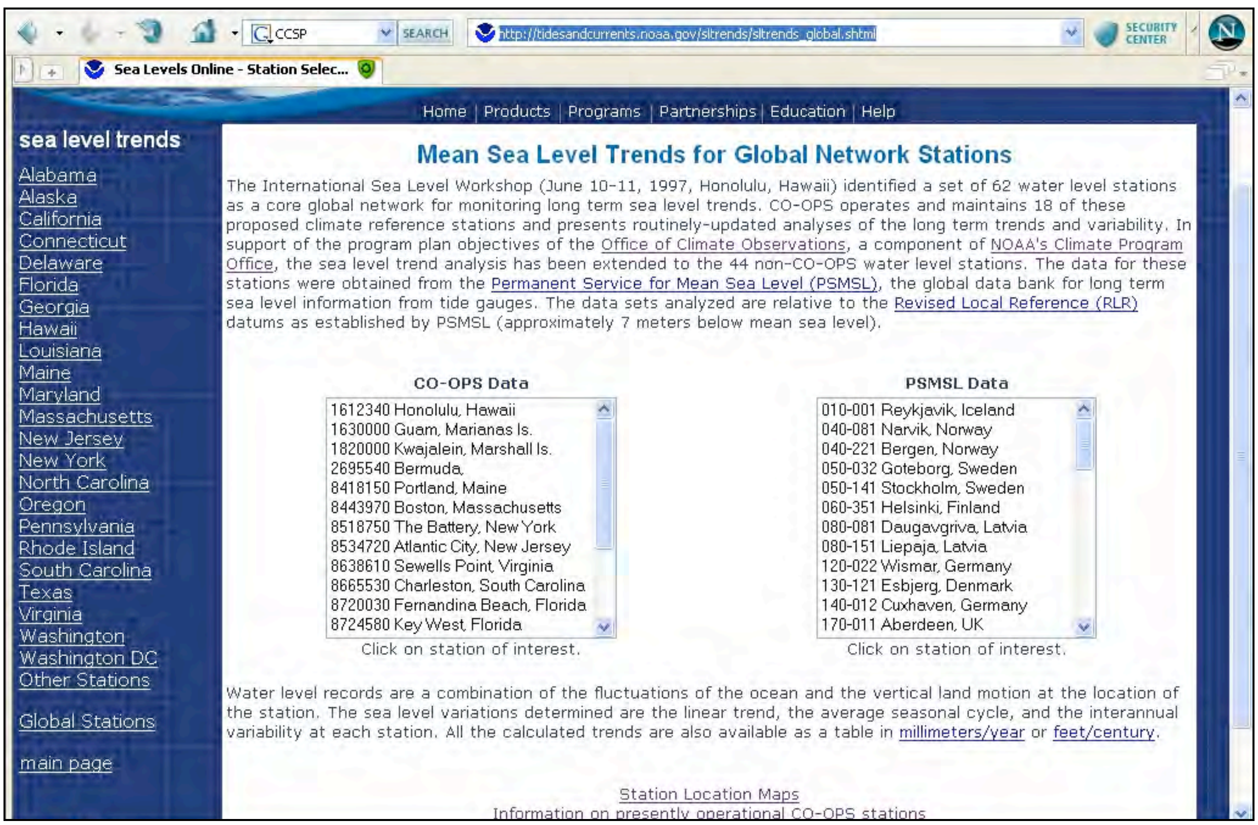

Figure 1. The NOAA web-site for viewing information on sea level trends and monthly mean sea level anomalies at global tide stations.

The following example for the international stations follows the presentation template using all available PSMSL RLR data for each station:

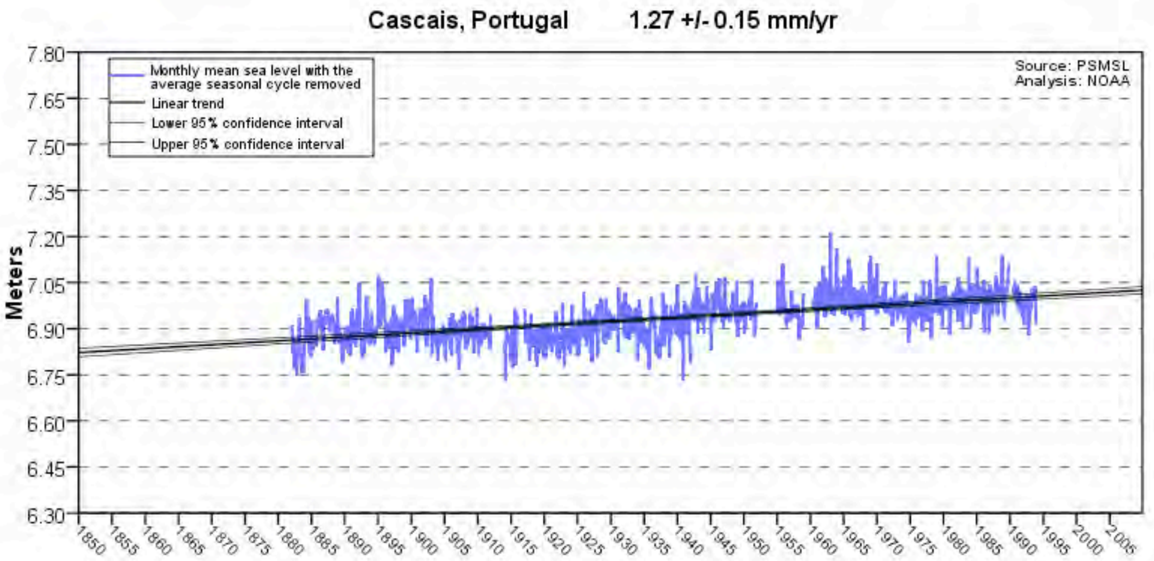

Figure 2. The sea level trend analysis.

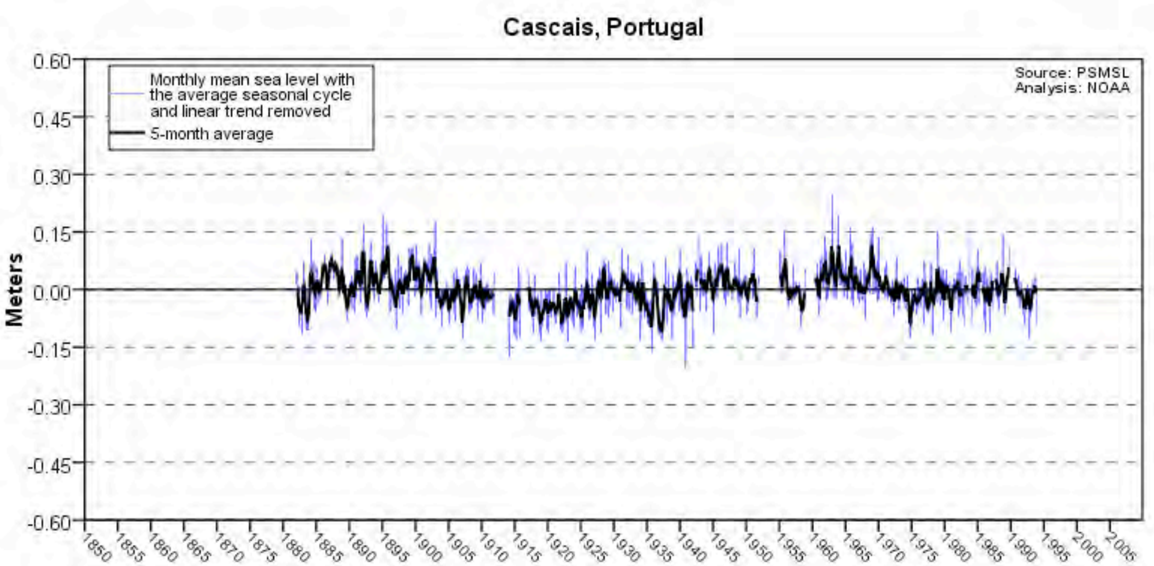

Figure 3. The interannual variation analysis.

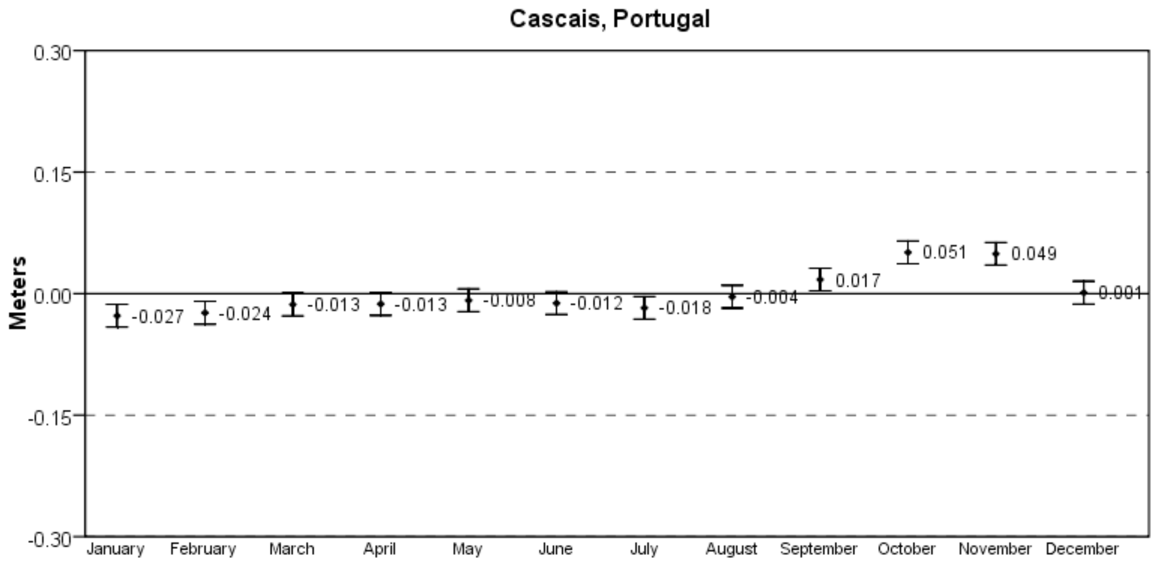

Figure 4. The average seasonal cycle analysis.

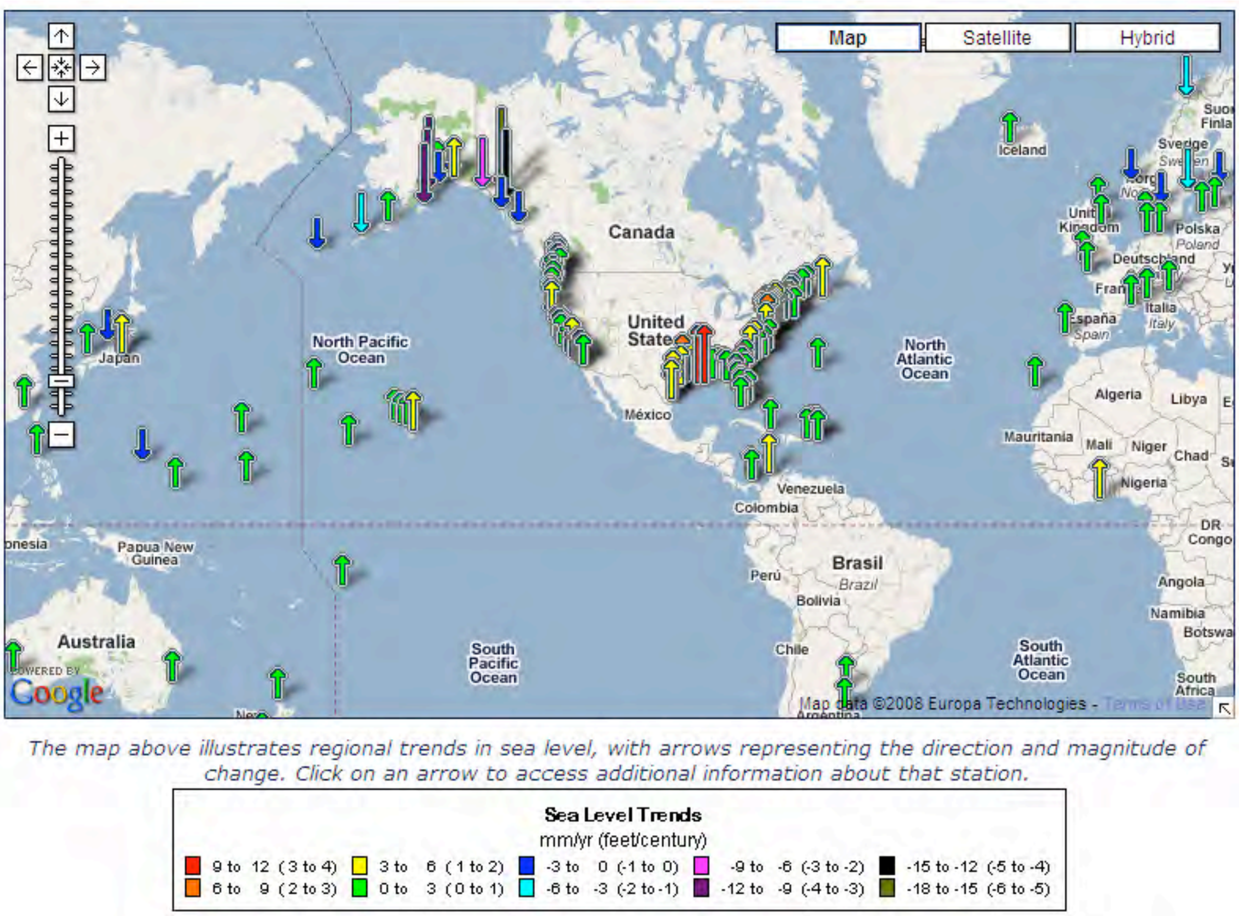

Figure 5. New Google map interface for Relative Sea Level Trends.

2. ACCOMPLISHMENTS

Efforts in FY2008 concentrated on getting the monthly sea level data compiled in a timely manner and generating routine reports established in the first year effort. These efforts have been coordinated with PSMSL, GLOSS and UHSLC programs.

In FY2008, linear sea level trends were recalculated for all NWLON stations with trends published in the previous NOAA Technical Report (Zervas, 2001), as well as analyses of 12 additional U.S. stations using all available data up to the end of 2006. The Sea Levels Online website was redesigned and a new Google Map interface was introduced to provide easier access for users to water level stations in their region of interest.

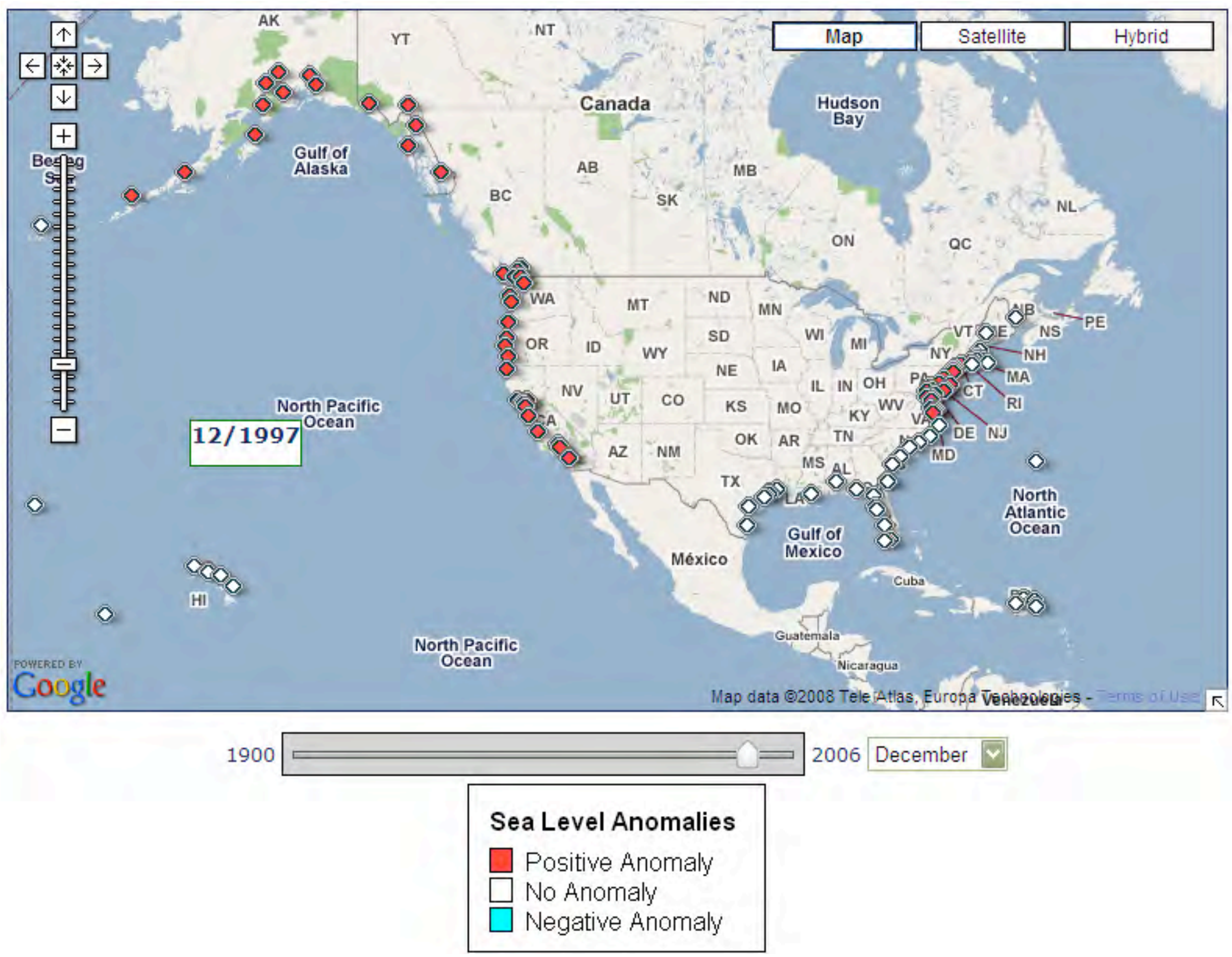

Figure 6. New Google map interface for Sea Level Anomalies (shown for December 1997).

CO-OPS has now extended the compilation of the data and the reports from the 62 global reference stations to nearly all of the 182 stations identified in Annex IV of the Global Sea Level Observing System (GLOSS) Implementation Plan 1997 (IOC Technical Series No. 50) (http://unesdoc.unesco.org/images/0011/001126/112650eo.pdf) as GLOSS-LTT (Long Term Trend). 45 of the GLOSS-LTT stations are CO-OPS stations and their sea level trends and variations were already available on Sea Levels Online.

A review of the PSMSL data available showed that a few of the GLOSS-LTT stations do not have enough data yet to obtain a reliable sea level trend. There are also a number of Scandinavian stations with long data sets that are no longer in operation; given the number of other stations in that region, these defunct stations were not analyzed. There are also a few river stations on the St. Lawrence River where sea level trends are not meaningful with respect to climate observations. The expanded global reference station network now consists of 159 stations, which means that a total of 97 stations have been added to the previous 62 climate reference stations.

Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr

[Source of data: PSMSL and NOAA; Analysis: NOAA]

Station Name	First Year	Last Year	Year Range	MSL Trend	95% Confidence Interval (+/-)
Reykjavik, Iceland	1956	2001	46	2.34	0.71
Barentsburg, Norway	1948	2006	59	-2.99	0.67
Murmansk, Russia	1952	2006	55	3.92	1.00
Narvik, Norway	1928	2001	74	-3.09	0.59
Heimsjo, Norway	1935	2006	72	-1.61	0.40
Maloy, Norway	1945	2006	62	0.93	0.52
Bergen, Norway	1883	2001	119	-0.52	0.23
Stavanger, Norway	1881	2006	126	0.42	0.21
Oslo, Norway	1885	2006	122	-4.53	0.34
Smogen, Sweden	1911	2007	97	-1.92	0.27
Goteborg, Sweden	1887	2003	117	-1.30	0.36
Klagshamn, Sweden	1929	2007	79	0.53	0.48
Kungholmsfort, Sweden	1887	2007	121	0.00	0.27
Landsort, Sweden	1887	2007	121	-2.85	0.32
Stockholm, Sweden	1889	2003	115	-3.94	0.35
Ratan, Sweden	1892	2007	116	-7.75	0.41
Furuogrund, Sweden	1916	2007	92	-8.17	0.61
Kemi, Finland	1920	2006	87	-7.01	0.67
Oulu/Uleaborg, Finland	1889	2006	118	-6.38	0.43
Raahe/Brahestad, Finland	1922	2006	85	-6.81	0.71
Pietarsaari/Jakobstad, Finland	1914	2006	93	-7.32	0.61
Vaasa/Vasa, Finland	1883	2006	124	-7.36	0.36
Kaskinen/Kasko, Finland	1926	2006	81	-6.54	0.73
Mantyluoto, Finland	1910	2006	97	-5.96	0.53
Turku/Abo, Finland	1922	2006	85	-3.71	0.66
Degerby, Finland	1923	2006	84	-3.77	0.64
Hanko/Hango, Finland	1887	1997	111	-2.76	0.42
Helsinki, Finland	1879	2001	123	-2.41	0.37
Hamina, Finland	1928	2006	79	-1.03	0.85
Daugavgriva, Latvia	1872	1938	67	0.16	0.99
Liepaja, Latvia	1865	1936	72	0.88	0.72
Kaliningrad, Russia	1926	1986	61	1.84	0.89
Warnemunde, Germany	1855	2005	151	1.20	0.12
Wismar, Germany	1848	2003	156	1.38	0.10
Gedser, Denmark	1898	2006	109	0.94	0.19
Kobenhavn, Denmark	1889	2006	118	0.49	0.21
Hornbaek, Denmark	1898	2006	109	0.25	0.23

Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr					
[Source of data: PSMSL and NOAA; Analysis: NOAA]					
Station Name	**First Year**	**Last Year**	**Year Range**	**MSL Trend**	**95% Confidence Interval (+/-)**
Korsor, Denmark	1897	2006	110	0.75	0.19
Slipshavn, Denmark	1896	2006	111	0.93	0.17
Fredericia, Denmark	1889	2006	118	1.03	0.12
Aarhus, Denmark	1888	2006	119	0.56	0.12
Frederikshavn, Denmark	1894	2006	113	0.16	0.16
Hirtshals, Denmark	1892	2006	115	-0.20	0.22
Esbjerg, Denmark	1889	1997	109	1.05	0.31
Cuxhaven, Germany	1843	2002	160	2.44	0.17
Aberdeen, UK	1862	2003	142	0.66	0.10
North Shields, UK	1895	2003	109	1.88	0.16
Sheerness, UK	1832	2006	175	1.64	0.10
Newlyn, UK	1915	2003	89	1.71	0.20
Brest, France	1807	2000	194	1.00	0.08
La Coruna, Spain	1943	2006	64	1.31	0.47
Cascais, Portugal	1882	1993	112	1.27	0.15
Lagos, Portugal	1908	1999	92	1.50	0.24
Marseille, France	1885	2000	116	1.20	0.16
Genova, Italy	1884	1997	114	1.20	0.14
Trieste, Italy	1905	2001	97	1.15	0.22
Tuapse, Russia	1917	2002	86	2.24	0.65
Ponta Delgada, Portugal	1978	2005	28	2.55	1.09
Tenerife, Spain	1927	1999	73	1.53	0.31
Takoradi, Ghana	1929	1970	42	3.35	0.50
Walvis Bay, Namibia	1958	1998	41	0.33	1.44
Simons Bay, South Africa	1957	2007	51	1.59	0.28
Port Elizabeth, South Africa	1978	2007	30	3.13	1.40
Durban, South Africa	1971	2007	37	0.63	0.62
Aden, Yemen	1879	1969	91	1.23	0.20
Karachi, Pakistan	1916	1994	79	0.48	0.53
Mumbai/Bombay, India	1878	1994	117	0.74	0.12
Cochin, India	1939	2004	66	1.37	0.32
Chennai/Madras, India	1916	2003	88	0.31	0.41
Vishakhapatnam, India	1937	1996	60	0.54	0.52
Ko Taphao Noi, Thailand	1940	2006	67	0.49	1.06
Ko Lak, Thailand	1940	2002	63	-0.48	0.26
Macau, China	1925	1985	61	0.25	0.50
Xiamen, China	1954	2002	49	1.02	0.60
Yuzhno Kurilsk, Russia	1948	1994	47	2.74	0.62
Mera, Japan	1931	2001	71	3.66	0.24
Aburatsubo, Japan	1930	1999	70	3.33	0.27
Kushimoto, Japan	1957	2007	51	3.09	0.62
Hosojima, Japan	1930	2007	78	-0.53	0.32
Tonoura/Hamada, Japan	1894	2002	109	0.38	0.24
Wajima, Japan	1930	1999	70	-0.80	0.26
Manila, Philippines	1901	1969	69	1.78	0.35
Legaspi, Philippines	1947	2005	59	5.22	0.80
Davao, Philippines	1948	2005	58	5.32	1.30
Jolo, Philippines	1947	1996	50	0.19	1.12
Townsville, Australia	1959	2006	48	1.11	0.44

Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr					
[Source of data: PSMSL and NOAA; Analysis: NOAA]					
Station Name	**First Year**	**Last Year**	**Year Range**	**MSL Trend**	**95% Confidence Interval (+/-)**
Newcastle, Australia	1925	1988	64	2.19	0.48
Sydney, Australia	1886	2003	118	0.59	0.11
Fremantle, Australia	1897	2003	107	1.48	0.27
Auckland, New Zealand	1903	2000	98	1.29	0.20
Wellington, New Zealand	1944	2005	62	2.41	0.35
Lyttelton, New Zealand	1924	2000	77	2.36	0.29
Guam, Marianas Islands	1948	1993	46	-1.05	1.72
Chuuk, Caroline Islands	1947	1995	49	0.60	1.78
Kwajalein, Marshall Islands	1946	2006	61	1.43	0.81
Wake Island	1950	2006	57	1.91	0.59
Pago Pago, American Samoa	1948	2006	59	2.07	0.90
Midway Atoll	1947	2006	60	0.70	0.54
Johnston Atoll	1947	2003	57	0.75	0.56
Honolulu, USA	1905	2006	102	1.50	0.25
Hilo, USA	1927	2006	80	3.27	0.35
Adak Island, USA	1957	2006	50	-2.75	0.54
Seward, USA	1964	2006	43	-1.74	0.91
Sitka, USA	1924	2006	83	-2.05	0.32
Ketchikan, USA	1919	2006	88	-0.19	0.27
Prince Rupert, Canada	1909	2006	98	1.09	0.27
Vancouver, Canada	1910	1999	90	0.37	0.28
Victoria, Canada	1909	1999	91	0.80	0.25
Tofino, Canada	1909	2006	98	-1.59	0.32
Neah Bay, USA	1934	2006	73	-1.63	0.36
Friday Harbor, USA	1934	2006	73	1.13	0.33
Seattle, USA	1898	2006	109	2.06	0.17
Astoria, USA	1925	2006	82	-0.31	0.40
Crescent City, USA	1933	2006	74	-0.65	0.36
San Francisco, USA	1897	2006	110	2.01	0.21
Los Angeles, USA	1923	2006	84	0.83	0.27
La Jolla, USA	1924	2006	83	2.07	0.29
San Diego, USA	1906	2006	101	2.06	0.20
Balboa, Panama	1908	1996	89	1.38	0.27
Buenaventura, Colombia	1941	1969	29	0.96	1.22
La Libertad, Ecuador	1948	2003	56	-1.22	0.97
Antofagasta, Chile	1945	2006	62	-0.75	0.48
Puerto Deseado, Argentina	1970	2002	33	-0.06	1.93
Puerto Madryn, Argentina	1944	2000	57	1.50	0.79
Quequen, Argentina	1918	1982	65	0.85	0.31
Buenos Aires, Argentina	1905	1987	83	1.57	0.30
Montevideo, Uruguay	1938	1995	58	1.21	0.69
Cananeia, Brazil	1954	2006	53	4.20	0.63
Cartagena, Colombia	1949	1992	44	5.31	0.37
Cristobal, Panama	1909	1980	72	1.41	0.22
Galveston Pier 21, USA	1908	2006	99	6.39	0.28
Pensacola, USA	1923	2006	84	2.10	0.26
Key West, USA	1913	2006	94	2.24	0.16
Bermuda	1932	2006	75	2.04	0.47
Mayport, USA	1928	2006	79	2.40	0.31

Linear mean sea level (MSL) trends and 95% confidence intervals in mm/yr					
[Source of data: PSMSL and NOAA; Analysis: NOAA]					
Station Name	**First Year**	**Last Year**	**Year Range**	**MSL Trend**	**95% Confidence Interval (+/-)**
Fernandina Beach, USA	1897	2006	110	2.02	0.20
Fort Pulaski, USA	1935	2006	72	2.98	0.33
Charleston, USA	1921	2006	86	3.15	0.25
Wilmington, USA	1935	2006	72	2.07	0.40
Sewells Point, USA	1927	2006	80	4.44	0.27
Washington, USA	1924	2006	83	3.16	0.35
Annapolis, USA	1928	2006	79	3.44	0.23
Baltimore, USA	1902	2006	105	3.08	0.15
Philadelphia, USA	1900	2006	107	2.79	0.21
Atlantic City, USA	1911	2006	96	3.99	0.18
Sandy Hook, USA	1932	2006	75	3.90	0.25
The Battery, USA	1856	2006	151	2.77	0.09
Kings Point/Willets Point, USA	1931	2006	76	2.35	0.24
Newport, USA	1930	2006	77	2.58	0.19
Woods Hole, USA	1932	2006	75	2.61	0.20
Boston, USA	1921	2006	86	2.63	0.18
Portland, USA	1912	2006	95	1.82	0.17
Eastport, USA	1929	2006	78	2.00	0.21
Saint John, Canada	1914	1999	86	2.75	0.33
Halifax, Canada	1895	2002	108	3.16	0.15
Pointe-Au-Pere, Canada	1900	1983	84	-0.36	0.40
Quebec, Canada	1910	2006	97	-0.17	0.49
Neuville, Canada	1914	2006	93	0.17	0.79
Argentine Islands, Antarctica	1958	2006	49	1.72	0.49

3. PUBLICATIONS AND REPORTS

Results, analyses, and data products are routinely updated and reported on via the CO-OPS web site at: http://tidesandcurrents.noaa.gov/sltrends/sltrends.html.

Evaluating the Ocean Observing System: Surface Currents

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1. PROJECT SUMMARY

The Integrated Ocean Observing System (IOOS) includes an array of moored and drifting buoys that measure SST and near-surface currents throughout the world's oceans. The success of the IOOS in resolving SST variations and reducing satellite SST bias is quantified in a quarterly report (Zhang et al., 2004). However, until this project was initiated, no comparable evaluation was performed for surface currents even though surface currents carry massive amounts of heat from the tropics to subpolar latitudes, leading (and potentially improving prediction of) SST anomalies. Current anomalies can also be an early indicator of phase shifts in the ENSO, NAO, and possibly other climate cycles. The GOOS/GCOS (1999) report specified that the IOOS should resolve surface currents at 2 cm/s accuracy, with one observation per month at a spatial resolution of 600 km. There is currently no requirement for potential satellite bias in surface currents.

The goal of this project is to maintain a quarterly "Observing System Status Report for Surface Currents", which evaluates how well the IOOS satisfied the GOOS/GCOS requirements, and evaluate the evolution of the globally averaged potential satellite bias. This product is being used as a guide for future drifter deployments in conjunction with NOAA/AOML's Drifter Operations Center, a branch of the Global Drifter Program, and may demonstrate where future moored observations are necessary in order to meet these requirements.

Many researchers routinely calculate surface currents from satellite observations of wind and altimetry. As an example, geostrophic currents derived from blended satellite altimetry fields are estimated at AOML and posted daily in near-real time at http://www.aoml.noaa.gov/phod/altimetry/.
However, careful, quantified comparison with the in-situ observations has only been published for a few regions such as the Kuroshio Extension (Niiler et al., 2003). Prior to this project, no one had performed this comparison globally using non-interpolated altimetry, and the observing system had not been evaluated in this context.

2. ACCOMPLISHMENTS

Near-real time drifter data is obtained at weekly resolution from the Global Drifter Program's drifter Data Assembly Center (DAC). The DAC identifies drifters which have run aground or been picked up, and removes these from the data stream. The DAC separate maintains a metadata file documenting the drogue-off date (date when each drifter lost its sea anchor). When a drifter has lost its drogue, it is significantly affected by direct wind forcing and no longer satisfies the GOOS/GCOS quality requirement for surface current measurement accuracy. We thus eliminate drogue-off drifters from our analysis.

Moored current measurements are collected by near-surface point acoustic meters on the Tropical Atmosphere-Ocean (TAO) array in the Pacific, the Prediction and Research moored Array in the Tropical Atlantic (PIRATA), the sustained array of ATLAS moorings in the tropical Indian Ocean (RAMA), the Kuroshio Extension Observatory (KEO) mooring at 32.3ºN, 144.5ºE and the PAPA mooring at 50°N, 145°W. Currents at daily resolution are downloaded from the TAO Project Office at PMEL each quarter to quantify the number of observations at each site, and the TAO office separately provides a record of days of observations per site, per quarter. Each quarter, these independent measures are compared to ensure accuracy.

The FY08 quarterly report (Figure 1) presents the overall spatial coverage of surface curent measurements for that quarter (top right), the spatial distribution of success at meeting GOOS/GCOS requirements (bottom left, requirements stated in top left panel), and a time series showing the month-by-month fraction of the world's oceans that were measured at the resolution and accuracy stated by these requirements (bottom right).

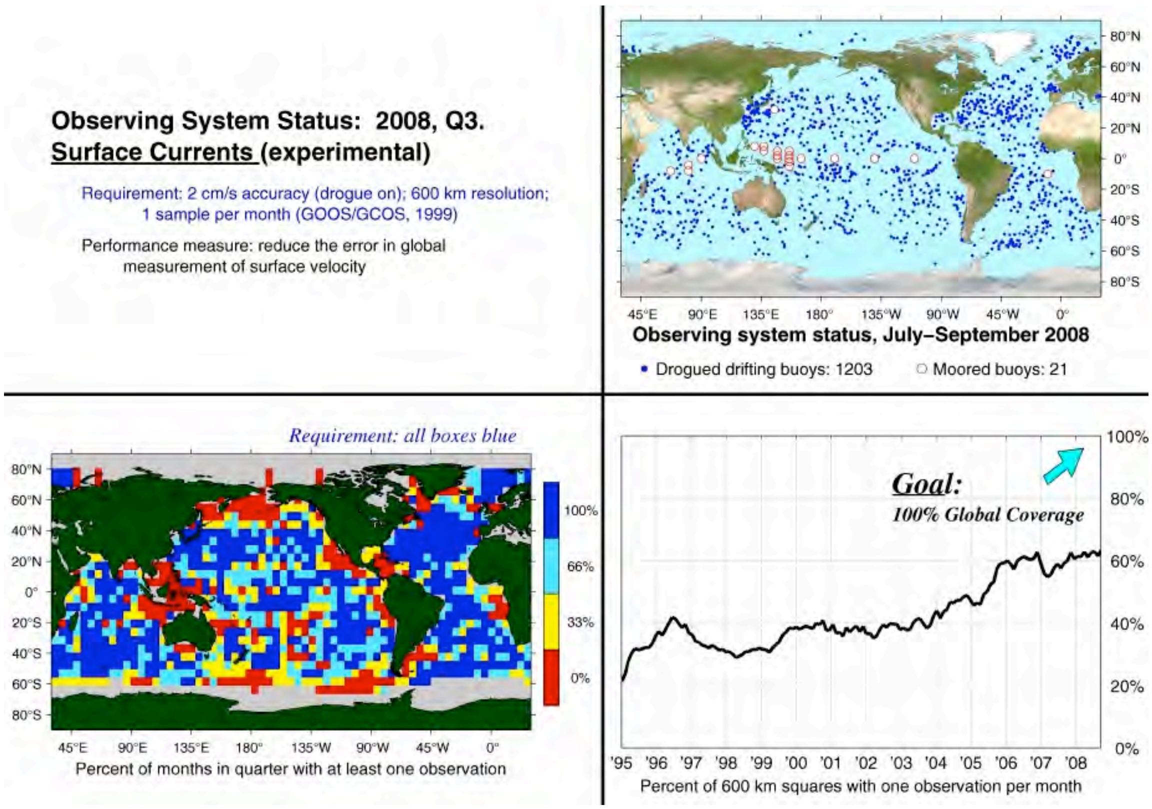

Figure 1. FY08 Q4 (calendar Q3) report evaluating the IOOS's performance for near surface current measurements.

The percent of 5° squares with at least one observation per month has effectively reached a plateau since early 2008, at slightly over 60%. Much of the shallow (too shallow for 15m drogued drifters) Indonesian Seas region remains unsampled, along with coastal divergent regions where drifters move rapidly away from the coast (e.g., the west coasts of Africa and South America, where drifters move into the convergent centers of the southern subtropical gyres which are heavily oversampled by the array). Regions along the ice edge of the southern ocean, and in marginal seas such as the Caribbean and Bering, are also persistent gaps in the array.

2.1. Evaluating potential satellite bias

Potential satellite bias error can be calculated for surface current measurements in analogy to the process for SST measurements. Satellite measurements are collected of intensity at various light frequencies, in particular infrared and microwave. A model is used to convert these measurements to surface temperatures in degrees C. Due to various biases that exist in the model, for example the influence of atmospheric dust, the resulting SST field can be significantly offset from actual SST. In-situ observations can be used to reduce this maximum bias, which varies spatially, and the resulting globally-averaged potential satellite bias error is a function of the number and distribution of the observing network.

For surface currents, models to convert satellite measurements to surface current estimates are less mature than with SST. The most developed example is NOAA's OSCAR, which includes both geostrophic and wind-driven components. However, as noted below, it is not immediately clear how to compare drifter measurements to OSCAR measurements, as differences may not necessarily be due to biases in the OSCAR model. In fact, our analysis funded by this project points to biases in the in-situ drifter measurements at high wind speeds.

For FY08, we chose to explicitly decompose drifter motion into (0) time mean, (1) geostrophic, (2) wind-driven and (3) slip components, given by time mean offsets and regression coefficients multiplying: (1) geostrophic current anomalies calculated from AVISO sea level anomaly fields using the Lagerloef et al. (1999) alogorithm, constant offsets for adjustments to the time-mean state, (2) friction velocity (proportional to the square root of the surface wind stress) and (3) wind speed at the surface. Wind stresses were derived from wind speeds using the Smith (1988) algorithm as implemented in COARE 3.0, with wind speeds from the Atlas et al. (1996, 2008) Variational Analysis Method scatterometer-based product. Drifter observations were divided into bins, with the best-fit coefficients derived via Gauss-Markov estimation. This approach requires estimating errors in the satellite-based estimates (a priori errors), and produces formal errors for the resulting ocean currents derived from satellite measurements (a posteriori errors). Maximum satellite bias can be derived from the distribution of a posteriori errors. We assume that a priori errors are dominated by errors in the geostrophic currents estimated from the AVISO product, and calculate them taking advantage of the fact that AVISO provides formal errors in the sea height anomaly that are a function of the altimetry coverage (Figure 2). We further assume that these errors are distributed over an eddy length scale, calculated as in Stammer (1999), to convert this to an error in geostrophic current. The present model results in infinite errors on the equator, an unrealistic artifact that we will address in FY09.

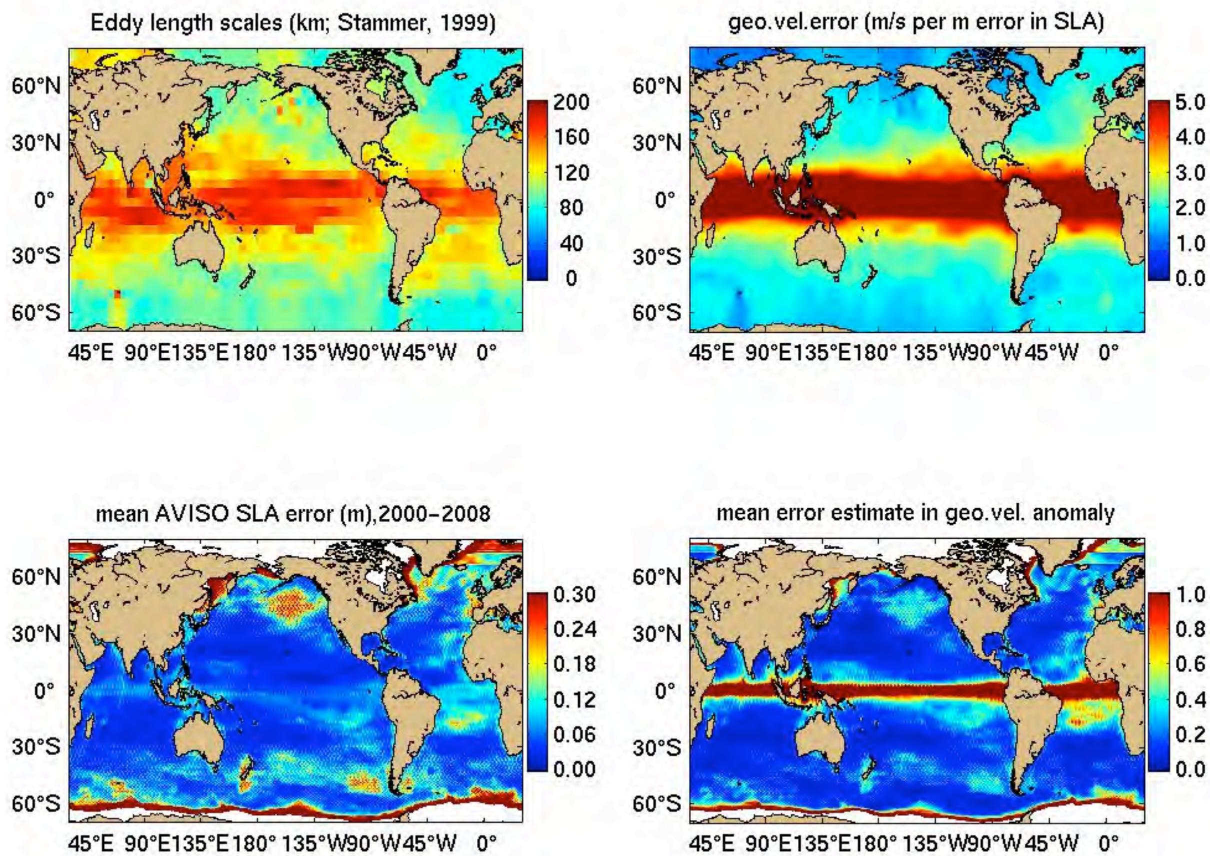

Figure 2. Eddy length scales (top left) and resulting error in geostrophic velocity anomaly (top right) in m/s, for a 1m error in sea height. The actual time-mean distribution of altimetric sea level anomaly, provided by AVISO, is shown in the bottom left panel. Resulting time-mean errors in satellite-derived geostrophic velocity anomaly is shown in bottom right.

As reported in last year's progress report, our previous work had focused on removing the Ekman component of drifter movement using the Ralph and Niiler (1999) parameterization (herafter RN99). The remaining motion, lowpassed to remove tides and inertial oscillations, was treated as dominated by geostrophic motion and compared to altimetry-based calculations. With our new approach, simultaneously decomposing the motion into wind and geostrophic components, we permit significant variations from the RN99 parameterization. For most of the globe, we find that RN99 works well. However, we find that the wind-driven component in some regions, particularly the Southern Ocean, exceeds the estimate that would be provided by RN99 (Figure 3).

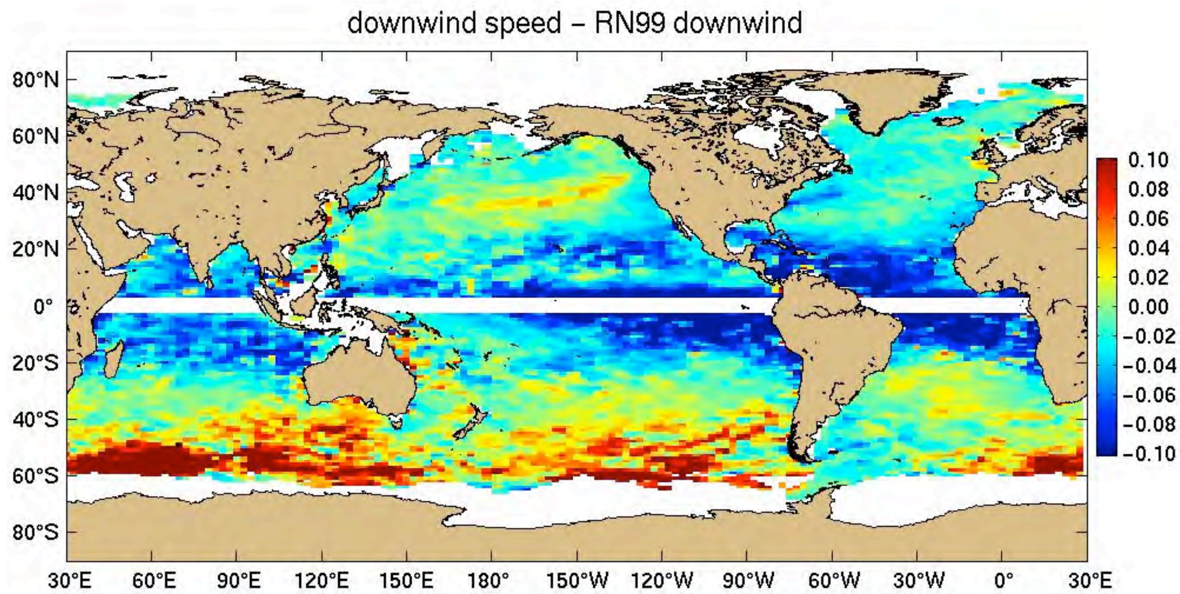

Figure 3. Difference (m/s) between the magnitude of the wind-driven component of drifter motion derived in our study and the RN99 result, calculated from the same wind field. The magnitude of the downwind component is shown; crosswind results are not significantly different. We find values 10-20 cm/s faster velocities in large subsections of the Southern Ocean. Negative results at low latitudes are due to the overly large a priori errors assigned in our Gauss Markov fit.

This result suggests that wind driven drifter motion significantly exceeds the RN99 estimate in regions with strong winds and waves, and will be a major focus of our work in FY09. Assessing what this motion is, and properly parameterizing it, will greatly increase the value of the drifter velocity data in data assimilation efforts.

Preliminary estimates of the potential satellite bias were presented by R. Lumpkin at this year's OCO annual workshop. They were derived by taking the distribution of a posteriori errors in the Gauss Markov model (Figure 4, left) and reducing those errors to the bias in the in-situ measurements where such measurements exist (Figure 4, right), with an assumed Gaussian distribution with width set by the eddy length scale (Figure 2, top right). Undrogued drifters are included in this estimate, with the larger slip used when assessing their bias error. For this "model" of surface currents from satellite observations, the maximum globally averaged satellite bias error is 15 cm/s. The current configuration of the IOOS has reduced the potential satellite bias error to 8.8 cm/s. We stress that these results are highly sensitive to the model as well as the configuration of the observing network, and smaller values may result from a better model… such as, perhaps, the OSCAR model. Testing this hypothesis hinges upon improving our parameterization of wind-driven motion, the focus of this study for FY09.

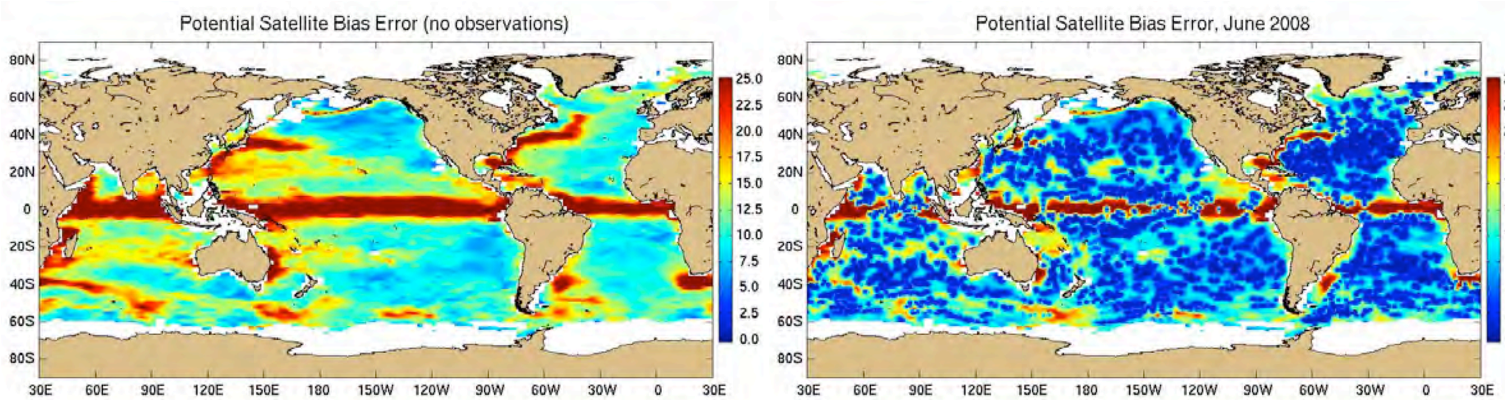

Figure 4. Distribution of satellite bias error (cm/s) with no observations for calibration (left), and distribution given the configuration of the drifter and moored buoy array in June 2008 (right).

2.2. Evaluating drifter-satellite correlations

As stated in our FY08 work plan, we completed a first global analysis of satellite- and drifter-derived geostrophic velocities for a number of purposes, including assessing errors in satellite-derived velocities from gridded altimetry and assessing potential biases in the observations. We calculated correlations between geostrophic velocity anomalies derived from satellite-altimetry and drifters. High correlation between both estimates of geostrophic velocity anomalies were identified in regions of high variability, such as western boundary currents and the Antarctic Circumpolar Current. Further analysis of the correlations indicates that the geostrophic velocities obtained from alongtrack altimetry observations always overestimate the drifter-derived low passed geostrophic velocities (Figure 5). This overestimation can be also observed in the Eddy Kinetic Energy (EKE) fields derived from each of these platforms. The EKE computed from alongtrack altimetry is usually larger than that computed from low passed drifter data; this is the opposite of what is found when comparing EKE from gridded altimetry to drifters. Differences could be attributed to ageostrophic motions not included in the altimetry velocity estimates, but seen in the drifter observations. Alternatively, the source for this discrepancy could be the low-pass filtering of the drifter observations intended to remove inertial and tidal motion. More generally, these differences indicate a mismatch between the spatial scales filtered from the alongtrack altimetry and the time scales filtered from the drifter trajectories.

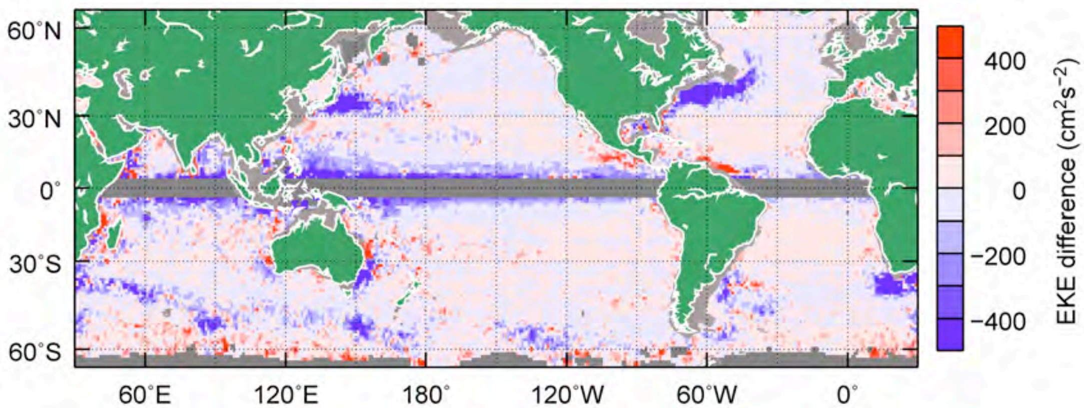

Figure 5. Difference between EKE derived from 5-day lowpass filtered Ekman-removed velocity anomalies derived from drifter data and geostrophic velocity anomalies derived from along-track altimetry data.

The PIs of this project, Lumpkin and Goni, also contribute the "Surface Currents" section for the State of the Ocean report using results generated in this study (Lumpkin and Goni, 2008).

3. PUBLICATIONS AND REPORTS

Lumpkin, R. and G. Goni, 2008: State of the Ocean in 2007: Surface Currents. In "State of the Climate in 2007", *Bulletin of the American Meteorological Society*, **89**, in press.

Lumpkin, R. and S. L. Garzoli, 2008: Interannual to Decadal Variability in the South-western Atlantic's Surface Circulation. *Geophys. Res. Lett.*, submitted.

Zhang, H.-M., R.W. Reynolds, R. Lumpkin, R. Molinari, K. Arzayus, M. Johnson, and T.M. Smith, 2008: An Integrated Global Ocean Observing System for Sea Surface Temperature Using Satellites and In situ Data: Research-to-Operations. *Bulletin of the American Meteorological Society*, in press.

4. CONFERENCES

Di Nezio, P. N., G. J. Goni, and R. Lumpkin, 2008: Global Comparison of Surface Currents derived from Drifter and Altimetry Observations. *ASLO Ocean Sciences Meeting 2008.*

Global Carbon Data Management and Synthesis Project

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1. PROJECT SUMMARY

The ocean plays a critical role in the global carbon cycle as it is a vast reservoir of carbon, naturally exchanges carbon with the atmosphere, and consequently takes up a substantial portion of anthropogenically-released carbon from the atmosphere. Although the anthropogenic CO_2 budget for the last two decades, i.e. the 1980s and 1990s, has been investigated in detail (Prentice et al., 2001), the estimates of the oceanic sink were not based on direct measurements of changes in the oceanic inorganic carbon.

Recognizing the need to constrain the oceanic uptake, transport, and storage of anthropogenic CO_2 for the anthropocene and to provide a baseline for future estimates of oceanic CO_2 uptake, two international ocean research programs, the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS), jointly conducted a comprehensive survey of inorganic carbon distributions in the global ocean in the 1990s (Wallace, 2001). After completion of the US field program in 1998, a five year effort – the Global Ocean Data Analysis Project (GLODAP) - was begun to compile and rigorously quality control the US and international data sets including a few pre-WOCE data sets in regions that were data limited (Key et al., 2004). Although these data have improved our understanding of the spatial distributions of natural and anthropogenic carbon in the ocean, they have yet to be fully exploited to examine the mechanistic controls on these carbon distributions or to understand the temporal patterns of variability.

Most of the approaches used to estimate anthropogenic CO_2 in the oceans are based on assumptions of steady state circulation and constant biology. It is becoming increasingly apparent that these assumptions may not hold especially in a time of global climate change. The most important component of an assessment of ocean biogeochemical change, whether of natural or anthropogenic origin, is high-quality observations. The WOCE/JGOFS data set provides an important point of reference for ocean carbon studies. Many other useful data sets have not been analyzed in such a context, however because there has not been a coordinated effort to bring these data together and no data management system to make navigation and exploitation of these data convenient.

The NOAA Office of Climate Observation's Carbon Network (hydrographic sections, underway pCO_2, and CO_2 moorings) is a valuable contribution to the Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). It is not sufficient, however, simply to collect and archive the data, if we expect the data to improve our understanding of the global carbon cycle and the role of the ocean in climate change.

Recognizing the need for proper data management and synthesis, NOAA's Office of Climate Observations (OCO) has funded several projects to manage and perform an initial interpretation of the data collected from the Carbon Network. In FY07 several of these projects were merged into one

management and synthesis project. The goal of the Global Carbon Data Management and Synthesis Project is to work together with the OCO carbon measurement projects to take the fundamental carbon observations and turn them into products that are useful for scientists and the public for understanding the ocean carbon cycle and how it is changing over time. This effort ranges from ensuring that the observations are of the highest quality and are mutually consistent with each other to combining the observations into a common data set that is available and easy for the community to use and explore to evaluating the time rate of change in global ocean carbon uptake and storage. This project brings together ocean carbon measurement experts, information technology experts and data managers to ensure the most efficient and productive processing possible for the OCO carbon observations.

2. BACKGROUND

Although ocean carbon uptake and storage plays a critical role in influencing global climate change, the community involved in studying ocean carbon is not as large nor is it as geared towards operational activities as the climate and physical oceanographic communities. There are no operational data centers ready to take the basic carbon observations and turn them into products like the climate forecasts or reanalysis products. As a consequence, the ocean carbon community is expected to provide the public with advanced analysis products, like global CO_2 flux maps or maps of the patterns of CO_2 uptake and storage, in addition to the basic observations. The generation of these products is the objective of this project, but it is a somewhat complicated process because it involves several data manipulation steps and coordination with many other investigators. For this report we divide the process into three categories: measurement coordination and initial quality control, data management and contextual quality control, then synthesis and interpretation.

The number of observations needed to address a global issue like ocean carbon uptake and storage is well beyond the capabilities of one lab or even one country. Thus, there are many laboratories from several countries involved in the assessment of global carbon distributions. To produce the greatest return on the US investment in ocean carbon measurements, we must ensure that all of the US laboratories are using consistent cutting-edge techniques, are assessing and documenting the data quality, and are coordinating the US measurements with the international programs so that once the data are combined we get the most extensive coverage possible. This is the measurement coordination and initial quality control portion of this project. Once the data are collected and the initial data quality has been documented, then the data must be pulled into a data management system that brings the individual laboratory data sets together into a common data base. At this point the data sets are large enough that it is awkward to manipulate without a data visualization program. Once the data set is assembled, the internal consistency of the data relative to any crossing or historical data must be checked. This is the data management and contextual quality control portion of the project. The final step in the process is taking the data set and examining it to understand how the current carbon distributions have changed and the mechanisms responsible for the observed changes. This last step is an evolving set of analyses that is continually improved and adapted as additional data are added to the data set. Each of these three steps is related and often requires iterative refinements of the previous steps to develop the final products leading to improved estimates of ocean uptake and storage.

The OCO ocean carbon network makes two basic types of observations: surface CO_2 observations with ships of opportunity and moorings and water column carbon observations with repeat hydrography cruises. The Global Carbon Data Management and Synthesis Project addresses both observation types. Because surface observations are collected in a different manner and have different requirements for developing the final product than the repeat hydrography data, the data management for these two data types is discussed separately. The activities and accomplishments for both data types in FY08 are discussed below.

3. ACCOMPLISHMENTS

The work conducted as part of this project is intimately connected with the carbon measurement projects funded by the OCO as separate efforts. The details of these measurement projects are described in the measurement project reports and are not repeated here except minimally as necessary to place the data management and synthesis efforts in context. The funds received for Global Carbon Data Management and Synthesis Project are instrumental in providing quality controlled data to the scientific community at large; for promoting and allowing the global synthesis and interpretation of national and international surface and water column carbon data; and integration of the carbon program elements within the NOAA Climate Observation Program.

3.1. Measurement Coordination and Initial Quality Control

a) Repeat Hydrography

Sabine (PMEL) and Dickson (Scripps) were editors on a revised Guide to best practices for ocean CO_2 measurements that was published in February 2008 and made available from CDIAC in both electronic and hardcopy versions (Dickson et al., 2008). This is a detailed guide for researchers making carbon measurements in the field that will hopefully standardize the methods being used and improve data quality.

The Princeton CLIVAR data synthesis activities were described in detail in the interim report submitted by Key a few months ago and significantly more information is contained in the NOAA PI progress reports. Princeton activities are limited to checking quality control flags and checking the data against existing data for systematic bias. This work is now routine. Once final data are submitted to CDIAC, the final data checks by CDIAC and/or Princeton are completed quickly, generally less than a week, and the data are submitted to CLIVAR Carbon Hydrographic Data Office (CCHDO) for merge with other data. In spite of receiving high priority, the CCHDO merge/posting is the rate limiting step in final data release. Key is also working closely with A. Kozyr at CDIAC to add additional cruises to the CLIVAR collection. These are repeat sections funded by different means, but have valuable data for "CLIVAR-type" science. The OVIDE, FICARAM and OISO studies (European work) have already been added to the CDIAC CLIVAR collection and the CARINA data will provide additional sections.

Over the last fiscal year CDIAC has received and processed the data from seven CLIVAR/CO_2 Repeat Hydrography cruises [A20_2003 (TALK), P02_2004 (TALK), P16S_2005 (TALK), P16N_2006, I09N_2007, I08S_2007, I06S_2008 (only underway), and P18_2007 (TALK and DOC only)]. The data have gone through routine QA-QC procedures and have been placed online on the CDIAC Repeat Hydrography web page: http://cdiac.ornl.gov/oceans/RepeatSections/repeat_map.html.

CDIAC compiled information from R. A. Feely, C. L. Sabine, F. J. Millero, A. G. Dickson, R. A. Fine, C. A. Carlson, J. Toole, T. M. Joyce, W. M. Smethie, A. P. McNichol, and R. M. Key to produce a numeric data package (NDP-089) describing the A20/A22 cruises (Feely et al., 2008).

Two CLIVAR/CO_2 Repeat hydrography cruises were run during FY08. The P18 cruise departed San Diego on 15 December 2007 and arrived in Punta Arenas on 23 February 2008 onboard the NOAA Ship *Ronald H. Brown*. The Miami and PMEL groups were responsible for the alkalinity and DIC measurements, respectively. Millero has made a preliminary evaluation of the P18 alkalinity data and a University of Miami Technical Report has been published: Global Ocean Repeat Hydrography Study: pH and Total Alkalinity Measurements in the Pacific Ocean P18 15th December 2007-18/21 January 2008-23 February 2008 (Millero et al. 2008a). The PMEL carbon group conducted the initial quality control of the P18 DIC data while on the ship using property plots: DIC-depth, DIC-potential temperature, DIC-salinity and DIC-LAT-depth contour plots were used to analyze the quality of the data (Figure 1). The difference plot indicates DIC anomalies ranging from 5-55 µmol/kg in the upper 1000 m of the water column. These anomalies are due to uptake of anthropogenic CO_2, changes in mixing and ventilation of the water masses, and changes in biogeochemical processes. We will continue to evaluate the relative contributions of each process to the total change in DIC over the 14-year interval once the data are finalized.

Cruise I06S on UNOLS vessel *Roger Revelle* departed Durban, South Africa on February 4, 2008 entering the southward-flowing Agulhas Current and traveled due south along a transect coinciding with Longitude 30 ˚E into the Antarctic Circumpolar Current down to the ice edge at 70 ˚S returning to Cape Town, South Africa on March 16, 2008. The Scripps and AOML groups were responsible for the alkalinity and DIC measurements, respectively. All of the data are still undergoing initial quality checks, but an initial examination of the carbon data has indicated very high DIC values in the shallow thermocline of the Southern Ocean south of 55˚S. The penetration of North Atlantic Deep Water from the north at a depth of 2000-3500 m has lower DIC values. This difference is attributed to better ventilation of the North Atlantic water mass compared to the older waters of Antarctic origin.

Over the past year Dr. Andrew Dickson (Scripps) finalized outstanding alkalinity data for earlier CLIVAR cruises: A20, P02, P16S. The quality-controlled data from these cruises has been submitted to CDIAC along with the appropriate reports for use in the associated NDP. One of these NDPs has now been published (Feely *et al.*, 2008), the others are still in process. In addition, Dickson has been working on the alkalinity data from the two remaining Indian Ocean cruises: I08S (2007) and I06S (2008) with two students: Emily Bockmon (a new student at SIO) on I08S, and J. Adam Radich on I06S (a participant in that cruise). The I06S data are almost final – they had been waiting for final salinity data that they now have – and will be submitted to CDIAC within a week or so. They will submit the final alkalinity data from I08S by the end of November 2008.

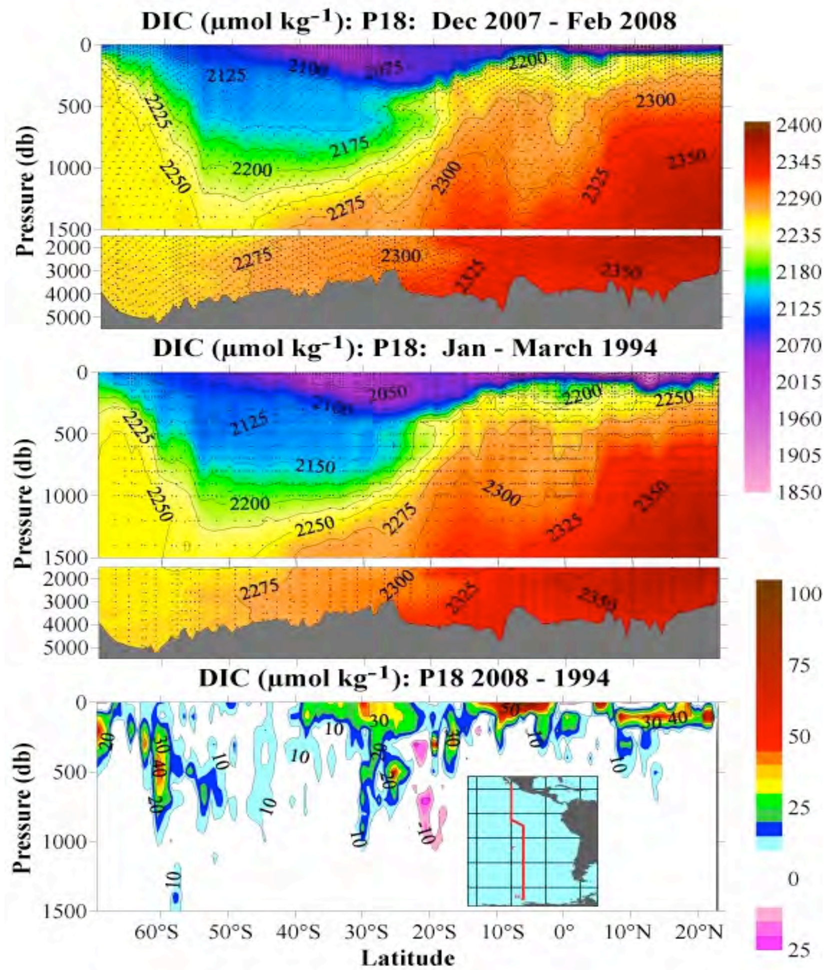

Figure 1. DIC in μmol kg^{-1} along the P18 section in the Pacific Ocean along 110-103 °W. The gridded difference plot is shown on the bottom panel for the fourteen year time difference between the cruises. The increases in DIC are the result of a combination of processes including anthropogenic CO_2 invasion and changes in circulation and biogeochemistry.

b) Surface CO_2

To conform to internationally agreed standards for the reporting of surface CO_2 data, the substantial AOML data holdings were recalculated based on the procedures outlined in Pierrot et al. (2008) and collated into yearly files. Metadata was updated to conform to the recommended format as put forth by CDIAC. Four year's worth of data from the *Explorer of the Seas* were processed and five years of data from the *Ronald H. Brown*. The 2003-2007 data from the *Skogafoss* that sailed from Norfolk VA to Reykjavik Iceland is being re-analyzed to account for a temperature bias in the sea surface temperature that was determined in part by co-locating 200K data points from the ¼ degree daily Reynolds sea surface temperature climatology.

All data from the *Ronald H. Brown* through January 2008 were reduced and posted on the AOML CO_2 website (www.aoml.noaa.gov/ocd/gcc). In addition, data and metadata were posted from the ship of opportunity *Gordon Gunter, Explorer of the Seas,* and *Xue Long.* The AOML website was reorganized to include pull down menus per ship and consistent with metadata and file structures.

During the 2008 fiscal year, data from 15 PMEL VOS cruises in the Pacific Ocean were processed and submitted to CDIAC, and data from 2 cruises are in final data processing. All current and previous VOS data files are quality controlled using the data protocol outlined in Pierrot et al. (2008).

During the 2008 fiscal year, new diagnostic software was written at PMEL to automatically process daily underway data files when they arrive via iridium satellite from the NOAA Ships *Ka'imimoana, David Starr Jordan, McArthur II* and from VOS container ships *OOCL Tianjin*, and *Albert Rickmers* and *Cap Van Diemen*. This software creates diagnostic plots of pCO_2, temperature, salinity, barometric pressure, pumps, water flow and gas flow. The plots are posted on an internal website and are used as a diagnostic tool for data processing and quality control of the underway pCO_2 data.

CDIAC received and processed the data from four Volunteer Observing Ships (VOS) lines: *Ka'imimoana* 2007 Cruises, *C/S Explorer of the Seas* Lines 2003-2007, OISO 6-12 (2006-2007) lines and *R/V Astrolabe Minerve* 28-40 cruises (1996-1999). The data were run through routine QA-QC procedures and placed online on the CDIAC VOS web page: http://cdiac.ornl.gov/oceans/VOS_Program/VOS_home.html.

CDIAC also received and processed data from TAO mooring platforms for 2004-2005. The data were run through routine QA-QC procedure and placed online on the CDIAC Mooring web page: http://cdiac.ornl.gov/oceans/Moorings/moorings.html.

CDIAC received and processed the Global Surface pCO_2 (LDEO) Database (Version 1.0). The database consists of more than 3 million measurements of surface water partial pressure of CO_2 obtained over the global oceans during 1968 - 2006 are listed in the Lamont-Doherty Earth Observatory (LDEO) database, which includes open ocean and coastal water measurements. A numeric data package (NDP-88) describes the data set and how it was developed (Takahashi et al., 2007). The data are available at: http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/LDEO_home.html. Alex Kozyr, together with Misha Krassovski developed and opened the Underway Measurement WAVES System that was populated with the LDEO database: http://cdiac3.ornl.gov/waves/underway/. The LDEO database is also available in the ODV and LAS format.

3.2. Data Management and Contextual Quality Control

a) Repeat Hydrography

Late last summer Princeton/Key submitted a very detailed report on current and planned activities with respect to this grant. That report also included a bit of background material to provide context for the current activities which have been primarily focused on the development of the CARINA dataset.

Approximately 3.5 years ago the European Union sponsored a large research contract called CARBOOCEAN. The goals of this work are very similar to those of WOCE and CLIVAR and CARBOOCEAN sought and obtained varying degrees of participation and "membership" by U.S. scientists. One requirement of the contract was that funded scientists make all of their historical (older than 2 years) data public. CDIAC was asked to be the primary data distribution center with "CARINA" used as the banner name. As part of the OCO Global Carbon Data Management and Synthesis Project, Bob Key at Princeton became actively involved in collecting and helping with the quality assessment/quality control of these data. Progress with the CARINA collection was steady until an international group of carbon scientists met in Iceland in July 2006. The primary reason for this workshop was to transfer GLODAP experience on secondary QC to the EU scientists. By this time the CARINA cruise list had grown to 89. This was the first CARINA meeting attended by other NOAA science team members (Sabine, Feely, Wanninkhof & Kozyr). Also attending were prominent Japanese ocean carbon scientists. By the end of the meeting the scope of CARINA had grown significantly. Rather than being a pure EU data set focused on the northern North Atlantic, CARINA would be 3 collections: the Arctic and its marginal seas, the Atlantic, and the entire Southern Ocean. Additionally, the collection would include all US and Japanese data in these 3 regions that had been generated since WOCE. Over the next six months the inflow of new cruise data exploded. The increase was partly due to the expanded scope, but mostly due to the fact that CARBOOCEAN is a contract rather than a grant and has deadlines that are strictly enforced. Including the US data wasn't a problem because these cruises had already been added to the Princeton holdings as part of the funded NOAA science team work. Also, adding the Japanese data was relatively easy because the number of cruises they had in the Southern Ocean was small and the data files were in excellent condition, only needing reformat and primary QC in most cases. One year later when the CARINA group met the cruise total was up to 160+ and this number does not include the US cruises. The final number is around 185 cruises none of which were in GLODAP and very few of which had previously been available to the scientific community. Accumulating high quality data from 185 cruises which had previously been available only to the original PIs is a clear indication that this synthesis effort has been successful beyond any expectation. The inflow of about 100 partial data sets in less than a year also meant that the workload required to complete the processing, do QC, etc. was no longer manageable – in fact it wasn't possible given the CARBOOCEAN deadlines. This became obvious shortly after the Iceland meeting and additional NOAA funding was requested via a new proposal to the GCC program. This proposal was ranked highly and was funded in full. Xiaohua Lin was immediately hired to help with the data processing.

Collection of new data for the CARINA project has now ended. The total number of "cruises" in the collection is 185 and 5 of these are actually compilations of cruises in a specific area. The cruises represent measurements from 1982 through 2006. Where data exist and where possible, salinity, oxygen, nutrients (nitrate, phosphate, silicate), alkalinity, total inorganic carbon and pH have been subjected to secondary quality control (quantification of systematic data bias: 2ndQC). The 2ndQC for this data collection was more complex than for the earlier GLODAP synthesis because the data covered a much longer time interval and many of the cruises were from regions known to have short time scale variability even in deep water. The derived adjustment factors from the 2ndQC are on-line and will be transferred to Princeton shortly. Preliminary versions of the adjustment table have already been used for software development at Princeton.

Recently, Princeton also developed the code to produce data files in EXCHANGE format (used by both CCHDO and CDIAC for web-based data distribution). As expected, this task was difficult, but the output from our code was recently vetted by CCHDO. Since these data distribution centers will not have to do any reformatting, the CARINA cruise data should be available on-line much quicker. Currently, neither CCHDO nor CDIAC has any public data for the Arctic. The CARINA-Arctic cruises will "initialize" the public data for both data centers. We will submit data from all of the CARINA cruises to the data centers by early December.

Both PMEL and AOML investigators from the Global Carbon Data Management and Synthesis Project are involved in the CARINA synthesis effort. Dr. Denis Pierrot (AOML) is a co-lead on the CARINA (Carbon in the North Atlantic) synthesis effort for dissolved inorganic carbon (DIC) in the North Atlantic Ocean which involves checking the data of 104 cruises. The tedious effort involves quality control and assessment of biases based on methods developed during the GLODAP effort (Key et al., 2004). Crossover routines were automated in Matlab, and tested and modified at AOML as part of this effort. The derived offsets are presented in Figure 2. The work will be detailed in a new journal: Earth System Science Data (ESSD) which is an international, interdisciplinary journal for the publication of articles on original research data.

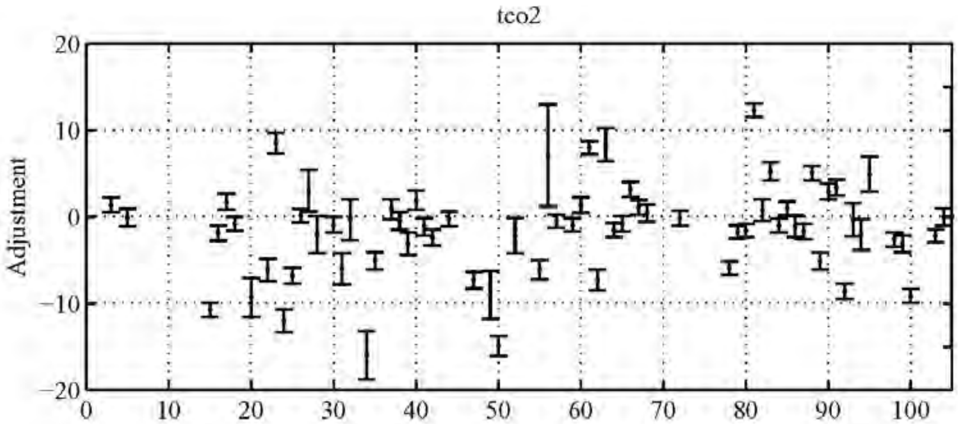

Figure 2. Derived DIC offsets for 104 cruises in the North Atlantic as part of the CARINA project. The Y axis shows the"TCO_2 offset" and the X-axis is an arbitrary sequence number. Offsets of less than 4 μmol kg^{-1} are considered within the uncertainty limit.

Dr. Chris Sabine (PMEL) is a co-lead on the Southern Ocean CARINA sub group. As with the Atlantic group, the Southern Ocean cruises have been examined for data quality and final adjustments have been determined. The synthesis results will be published in a series of articles in ESSD during FY09. Drs. Sabine and Feely are also working with members of the North Pacific Marine Science Organization (PICES) to begin a synthesis effort similar to CARINA for the Pacific. Nearly 200 Pacific cruises that have not been previously released have been identified for the effort.

Brendan Carter, a Scripps graduate student, has been working on a model for Antarctic Intermediate Water Formation based on data from an NSF-supported winter cruise off the coast of Chile (2005). This winter data has allowed him to identify plausible end-members (based on salinity and potential alkalinity) which, when mixed – together with addition or removal of fresh water – comprise Antarctic Intermediate Water (AAIW). He has applied his model to the GLODAP data set for the southern Pacific Ocean, and it appears to adequately represent AAIW over a significant region. He is now using this data to characterize changes in AAIW composition (defined on a particular isopycnal) that occur with time. A draft manuscript has been prepared which he intends to submit to *Global Biogeochemical Cycles* by the end of the year.

The alkalinity data in the GLODAP data set is significantly noisier than that from the 2005 cruise, and from recent CLIVAR cruises: this limits the sensitivity of the end-member analysis. Brendan is now starting to look at the recent CLIVAR data from the Southern Ocean to see the effects of using higher-quality data, and is also extending his analysis into other ocean basins.

b) Surface CO_2

Global Carbon Data Management and Synthesis Project investigators were involved in two surface CO_2 synthesis efforts. First, we have continued to work with Dr. Taro Takahashi (LDEO) in his global CO_2 synthesis. During this past year Dr. Takahashi released the quality controlled data compilation that underlies his latest CO_2 climatology. These data are available from CDIAC. Second, at the "Surface Ocean CO_2 Variability and Vulnerability" (SOCOVV) workshop in April 2007, participants agreed to establish a global surface CO_2 data set that would bring together, in a common format, all publicly available CO_2 data for the surface oceans. This activity, named Surface Ocean Carbon ATlas (SOCAT), has been called for by many international groups for many years, and has now become a priority activity for the marine carbon community. This data set will serve as a foundation upon which the community will continue to build in the future, based on agreed data and metadata formats and standard 1st level quality-control procedures.

An extended 1st level quality-controlled data set has been developed, building on the work started in 2001 as part of the EU ORFOIS project by Dorothee Bakker (UEA), which now continues as part of the EU CARBOOCEAN project, where Benjamin Pfeil and Are Olsen (Bjerknes Centre for Climate Research) have compiled the publicly-available surface CO_2 data held at CDIAC into a common format database based on the IOCCP recommended formats for metadata and data reporting. The community is in the process of forming regional groups to perform 2nd level quality control checks on the data.

In FY08 PMEL released the Ocean Carbon Data Management System (OCDMS -- http://ferret.pmel.noaa.gov/OCDMS/) – an operational Live Access Server (LAS) for the underway LDEO ocean carbon data collection from Taro Takahashi (NDP-88 at CDIAC). The Takahashi collection was selected as the initial target for this service, because at the time of planning the project it was the most complete collection of underway cruises that had been assembled. The tools and techniques developed for the OCDMS are being re-used and extended to support the Surface Ocean Carbon ATlas (SOCAT) effort.

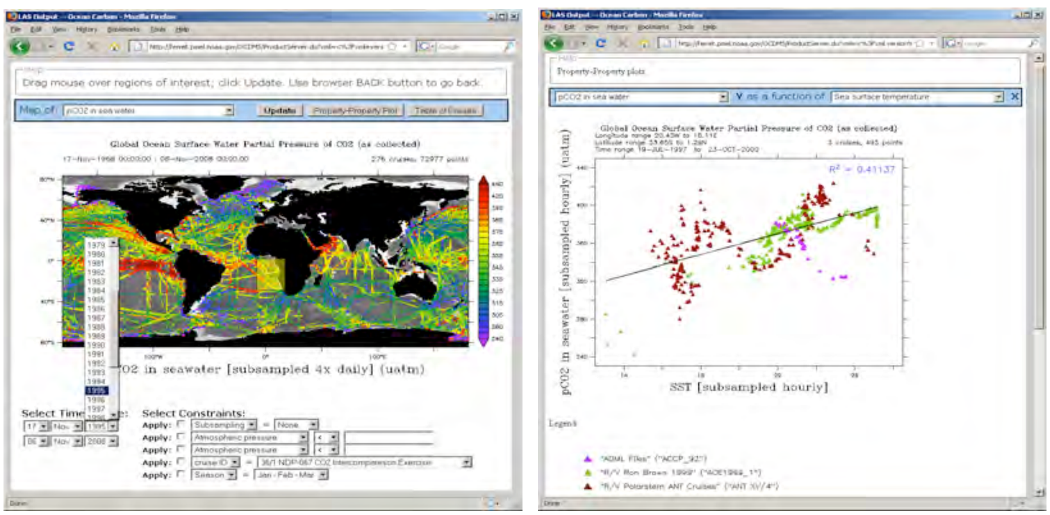

Figure 3. Web access to the Takahashi 2007 underway carbon collection.

The data base schema to accommodate the Takahashi collection was developed by Jon Callahan during FY06-07. In the course of that work hundreds of errors were discovered in the data and reported back to LDEO, ultimately to be incorporated into the official release of NDP-88. In February of 2008 Jon left the TMAP group and Jeremy Malczyk assumed responsibility for the ocean carbon data services. TMAP announced the operational release of the Takahashi OCDMS to the Carbon research community in March 2008. Figures 3a and b are screen snapshots of the server.

The server provides carbon researchers with the ability to select arbitrary regions in space and time; to click-and-drag/zoom into features of interest; to further constrain the selection based upon season, cruise ID, and the values of measured parameters; to examine the relationships between variables as property-property plots that are color-coded by cruise; and to download arbitrary subsets of data. This work was presented at the SOCAT 2nd level QC Technical Workshop in Paris in June 2008 and at the Office of Climate Observations annual review meeting in September 2008 in Silver Spring.

The OCDMS server made it possible for the first time to include historical ocean carbon observations in the OC Observing System Monitoring Center (OSMC) as we see in Figure 4. Due to limitations in the metadata, the Takahashi collection in the OSMC appears as a single monolithic (virtual) cruise. The correct representation of the ocean carbon observing system will be achievable using the more complete metadata that will become available through the SOCAT collection during FY09.

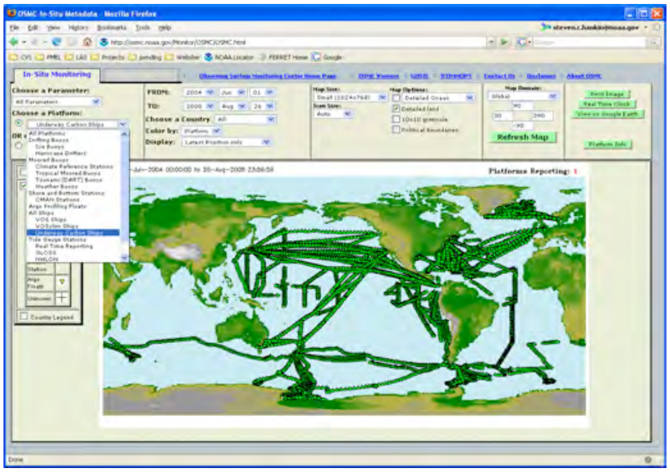

Figure 4. Underway carbon observing system seen through the OSMC.

From the middle of FY08 the focus of carbon data management work shifted to the community-sponsored SOCAT collection. The SOCAT data management effort is a close partnership between PMEL and the Bjerknes Centre for Climate Research, Bergen, Norway (Benjamin Pfeil). The initial SOCAT collection expands the scope of the data from 3.8 million observations in the Takahashi version 1.0 collection to 9.5 million observations expected in the January 2009 version of SOCAT. From the researcher's perspective the data management system appears to be very similar to the OCDMS. The underlying database design, however, has advanced significantly. Figure 5 shows one of the experimental products to emerge from this effort: an on-the-fly calculation produced by the server that shows SOCAT observation anomalies relative to climatology, based upon gridded climatology fields published by Takahashi in 2008. Such capabilities will be part of the system that will be provided to the SOCAT community in FY09 to support secondary quality control of the ocean carbon climate data record.

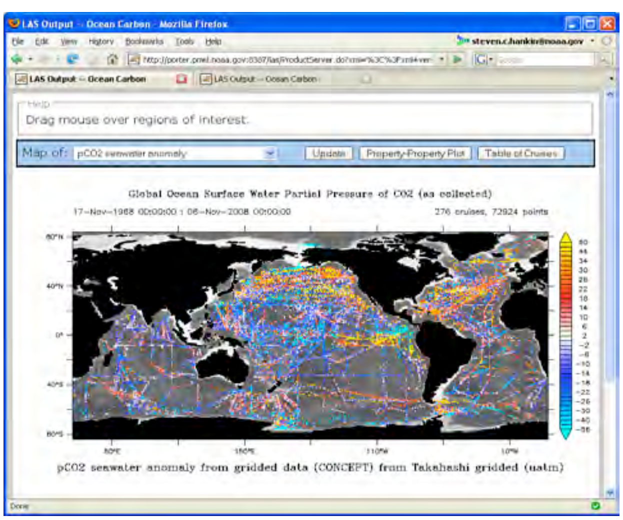

Figure 5. Underway pCO_2 anomalies from climatology generated on-the-fly by LAS.

3.3. Synthesis and Interpretation

a) Repeat Hydrography

Sabine et al. (2008) used the extended multiple linear regression (eMLR) technique to investigate changes over the last decade in DIC inventories on a meridional line (P16 along 152°W) up the central Pacific and on a zonal line (P02 along 30°N) across the North Pacific. Maximum changes in the total DIC concentrations along P02 are 15–20 μmol kg^{-1} over 10 years, somewhat higher than the ~1 μmol kg^{-1} yr^{-1} increase in DIC expected based on the rate of atmospheric CO_2 increase. The maximum changes of 15–20 μmol kg^{-1} along the P16 line over the 14/15-year time frame fit with the expected magnitude of the anthropogenic signal, but there is a deeper than expected penetration of the signal in the North Pacific compared to the South Pacific. The effect of varying circulation on the total DIC change, based on decadal alterations of the apparent oxygen utilization rate, is estimated to be greater than 10 μmol kg^{-1} in the North Pacific, accounting for as much as 80% of the total DIC change in that region (Figure 6). The average anthropogenic CO_2 inventory increase along 30°N between 1994 and 2004 was 0.43 mol m^{-2} yr^{-1}, with much higher inventories in the western Pacific. Along P16, the average Northern Hemisphere increase was 0.25 mol m^{-2} yr^{-1} between 1991/1992 and 2006 compared to an average Southern Hemisphere anthropogenic CO_2 inventory increase between 1991 and 2005 of 0.41 mol m^{-2} yr^{-1}.

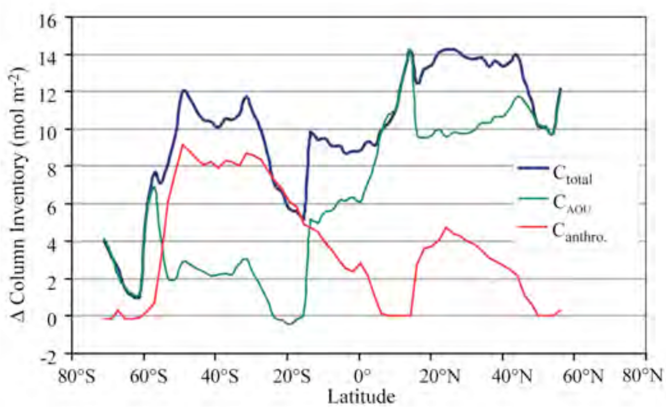

Figure 6. Column inventories of the change in anthropogenic CO_2 (solid black line), circulation carbon changes estimated from AOU (light gray dotted line), and the total DIC change (dark gray dashed line) along the P16 section.

Further analysis was performed on the A16 data by AOML investigators and publications that are in preparation have been revised based on refinements of the multi-linear regression techniques and other approaches to estimate anthropogenic CO_2. Chanson et al (resubmitted, 2008) showed that the updated TROCA method yields unrealistic anthropogenic CO_2 values when applied to the Atlantic data. Wanninkhof et al. (in preparation, 2008) compared several methods of estimating decadal increases of anthropogenic CO_2 that suggest that on regional scale an extended multi-linear regression along density provides the most consistent estimate based on diagnostics with models and transient tracers.

During the WOCE program, the I08S cruise was carried out from 12/2/1994 (31.5°S, 110.2°E) to 12/28/1994 (63.3°S, 82°E), while I09N cruise was from 1/26/1995 (31.2°S, 106.3°E) to 3/3/1995 (2.7°N, 80°E). This north-south cruise line was re-occupied during the CLIVAR/CO_2 Repeat Hydrographic program in March-April of 2007. To investigate the temporal changes in DIC from 1994 to 2007 along this cruise line, we have analyzed the data along the isopycnal surfaces. Comparisons of DIC along isopycnal surfaces with sigma-theta of 26.0, 26.2, 26.4, 26.6, 26.8, 27.0, and 27.2 for I09N and I09N/I08S are illustrated in Figures 7a,b. These DIC values are normalized to a salinity of 35 after correcting for AOU. In Figure 7a, comparisons of $DIC_{n,AOU}$ values from I09N stations between 15°N and 12°S along isopycnal surfaces are shown. The figure shows small DIC increases in the equatorial region where the invasion of CO_2 is inhibited by the upwelling of subsurface water. The comparison of $DIC_{n,AOU}$ values in the temperate region between 12°S and 40°S is shown in Figure 7b. Higher DIC increases in the temperate region are observed as compared with those in equatorial region. The extra DIC has penetrated along isopycnal 27.2 in the temperate region while there is negligible penetration along isopycnal 26.8 in the equatorial region. The areas between two curves with solid and open circles in each isopycnal surfaces are integrated, and the mean changes in DIC are determined. The DIC increases vary for each isopycnal interval, with increases of 4.8 µmol/kg along 26.8, and 7.0 µmol/kg along 26.2 in the equatorial region, while in temperate region they change from 7.8 µmol/kg along 27.2 to 15.2 µmol/kg along 26.4 isopycnal. Using the estimated thickness of isopycnal horizons between 15^{o}N and 12^{o}S, we obtained a mean DIC inventory change of 0.43 µmol/kg/yr in the Equatorial Indian between 1995 and 2007, which is equivalent to 0.16 mol/m^2/yr CO_2 uptake rate. For the temperate Indian Ocean, the DIC increase is much faster. We have seen significant DIC increases along each isopycnal horizon. Based on the estimated thickness of isopycnal layers between 12°S and 40°S, that are much greater than in the equatorial region, the mean DIC inventory change is estimated to be 0.90 µmol/kg from 1995 to 2007, which is equivalent to 0.82 mol/m^2/yr. The depth of isopycnal surfaces with sigma-theta ranging 26.0 to 26.6 shows that these density surfaces shallow starting from 25^{o}S latitude. A separation of temperate region into subsections for analysis of DIC increase is necessary to improve quantification of DIC temporal increases in the Indian Ocean.

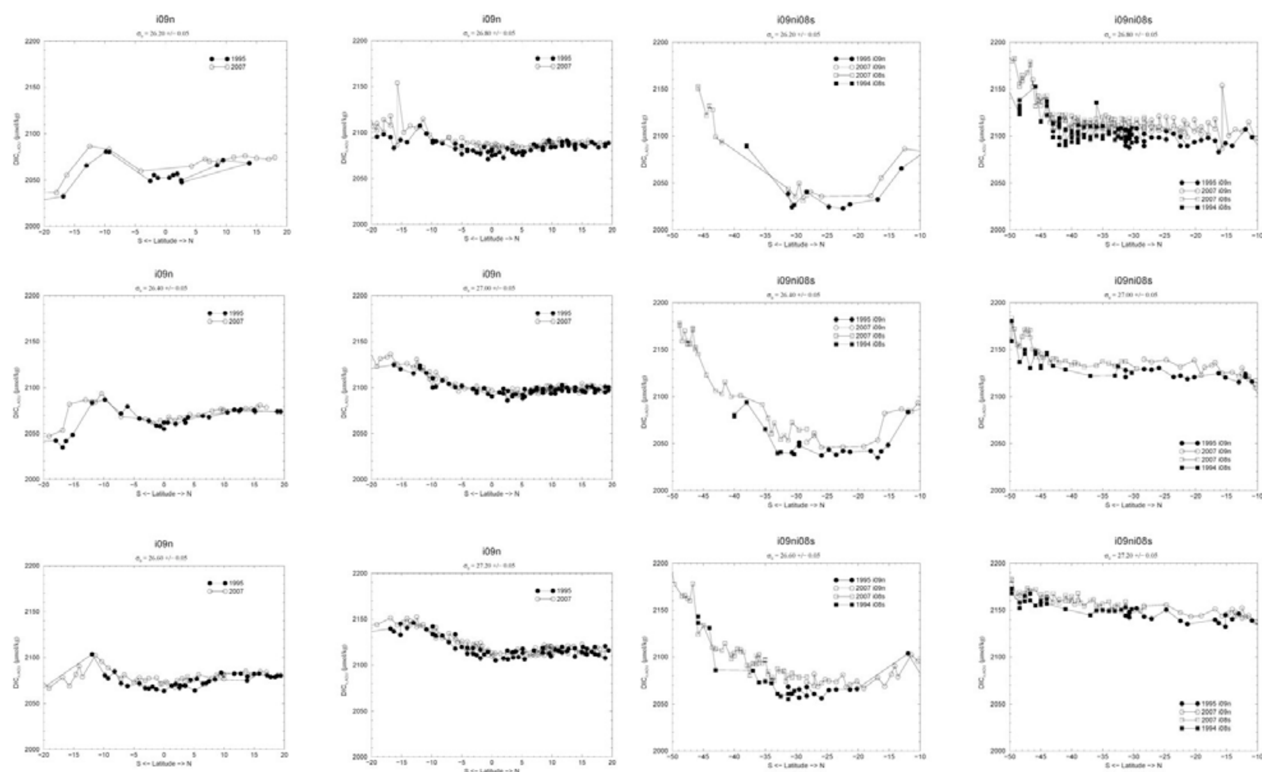

Figure 7. a) Comparison of DIC along isopycnal surfaces in the equatorial Indian Ocean for 1995 and 2007; b) Comparison of DIC along isopycnal surfaces in the temperate Indian Ocean for 1995 and 2007.

Frank Millero made an international presentation based on the repeat hydrography data in June 2008 in Trieste, Italy on the carbon dioxide system in the world oceans. Millero has been a part of two papers published on the carbonate system this year based on the repeat hydrography data (Millero et al. 2008b; Sabine et al. 2008). Dr. Millero is working on the SCOR WG 127 committee and has published a number of papers on the reference salinity (S_R) of sea water and density methods of determining the absolute salinity of seawater (S_A) (Millero et al. 2008c).

b) Surface CO_2

AOML and PMEL investigators have been involved in the latest update of the Takahashi CO_2 climatology (Takahashi et al., 2008). The climatology gives the mean surface water pCO_2 distribution over the global oceans in non-El Niño conditions with a spatial resolution of 4° (latitude) x 5° (longitude) for a reference year 2000. It is based upon about 3 million measurements of surface water pCO_2 obtained from 1970 to 2006. The database used for this study is about 3 times as large as the 0.94 million used for our earlier paper (Takahashi et al., 2002). The net air-sea CO_2 flux is estimated using the sea-air pCO_2 difference and the air-sea gas transfer rate that is parameterized as a function of (wind speed)^2 with a scaling factor of 0.24. This is estimated by inverting the bomb ^{14}C data using Ocean General Circulation models and the 1979-2005 NCEP-DOE AMIP-II Reanalysis (R-2) wind speed data.

The equatorial Pacific (14°N-14°S) is the major source for atmospheric CO_2, emitting about +0.44 Pg-C yr^{-1}, and the temperate oceans between 14° and 50° in the both hemispheres are the major sink zones with an uptake flux of -0.63 Pg-C yr^{-1} for the northern and –0.91 Pg-C yr^{-1} for the southern zone. The high latitude North Atlantic, including the Nordic Seas and portion of the Arctic Sea, is the most intense CO_2 sink area on the basis of per unit area, with a mean of $–2.3 \times 10^6$ gram-C month^{-1} km^{-2}. This is due to the combination of the low pCO_2 in seawater and high gas exchange rates. In the ice-free zone of the Southern Ocean (50°S-62°S), the mean annual flux is small because of a cancellation of the summer uptake CO_2 flux with the winter release of CO_2 caused by deepwater upwelling. The annual mean for the net sea-air CO_2 flux over the global oceans is estimated to be 1.4 ± 0.7 Pg-C yr^{-1}. Taking the pre-industrial steady state ocean source of 0.4 ± 0.2 Pg-C yr^{-1} into account, the total ocean uptake flux including the anthropogenic CO_2 is estimated to be 1.8 ± 0.7 Pg-C yr^{-1} in 2000.

During the past fiscal year, final adjustments were made to the CO_2 climatology. Of particular note in this update is the large effect that the assumptions of increase in surface water pCO_2 have in determining the climatological fluxes. Based on the re-analysis and increased data coverage the global air-sea CO_2 flux was 0.2 Pg C/yr greater than the previous iteration. An error estimate of air-sea CO_2 flux was determined that breaks down the uncertainty in the different parameters in the estimate of the climatological flux. The net climatological global sea-air flux may be subject to random errors of (Takahashi et al., 2008):

± 0.18	Pg-C yr^{-1} (± 13%)	from the ΔpCO_2 measurements,
± 0.42	Pg-C yr^{-1} (± 30%)	in the scaling factor for the gas transfer velocity parameterization,
± 0.28	Pg-C yr^{-1} (± 20%)	in wind speeds
± 0.5	Pg-C yr^{-1} (± 35%)	for the mean rate of pCO_2 change in ocean water

The results indicate that the largest source of error in the climatological fluxes is the correction for the rate of change of surface water pCO_2. This uncertainty will not impact the goal of the NOAA effort to determine the seasonal fluxes as the mean rate of change is measured. However, the uncertainty due to ΔpCO_2 measurements will be significantly greater due to a dearth of observations on such short timescales.

3.4. Ocean Acidification

Hydrographic surveys and modeling studies have revealed that the chemical changes in seawater resulting from the absorption of carbon dioxide are lowering seawater pH. For example, the time series data at Ocean Station Aloha shows an average pH decrease of approximate 0.02 units per decade in the Northeast Pacific (Figure 8; after Feely, 2008). The pH of ocean surface waters has already decreased by about 0.1 units from an average of about 8.21 to 8.10 since the beginning of the industrial revolution. Estimates of future atmospheric and oceanic carbon dioxide concentrations, based on the Intergovernmental Panel on Climate Change (IPCC) CO_2 emission scenarios and coupled ocean-atmosphere models, suggest that by the middle of this century atmospheric carbon dioxide levels could reach more than 500 ppm, and near the end of the century they could be over 800 ppm. This would result in an additional surface water pH decrease of approximately 0.3 pH units by 2100. Ocean acidification may be one of the most significant and far-reaching consequences of the increase of carbon dioxide in the atmosphere. Some call this the “other CO_2 problem” because, like global warming, it is driven by anthropogenic CO_2 (Doney et al., 2008). It is conceivable that the basic food-web structure of the ocean could change over the next 50 years. It is imperative that we rapidly improve our fundamental understanding of the impacts of ocean acidification on ocean chemistry and ocean biology. Because these changes are unprecedented in the modern era, we cannot predict with confidence how marine ecosystems will respond to this stress in the future. This rapidly emerging scientific issue and possible ecological impacts have raised serious concerns across the scientific and fisheries resource management communities. Though this is a global problem (Sabine et al., 2004), the North Pacific (Feely et al., 2004; Feely et al., 2008) has been shown to be one of the ocean regions most sensitive and vulnerable to ocean acidification. There is new evidence that corrosive “acidified” water is upwelling on the continental shelf of western North America (Feely et al., 2008).

The Global Carbon Data Management and Synthesis Project has been providing information directly related to better understanding the effects of ocean acidification. The data base of carbon measurements managed by this project is actively being utilized to initialize models of ocean acidification and Dr. Richard Feely, along with other project PIs, has been actively involved in developing the NOAA strategy for investigating and monitoring ocean acidification and its consequences. We have helped organize and participated in the Ocean Carbon and Biogeochemistry Scoping Workshop on Ocean Acidification at Scripps Institution of Oceanography in October 2007; http://www.whoi.edu/sbl/liteSite.do?litesiteid=19977 and participated in the 2nd International Symposium on Oceans in a High CO_2 World in Monaco in October 2008; http://www.highco2world-ii.org/main.cfm?cid=975. This is an important scientific issue in the ocean community and will likely play a much more prominent role in our interpretation of ocean carbon data in FY09 and beyond.

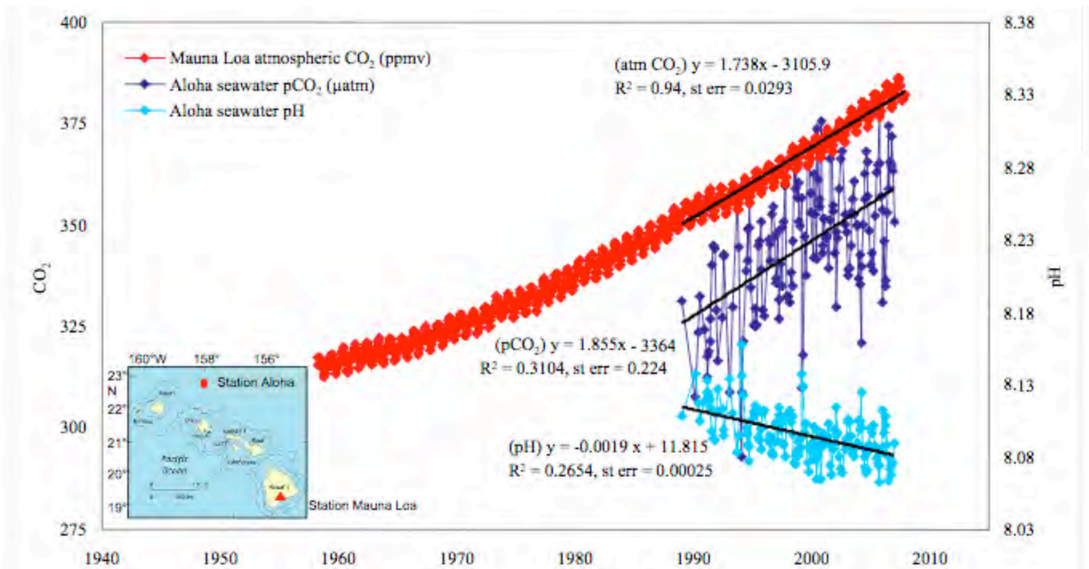

Figure 8. Time series of atmospheric CO_2 at Mauna Loa (ppmv) and surface ocean pH and pCO_2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean. Note that the increase in oceanic CO_2 over the last 17 years is consistent with the atmospheric increase within the statistical limits of the measurements (From Feely, 2008).

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Optimal network design to detect spatial patterns and variability of ocean carbon sources and sinks from underway surface pCO_2 measurements

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1. PROJECT SUMMARY

In agreement with the Intergovernmental Panel on Climate Change (IPCC), the *Second Report on the Adequacy of the Global Observing System for Climate in Support of the United Nations Framework Convention on Climate Change (UNFCCC)* concludes that there remain serious deficiencies in the ability of the current global observing systems for climate to meet the observational needs of the UNFCCC. One continuing aspect of the effort to redress the identified deficiency has been to expand the surface ocean pCO_2 measurement program in order to quantify our understanding of the seasonal and interannnual variability of air-sea CO_2 fluxes in the world oceans. While there is a reasonably good understanding of the major sources and sinks of CO_2 based on the sea surface pCO_2 climatology developed by Takahashi et al. (2002), the motivation for this study is to produce the optimal global pCO_2 sampling network design to provide a region-by-region estimate of the sampling required to quantify fluxes of CO_2 to the nearest 0.1 Pg C/year (Figure 1), updating and expanding the preliminary effort of Sweeney et al. (2002). The Surface Ocean CO_2 Atlas Project (SOCAT) has decided to standardize all measurements to fCO_2 (IOCCP Report #9) and we have done the same, using the methods described in Dickson and Goyet (1994) from the measured sea surface temperature and pressure.

2. ACCOMPLISHMENTS

1) We have processed the Takahashi pCO_2 dataset with over **4 million** measurements and calculated fCO_2 at the reported sea surface temperature (SST) and sea level pressure (SLP) values from those data. The atmospheric data comes from the GlobalView xCO_2 dataset interpolated to the latitude and time of each individual measurement. These xCO_2 values were then converted at the same SST and SLP into fCO_2 values for the atmosphere. The atmospheric value was subtracted from the oceanic value to determine the $DfCO_2$. The annual mean fluxes were calculated using the observed “long term mean” wind speeds from NCEP, and the observed sea surface temperature and salinity from the World Ocean Atlas (2001, Conkwright et al.) according to the formulas in Wanninkhof (1992). We have reanalyzed our results using the new gas-transfer velocity from Sweeney et al. (2006). This has resulted in a 33% reduction in the calculated fluxes, leading to a substantial increase in the target accuracy necessary to estimate each region to within 0.1 Pg. (Figure 1, Table 1).

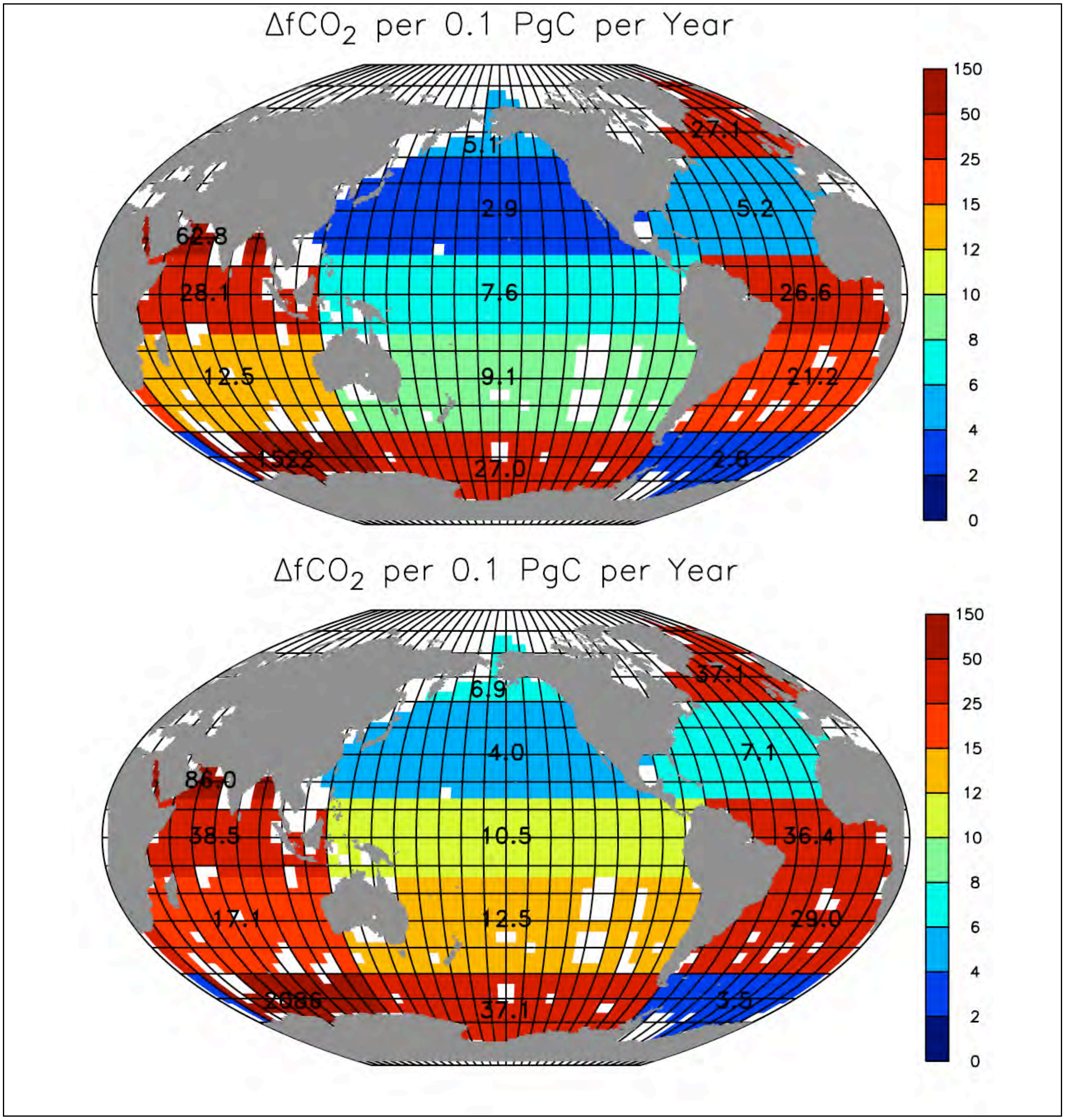

Figure 1. Target DfCO_2 to estimate a regional CO_2 flux within ± 0.1Pg-C/yr for the major oceanic regions. Fluxes in the top panel use the Wanninkhof 1992 wind speed/gas exchange relationship, while those in the lower panel use the Bomb-^{14}C derived relationship from Sweeney et al. (2006) that is 30% lower, resulting in larger tolerances to achieve the desired ±0.1 Pg accuracy.

Table 1. Mean annual sea-air fCO_2 difference, annual flux and the sea-air fCO_2 required for 0.1 Pg C flux. All the values are from the assembled fCO_2 database. The long-term mean wind speed data from NCEP and the wind speed dependence of gas transfer coefficient of Wanninkhof (1992) have been used.

Ocean Regions	Ocean Area (10^6 km^2)	Average $DfCO_2$ (matm)	Annual Flux (PgC/yr)	$DfCO_2$ per 0.1 PgC/yr uptake
Polar North Atlantic	9.3	-31.8	-0.12	27.1
Temperate North Atlantic	28.0	-10.7	-0.21	5.2
Equatorial Atlantic	19.1	17.4	0.07	26.6
Temperate South Atlantic	26.2	-15.2	-0.07	21.2
Polar South Atlantic	12.2	-0.1	< 0.01	2.6
Polar North Pacific	5.3	2.1	0.04	5.1
Temperate North Pacific	46.8	-12.5	-0.43	2.9
Equatorial Pacific	54.8	29.9	0.39	7.6
Temperate South Pacific	48.4	-16.6	-0.18	9.1
Polar South Pacific	22.9	3.4	0.01	27.0
Temperate North Indian	4.6	30.2	0.05	62.8
Equatorial Indian	21.6	17.9	0.06	28.1
Temperate South Indian	28.9	-24.6	-0.20	12.5
Polar South Indian	9.0	3.0	<< 0.01	1522
Global Oceans	337.1	-2.9	-0.6	0.5

Table 2. Mean annual sea-air fCO_2 difference, annual flux and the sea-air fCO_2 required for 0.1 Pg C flux. As in Table 1, but using the wind speed dependence of gas transfer coefficient of Sweeney et al. (2006).

Ocean Regions	Ocean Area (10^6 km^2)	Average $DfCO_2$ (matm)	Annual Flux (PgC/yr)	$DfCO_2$ per 0.1 PgC/yr uptake
Polar North Atlantic	9.3	-31.8	-0.09	37.1
Temperate North Atlantic	28.0	-10.7	-0.15	7.1
Equatorial Atlantic	19.1	17.4	0.05	36.4
Temperate South Atlantic	26.2	-15.2	-0.05	29.0
Polar South Atlantic	12.2	-0.1	-0.03	3.5
Polar North Pacific	5.3	2.1	0.03	6.9
Temperate North Pacific	46.8	-12.5	-0.31	4.0
Equatorial Pacific	54.8	29.9	0.29	10.5
Temperate South Pacific	48.4	-16.6	-0.13	12.5
Polar South Pacific	22.9	3.4	0.01	37.1
Temperate North Indian	4.6	30.2	0.04	86.0
Equatorial Indian	21.6	17.9	0.05	38.5
Temperate South Indian	28.9	-24.6	-0.14	17.1
Polar South Indian	9.0	3.0	<< 0.01	2086
Global Oceans	337.1	-2.9	-0.29	0.6

2) We have quantified the variability in surface pCO_2 (Figure 2) and determined which times in the annual cycle surface pCO_2 and associated air-sea fluxes are most variable and therefore need more sampling and/or sampling at a specific time of year (Figure 3). Comparing both panels, there are regions with highly variable fCO_2 and a low net flux (such as in and around the Ross Sea) as well as regions with fairly low air/sea variability but significant flux (downstream from the Agulhas Retroflection for example)

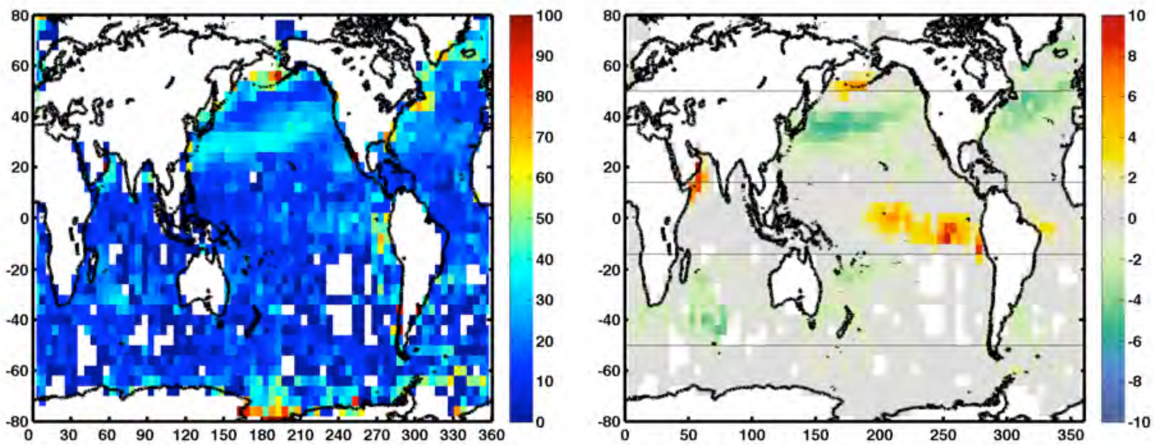

Figure 2. (left) The standard deviation of the monthly mean $DfCO_2$ for each bin indicates the amplitude of the annual cycle there; (right) Annual flux (in Tg, 10^{12} g) from available measurements -- the large expanse of gray indicates large undersampled areas, representing a large fraction of the assumed air/sea carbon flux. The net flux in this panel is 0.43 Pg into the ocean.

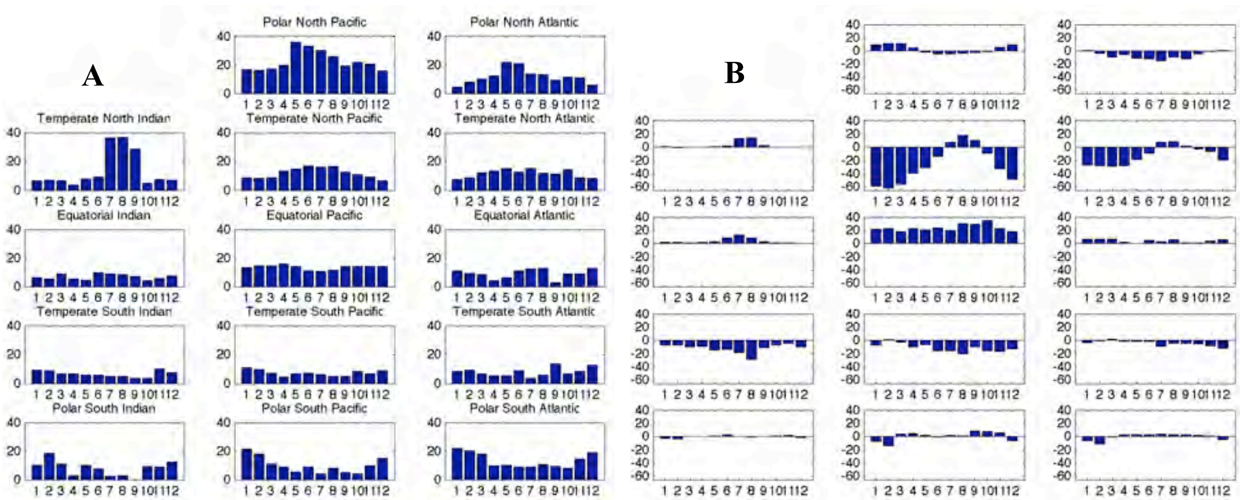

Figure 3. A) The monthly standard deviation of $DfCO_2$ for each region; B) The monthly flux (in Tg) from each region, positive is out of the ocean. Note the more pronounced seasonal cycle in the poleward boxes, and the generally larger variance in the Pacific sector.

3) A spatial *decorrelation length scale* analysis of the database was performed. This analysis uses a simple approach to resampling a series of data that assumes that a *linear interpolation* of the data set represents the true data set. The interpolated data is then resampled by the INDEX at regular intervals. The subsampled data (equal number of samples away from each other) is then linearly interpolated and resampled at the original sampling resolution from which a comparison

is made. This routine is meant to estimate the sample spacing needed to get a standard deviation within 5% of the range in the original data.

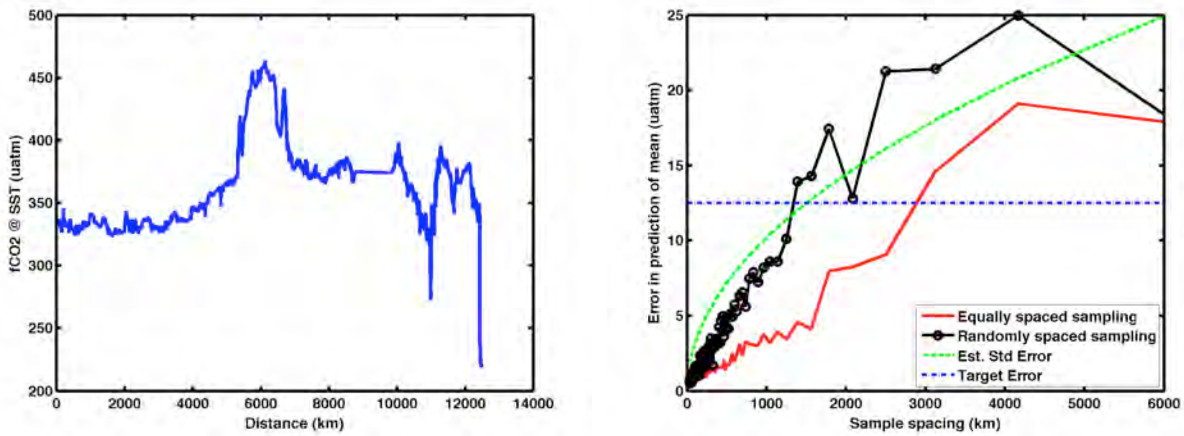

Figure 4. (left) The measured fCO_2 for one of the cruises in the database (0304 from New Zealand to Alaska); (right) the decorrelation length-scale analysis for this cruise. In (b) the standard error in the mean is indicated in green, sampling with equal space-intervals in red, sampling with randomly spaced intervals in black with circles, and the blue line indicates the target ΔfCO_2 needed to estimate the flux of CO_2 to the nearest ±0.1 Pg of C/yr in the temperate South Pacific. The calculated length scale in this example is about 3000km.

As an example, a cruise track (0304) is presented, along with the results that the method provides for estimating the observed variability within the data based on regularly spaced samples. For this cruise, randomly spaced subsamples at ~1200km and regularly spaced subsamples at ~3000km approximate the observed variability in the data to with the 5% necessary, in order to estimate the total air-sea flux for this region to within ±0.1 Pg.

The analysis of the length scales in the assembled dataset on the 4° by 5° grid is presented as Figure 5. One essential caveat to the length and time scale analysis is that wind speeds are highly variable and using wind speeds averaged over months will bias the calculated gas exchange coefficient. The figure below represents a maximum spacing applicable to wind speeds averaged over months rather than those averaged over a shorter time (hourly) period.

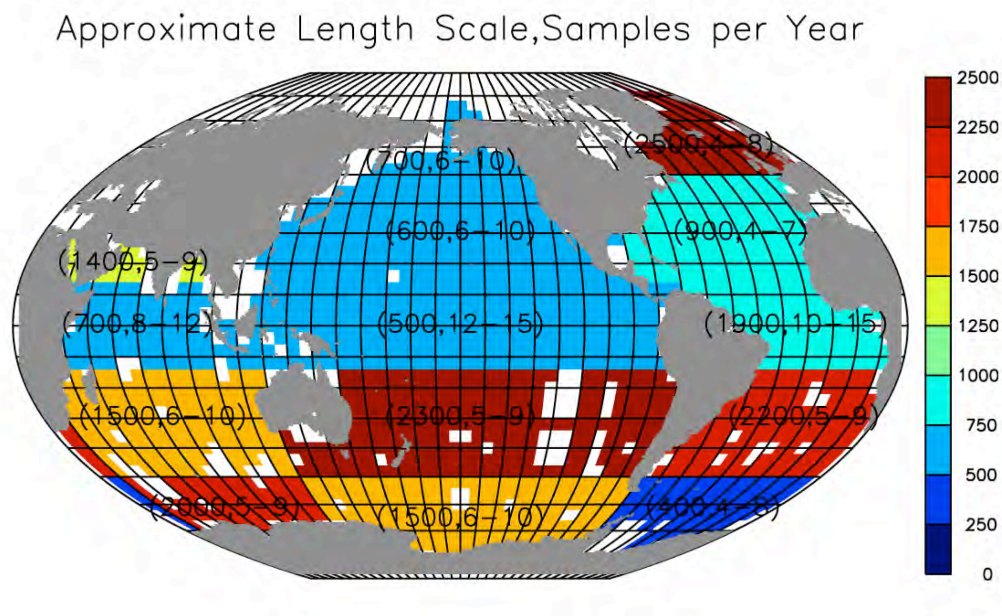

Figure 5. Calculated length-scale and frequency per year for regularly spaced measurements necessary to capture the observed variability in order to estimate the total regional flux of CO_2 to within ±0.1 Pg.

4) The temporal *decorrelation length scale* analysis of the database uses the same routine as for the spatial decorrelation. Each of the bins is treated as an undersampled time series. All measurements in a given bin were sorted according to the Julian day and the routine determines the number of measurements per year necessary to estimate the total regional flux within 5%. In general, the number of samples required in each region is between 4 and 15. Comparing these results to those presented by Sweeney et al. shows good agreement.

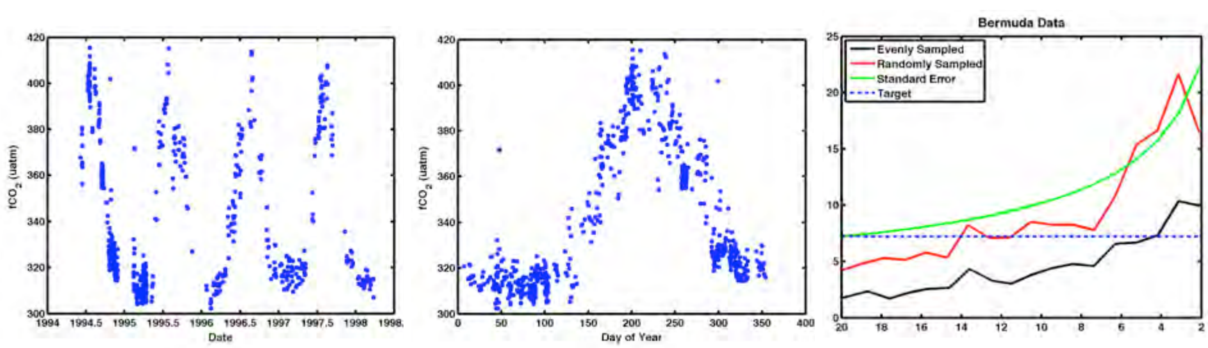

Figure 6. (left) The measured fCO_2 from the Bermuda Biological Research Station; (center) the same measurements as a function of day of year; (right) the decorrelation time-scale analysis for these data. On the right, the standard error in the mean is indicated in green, sampling with equal space-intervals in red, sampling with randomly spaced intervals in black with circles, and the blue line indicates the target ΔfCO_2 needed to estimate the flux of CO_2 to the nearest ±0.1 Pg of C/yr in the temperate North Atlantic. The calculated number of observations per year is ~4 for regularly spaced measurements and 12-15 for irregularly spaced measurements.

Observation-Based Quantification of Seasonal to Interannual Changes in Air-Sea CO_2 Fluxes

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1. INTRODUCTION

The ocean is the primary long-term sink for anthropogenic CO_2 taking up, on average, 1.5-2 Pg C yr^{-1}, or about 20-30% of the current annual release of anthropogenic CO_2. However, the oceanic uptake of CO_2 is highly variable in time and space. To be able to provide meaningful predictions of future atmospheric CO_2 levels, including the possible feedbacks on oceanic partial pressure of CO_2 (pCO_{2sw}), in response to climate and global change a high priority is placed on determining pCO_{2sw} fields and the derived air-sea CO_2 fluxes as part of the interagency US Ocean Carbon and Biogeochemistry Program (OCB). This effort provides and interprets CO_2 flux maps using a combination of *in situ* observations of pCO_2 from Volunteer Observing Ships (VOS), pCO_2 climatological data, and remotely sensed and assimilated sea surface temperature (SST) and wind products (NCEP II). High resolution *in situ* mixed layer depths are being tried as a predictor of pCO_{2sw}. The work is based on the basic premise is that the spatial distributions of pCO_{2sw} at seasonal resolution can be established through simple regional correlations of pCO_{2sw} with SST and other parameters that directly or indirectly control the pCO_{2sw} dynamics in surface water. This is a powerful approach to address the problem of interannual variability of pCO_{2sw} that is inherently data limited. The focus is on developing and validating methods to determine seasonal to interannual variability in the air-sea CO_2 flux over the past two decades.

2. PROJECT GOALS

We are applying innovative methods to estimate seasonal to interannual air-sea CO_2 fluxes utilizing the updated air sea CO_2 climatology of Takahashi et al. (2009), the large observational database of surface pCO_2 measurements from ships of opportunities and moorings from the SOCAT database (see, http://ioc3.unesco.org/ioccp/Synthesis.html), and winds to produce high-resolution estimates of the fluxes. The focus is on quantifying flux anomalies on seasonal to interannual timescale through determining regional algorithms of partial pressure of CO_2 in seawater, pCO_{2sw}, with remotely sensed and assimilated parameters. The effort involves a basic research component of understanding the causes of the variability and its relationship to climate indices such as ENSO, and product delivery of seasonal fluxes. The product that is developed is an automated routine to estimate seasonal air-sea CO_2 fluxes within 6 to 12-months of present utilizing remotely sensed SST from NCEP, the "Reynolds" optimal interpolated SST (Reynolds et al. 2007), and NCEP II re-analysis winds. In addition, there is ongoing research on improving the estimates and to improve the mechanistic understanding of the controls on pCO_{2sw}. These research efforts are done in a systematic fashion that include using updated pCO_{2sw} values, investigating the fidelity of the pCO_2/SST relationships by region, utilizing improved remotely sensed, assimilation and in situ products, and investigating the utility of other products such as salinity and mixed layer depth obtained from the FOAM assimilation model. The scope of the research has expanded from what was proposed in that this effort is providing partial support to serving a regional ocean acidification product (Gledhill et al., 2008). Furthermore, there is stronger collaboration with modeling groups and international efforts than originally proposed.

The specific components of the effort as outlined in the proposal and current status, italicized, are as follows:

1. We have produced an automated routine to estimate seasonal air-sea CO_2 fluxes within 6 to 12-months of present utilizing remotely sensed SST, wind and other relevant products obtained from NESDIS and NASA. The seasonal estimates are posted on the web for comparison, validation, and initializing of models. *This is now a routine deliverable that is updated annually. Since the effort involves level-3 (fully quality controlled) satellite and assimilation data that is not available sooner than 6-months, the lag from present is 6-months to a year.*
2. The regional relationships of pCO_{2sw} and SST based on the Takahashi pCO_{2sw} climatology have been improved. The methodology has been validated by comparison with ongoing timeseries from moorings and Volunteer Observing Ships. *We are now using the Takahashi et al. (2009) climatology and are performing a thorough comparison of results with current data.*
3. The regional relationships of pCO_{2sw} and SST have been re-assessed using the pCO_{2sw} data obtained from the NOAA/OCO pCO_2 projects and affiliated efforts. *This has been done in part by applying the procedure to model output.*
4. Improved algorithms are developed utilizing other remotely sensed and high-density data in regions where the $\partial pCO_2/\partial SST$ have poor predictive capabilities. *This is an ongoing effort and the focus of year-3. Our current analysis suggests that the method works extremely well in the subtropical gyres but has less fidelity at high latitudes and upwelling regions. We are investigating multi-annual relationships for these areas.*

Details of the work done in the first two years of this effort are listed in the results and accomplishment section below.

2.1. Method

Determination of monthly fluxes

For the quasi-operational product we are using the pCO_{2sw} climatology described in Takahashi et al. (2009) and empirical relationships between pCO_2 and SST that is described in detail in Park et al. (2006). In short, the flux of CO_2, F_{CO2} for every pixel and every month is calculated using the basic flux equation:

$$F_{CO2} = k\, K_0\, (pCO_{2sw} - pCO_{2air})$$

Where k is the monthly mean gas transfer velocity, K_0 is the solubility of CO_2, pCO_{2sw} is the estimated pCO_2 in surface seawater using the $\partial pCO_2/\partial SST$ algorithms The monthly pCO_{2sw} for each latitude 4^o × longitude 5^o pixel for an individual year other than 2000 is estimated from the global ΔpCO_2 climatology from Takahashi et al. *(2009)*, together with global records of SST anomalies compared with the climatology normalized to the year 2000 in the following manner:

$pCO_{2sw\,ym} = [pCO_{2sw\,2000m} + (\partial pCO_{2sw}/\partial SST)_{2000m} \times \Delta SST_{ym-2000m}]$

Where subscript "ym" is the year and month, and subscript "*2000m"* refers to the month in 2000.

The flux in turn is determined from:

$F_{ym} = k_{ym}\, K_{0,ym}\, \{pCO_{2sw\,ym} - pCO_{2AIR\,2000m}\}$

The solubility $K_{0,ym}$ is determined from monthly SST and climatological salinity using the solubility equations of Weiss (1974). We estimate k from the 2nd moment of the wind and the coefficients proposed in Sweeney et al. *(2007)*:

$k = 0.26 * 2^{nd}$ moment $(Sc/660)^{-0.5}$

The 2^{nd} moment is defined as $\sum U_{10}^2/\, n$, where U_{10} is the wind speed at 10 m height obtained from the NCEP II reanalysis product. This procedure accounts for the variability in the wind. The 0.26 coefficient is different from that first proposed by Wanninkhof (1992) based on an improved assessment of the global ^{14}C inventory used to constrain the global gas transfer velocity and a different wind product than used in the original work (see, Sweeney et al., *2007).*

2.2. Results and Accomplishments

The results and accomplishments are presented in terms of the objectives outlined in the proposal.

A. Produce an automated routine to quantify seasonal air-sea CO_2 fluxes from remotely sensed SST and wind: Following the procedures above and detailed in Park et al. (2006) a seasonal flux product is served from the AOML CO2 website (http://www.aoml.noaa.gov/ocd/gcc/movieloop.html). Based on user feedback, we will provide anomaly maps, numerical tables and short descriptions of observed phenomena for the full 26-years we now have produced in year 3. An example of anomaly maps and descriptions can be found in Sabine et al. (2009) and is reproduced in Figure 1.

B. The regional relationships of pCO_{2sw} and SST based on the Takahashi pCO_{2sw} climatology will be improved: We updated our procedure to incorporate the updated climatology presented in Takahashi et al. (2009). Furthermore we used a new wind speed product (NCEP II) and an updated gas exchange wind speed relationship (Wanninkhof et al.*, 2009)*. The unique algorithms between pCO_{2sw} and SST for El Niño and Non-El Niño periods for different time periods in the Eastern Equatorial Pacific (10˚S-6˚N, 165˚E-280˚E) are updated (Feely et al., 2006). Figure 2 shows the annual climatology as presented by Takahashi et al. (2009) along with the regional magnitude of interannual variability over the ocean. The average air-sea CO_2 flux over the past 25-years with this method is -1.44 ± 0.12 Pg C yr^{-1}. The results show a strong correlation with the ENSO cycle, which confirms a central hypothesis of our proposal that large-scale climate reorganizations have a key effect on interannual variability of air-sea CO_2 fluxes. Figure 3 shows the pixels where the

$\partial pCO_2/\partial SST$ relationships have changed from the previous climatology. Although the interannual variability globally has not changed appreciably between the two analyses, the regions of variability are appreciably different.

C. Reassessment of regional relationships of pCO_{2sw} and SST based on the Takahashi pCO_{2sw} climatology. The central assumption of our approach that seasonal relationships between pCO_{2sw} and SST are applicable to infer interannual variability in pCO_{2sw} from interannual temperature anomalies is difficult to validate. Based on sparse time series reasonable agreement was found at the HOT and BATS time series and in the Equatorial Pacific (Park et al. 2006). In collaboration with Drs. S. Doney and I. Lima of WHOI we tested our approach using the output of the NCAR biogeochemistry model (Doney et al. 2009). The interannual variability of the model air-sea CO_2 fluxes can, in this manner, be directly compared with our empirical method. As shown in Figure 4 there is very good agreement both in magnitude and phasing of interannual variability in this comparison. The NCAR model shows an average net flux of -1.55 ± 0.17 Pg C yr^{-1} while applying our approach using the model output pCO_{2sw} yields -1.49 ± 0.13 Pg C yr^{-1}. The largest differences are observed in the Southern Ocean where our approach appears to underestimate variability.

D. Improve algorithms utilizing other remotely sensed and high-density data in regions where the $\partial pCO_2/\partial SST$ have poor predictive capabilities. This will be a major focus of year-3 along with providing robust error estimates. From our analyses to date it is clear that high latitude regions will require an adapted approach. Figure 5 shows the correlation coefficients (r^2) of the relationships with correlations coefficients. In regions where $r^2 < 0.5$ it is assumed that there is no interannual change in pCO_{2sw}. The trends in pCO_{2sw} are not well correlated with temperature in the boreal winter season and high latitudes. These are the areas of focus. Following Lueger et al. (2008) we are investigating if mixed layer depth provides an improved predictive capability in these regions.

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4. WEB LINKS

http://www.aoml.noaa.gov/ocd/gcc
http://www.pmel.noaa.gov/CO2/uwpCO2/eq_pacific.html

5. FIGURES AND CAPTIONS

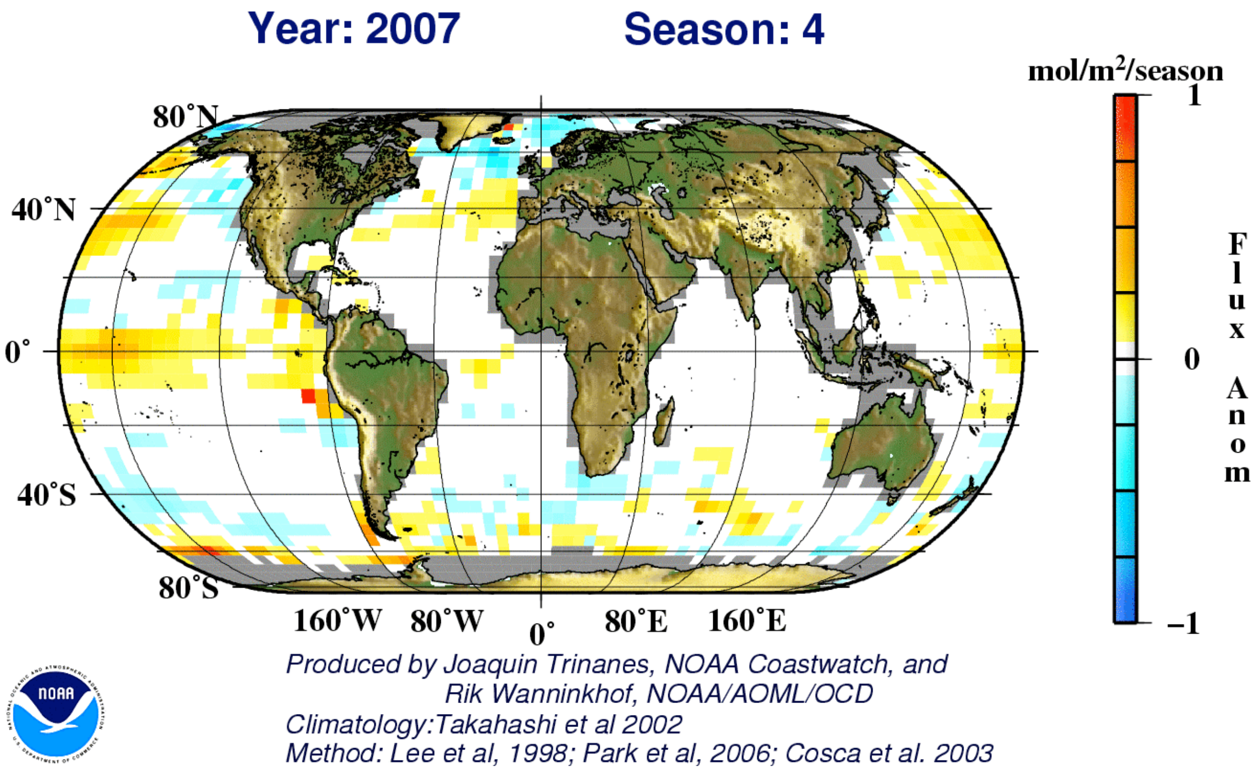

Figure 1. Map of the air-sea CO_2 flux anomaly for season 4 of 2007 (September-December) compared to the corresponding 25-year seasonal average (1982-2007). The figure clearly shows the large outgassing anomaly in the central and western Equatorial Pacific in response to the 2007/2008 La Nina event. Coastal pixels and those with ice cover are masked in gray.

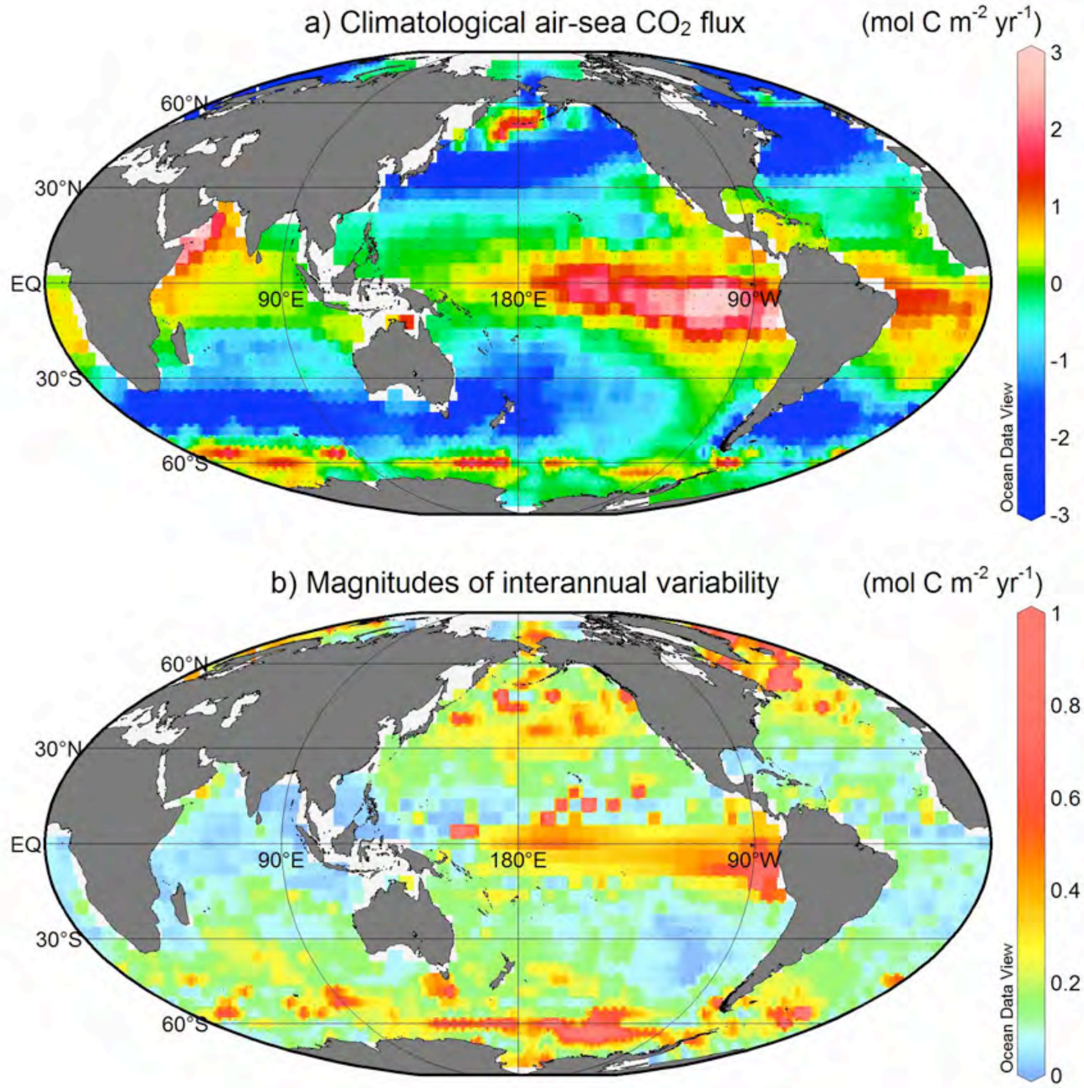

Figure 2. (a) Climatological air-sea CO_2 flux map from Takahashi et al. 2009 and magnitudes of interannual variability determined by our method. (plots provided by Dr. Geun-Ha Park, AOML/CIMAS)

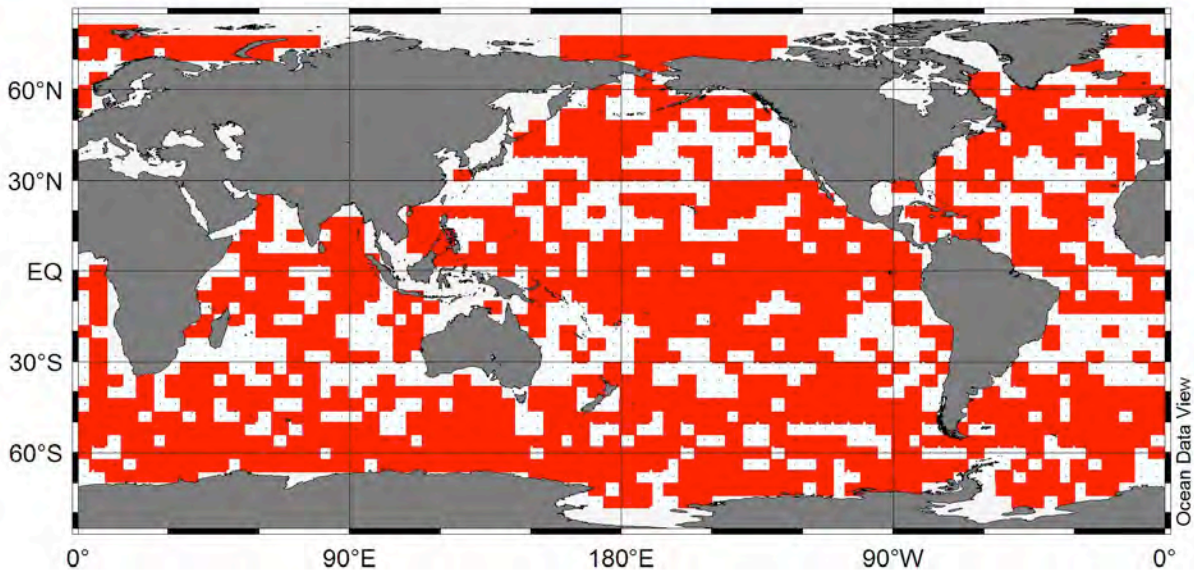

Figure 3. Map showing for which pixels the $\partial pCO_2/\partial SST$ relationships have changed between the Takahashi 1995 climatology and the Takahashi 2000 climatology which is now being used for our effort. The pixels colored red are those where the slope of the relationship changed signs in at least one of the seasons. (plots provided by Dr. Geun-Ha Park. AOML/CIMAS)

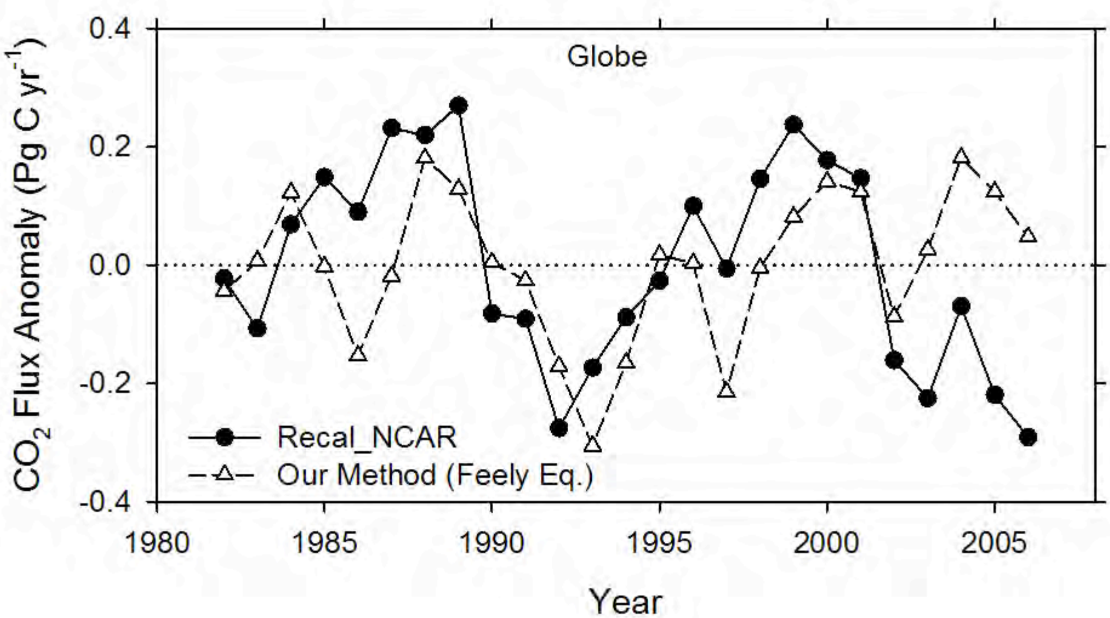

Figure 4. Comparison between the interannual variability of the NCAR model output (solid line with solid circles labelled "Recal_NCAR"), with our approach applied to the NCAR pCO_{2sw} output for year 2000 (dashed line with open triangles labelled "Our method (Feely Eq.)"). (plots provided by Dr. Geun Ha Park, AOML/CIMAS)

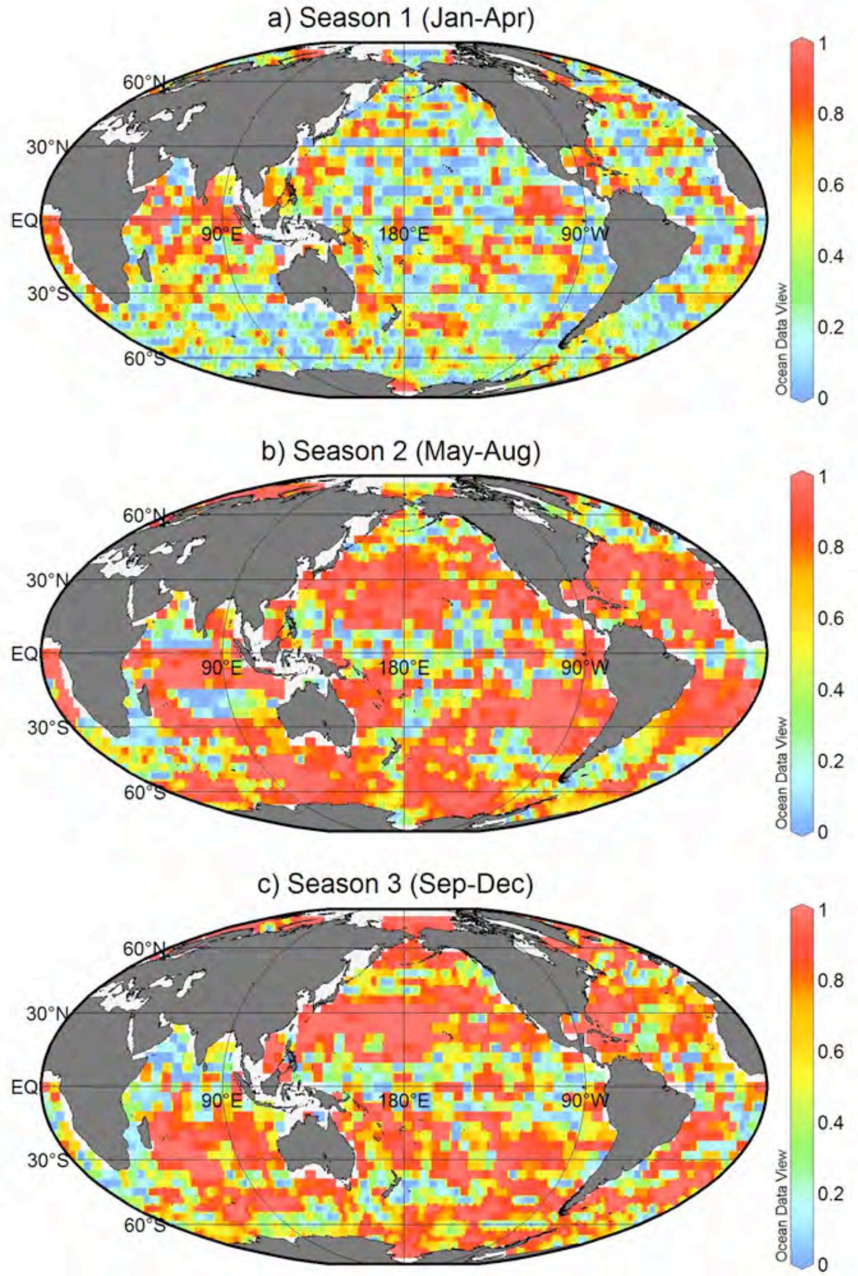

Figure 5. Seasonal maps providing the correlation coefficients of the $\partial pCO_2/\partial SST$ relationships derived from the Takahashi 2000 climatology (Takahashi et al. 2009). For pixels where $r^2 < 0.5$ it is assumed that there is no interannual variability in pCO_{2sw}. (plots provided by Dr. Geun-Ha Park, AOML/CIMAS)

Using Models to Improve our Ability to Monitor Ocean Uptake of Anthropogenic Carbon

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1. PROJECT SUMMARY

How is the ocean carbon cycle responding to human activity? Recently a number of studies have argued that the rate of carbon uptake by the ocean has been slowing over the last decade. This could occur if climate-induced changes in the ocean/atmosphere system are leading to changes in the exchange of carbon between the atmospheric and oceanic reservoirs. However, the detection of changes in carbon uptake by the ocean are complicated by the fact that the ocean exhibits variability in its circulation on nearly all time scales over which we measure. Or this reason the detection of the rate of carbon uptake becomes a signal-to-noise problem.

The main goal of this project is to use models and remotely sensed altimetry data to reduce uncertainty in estimate the rate of uptake of anthropogenic carbon by the ocean from Repeat Hydrography measurements. Models and satellite data will be important to developing our mechanistic understanding of the natural background variability of carbon, and for developing better methods to separate the natural carbon signal from the anthropogenic signal.

Over the last four months, we have completed (and submitted; Rodgers et al., 2008) a research project focused on a model/data synthesis of carbon variability in the ocean. In the study, we used observations and ocean models to identify mechanisms driving large seasonal to interannual variations in dissolved inorganic carbon (DIC) and dissolved oxygen (O_2) in the upper ocean. We began with observations linking variations in upper ocean DIC and O_2 inventories with changes in the physical state of the ocean. Models were subsequently used to address the extent to which the relationships from short-timescale (6 months to 2 years) repeat measurements are representative of variations over larger spatial and temporal scales.

The main new result of the study was that convergence and divergence (column stretching) attributed to baroclinic Rossby waves can make a first-order contribution to DIC and O_2 variability in the upper ocean. This results in a close correspondence between natural variations in DIC and O_2 column inventory variations and sea surface height (SSH) variations over much of the ocean. Oceanic Rossby wave activity is an intrinsic part of the natural variability of the climate system and is elevated even in the absence of significant interannual variability in climate mode indices.

2. PUBLICATIONS/PRESENTATIONS

Rodgers, K.B., R.M. Key, A. Gnanadesikan, J.L. Sarmiento, O. Aumont, L. Bopp, S.C. Doney, J.P. Dunne, D.M. Glover, A. Ishida, M. Ishii, A. Jacobson, C. Lo Monaco, E. Maier-Reimer, N. Metzl, F.F. Pérez, A. Rios, R. Wanninkhof, P. Wetzel, C.D. Winn, and Y. Yamanaka, 2008:

Altimetry helps to explain patchy changes in hydrographic carbon measurements. *J. Geophys. Res.*, submitted.

A Web Site for NCEP's Global Ocean Data Assimilation System (GODAS): Date Link, Data Validation and Global Ocean Monitoring Products

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1. PROJECT SUMMARY

The mission of the project is to maintain and improve a comprehensive web site for the operational Global Ocean Data Assimilation System (GODAS) developed by the National Centers for Environmental Prediction (NCEP). The web site, hosted by the Climate Prediction Center (CPC) of NCEP, provides the user community an easy access to the GODAS data, the GODAS validation skill, and the global ocean monitoring products based on GODAS. The web site contains numerous plots of climatology and anomalous fields of various oceanic variables in different basins of the global ocean and cover time scales from weekly to interannual to decadal from 1979 to present.

A recent significant advance of the project was the implementation of "Monthly Ocean Briefing" at CPC in May 2007. The ocean briefing is composed of a conference call and PPT presentation and participated by both internal and external colleagues. The PPT provides a comprehensive review and interpretation of the recent evolutions and current conditions of the state of the global ocean, its interactions with atmosphere, and model SST predictions. The PPT is freely accessible on the web site and is downloaded by a broad national and international community.

The GODAS was developed by the Environmental Modeling Center (EMC) of NCEP for the initialization of the oceanic component of the NCEP's Climate Forecast System (CFS). The retrospective ocean analysis since 1979 and the near real time updates have been made available for dissemination to the general public through the GODAS web site supported by this project. CPC acts as the "Point of Contact" for the GODAS user community, and strives to provide national and international communities timely and comprehensive information on oceanic variability in support of climate research, attribution and prediction.

1.1. Background

The in situ ocean observation network managed by the NOAA's Climate Observation Division (COD) has greatly enhanced our knowledge of the state of the global ocean and is critical for the ocean reanalysis efforts in the past decade. The operational Global Ocean Data Assimilation System (GODAS) developed by the National Centers for Environmental Prediction (NCEP) assimilates in situ observations into an oceanic general circulation model forced by atmospheric fluxes. Currently, assimilated observations include temperature profiles from XBT**,** profiling floats and TAO moorings. The GODAS is used to initialize the oceanic component of the NCEP's Climate Forecast System (CFS) (Saha et al. 2007) and was implemented in 2003 (Behringer and Xue 2004). The retrospective global ocean reanalysis for 1979-2004, and its real time updates, constitute a unique dataset that can be used to diagnose the past oceanic variability and to monitor the recent trend and current oceanic conditions in support of climate research, attribution and prediction.

To gain a broader dissemination of GODAS data products, and to increase research community's involvement in the assessment of GODAS towards increasing the effectiveness of the NOAA's ocean observing systems, the NOAA's COD currently supports the CPC to maintain and improve a comprehensive web site for GODAS. The web site contains data link, data validation, and global ocean monitoring products.

1.2.Website

http://www.cpc.ncep.noaa.gov/products/GODAS/

1.3. Partnership

The project is coordinated with the production and improvement of GODAS by the Environmental Modeling Center (EMC) of NCEP. CPC also envisions to work with the expert team members supported by the Climate Observation Division (COD) to validate, and to enhance, the GODAS products with in situ observations. The project also contributes to the "Bulletin of the American Meteorological Society" (BAMS) Annual Climate Review Report by providing authors month-to-month oceanic variability within the calendar year through "Monthly Ocean Briefing". The PI will contribute to the section of the BAMS report on sea surface temperature with Dr. Richard Reynolds.

2. ACCOMPLISHMENTS:

2.1. GODAS web site statistics

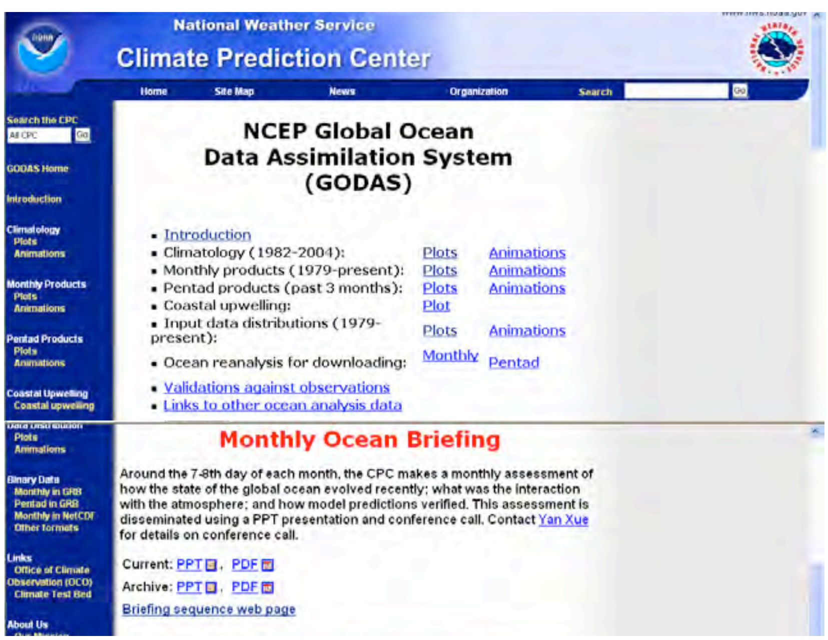

Figure 1. The home page of the GODAS web site.

The home page of the GODAS web site, shown in Figure 1, has been revised to include a section on “Monthly Ocean Briefing” (MOB). Details about MOB are described in the next section. The ocean briefing PPT presentations are displayed on the home page as “Current” and “Archive”. The “Current” is for the latest PPT presentation, while the “Archive” is for those PPT presentations made since May 2007. One significant addition to the GODAS web site is the “Briefing Sequence Web Page” (BSWB), which contains all the plots used in MOB and other additional plots. All the plots on BSWB are updated in near real time. Having those plots available on the web is particularly useful for users who want to monitor the evolution of the state of the global ocean closely in time.

The GODAS web site statistics have been monitored since January 2008 (Figure 2) and the web site receives about 50,000.00 hits per month by September 2008.

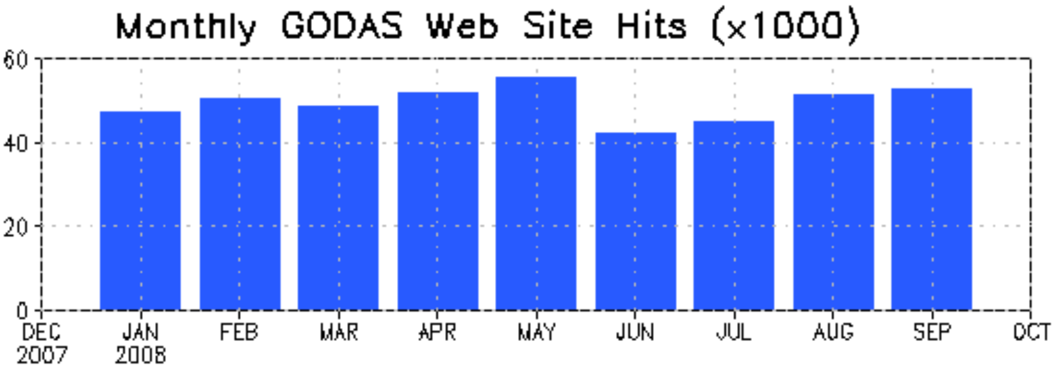

Figure 2. The accumulative hits within a month on the GODAS web site for 2008-present.

2.2. Monthly Ocean Briefing

The GODAS web site contains various plots and animations that are updated in near real time, and are used by forecasters and researchers to monitor the recent evolutions and the current conditions of the state of the global ocean. However, users can be better served by providing a synthesis of plethora of such products and by summarizing (a) how the state of the ocean evolved recently, (b) what is its interactions with the atmosphere, and (c) how it will likely evolve in near future. Since CPC has access to the operational oceanic and atmospheric reanalysis data and the seasonal climate outlooks made by the NCEP’s CFS, CPC is well positioned to provide the user community with a timely and accurate assessment and interpretation of the evolution of the state of the global ocean, its interaction with the atmosphere, and its prediction by CFS. To accomplish this, an operational product referred to as “Monthly Ocean Briefing” (MOB) was implemented in May 2007 at CPC. The MOB is composed of a conference call and a PPT presentation, and is held around the 7th day of each month. The schedule of MOB is sent by email to a growing distribution list that contains both internal and external colleagues. The distribution list and conference call are open to anyone who is interested in the ocean briefing. During the past year so, the ocean briefing has been well received by internal and external participants, and feedback received so far indicates that the ocean briefing is very informative and useful, and further, is becoming a valuable tool for both research and operational community.

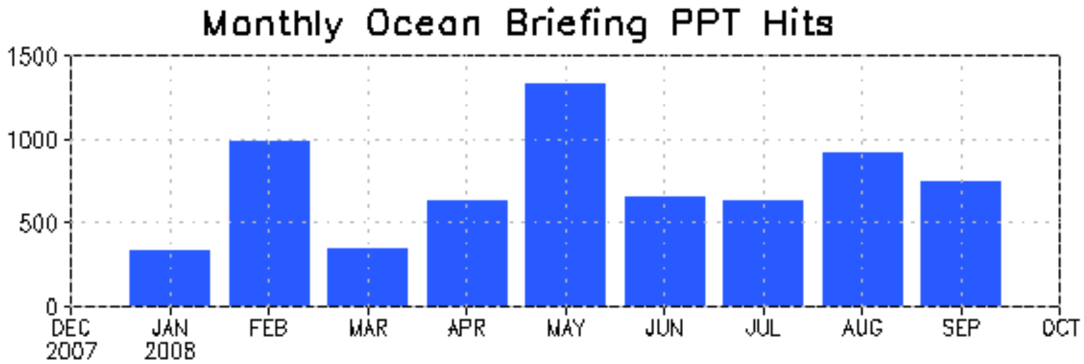

Figure 3. The accumulative hits within a month on the current "Monthly Ocean Briefing" PPT for 2008-present.

Through interactions with the user community, the content of the PPT presentation has improved with time. A major improvement made in FY08 included an expansion and improvement of the plots used in MOB, making the plots available in near real time on the web, standardizing the ocean briefing PPT to include a fixed set of plots, while keeping the provision to address unique climate events of interest, e.g. the 07/08 La Niña cycle.

Contributions from external community have been highly encouraged. Dr. Mike McPhaden from the NOAA's Pacific Marine Environmental Laboratory (PMEL) has been participating MOB regularly, and helped us monitor the biases of the GODAS subsurface temperature by providing us their real time TAO subsurface temperature analysis, and also assisted us in interpreting the tropical Pacific oceanic variability related to ENSO. Dr. Frank Schwing from the NOAA's the Southwest Fisheries Science Center (SWFSC) has been participating MOB regularly, and helped us monitor the coastal upwelling along the western coast of North America, and assisted us in evaluating the effects of physical forcing on boundary ecosystems such as the California Current Ecosystem (CCE). Dr. David Enfield from the NOAA's Atlantic Oceanographic and Meteorological Laboratory (AMOL) has been actively involved in MOB, and has helped us design plots to monitor and assess the SST variability in the Atlantic Hurricane Main Development Region and to study ocean's impacts on hurricane. Regular participants also include folks from the International Research Institute for Climate and Society, NOAA's Earth System Research Laboratory, NASA's Global Modeling and Assimilation Office, Center for Ocean-Land-Atmosphere Studies, NCAR and NOAA headquarters.

Although MOB has been regularly attended by 15-30 folks from internal and external institutions, the PPT presentation displayed on the web site is usually reviewed by 500-1000 folks by the national and international community. The monthly hits on the current month PPT has an upward trend (Figure 3). The hits had peaks in February and May 2008 that coincided with our "Annual Ocean Review" in early spring and a significant expansion of MOB in late spring. The hits on the ocean briefing PPT has settled down at the level of about 700-1000 hits per month by fall 2008 (Figure 3).

2.3. Real time heat budget analysis for ENSO

We have implemented a near real time heat budget analysis based on GODAS. The methodology of Stevenson and Niller (1983) is used in which surface advection and vertical entrainment terms are explicitly calculated with the GODAS velocity and GODAS mixed layer depth. The heat budget analysis has been used to analyze the evolution of the 07/08 La Niña cycle, and the results have been presented at the 33rd Climate Diagnostics and Prediction Workshop held in Lincoln, Nebraska. The heat budget analysis not only helps us understand the physical mechanism for the past ENSO events, and but also assists us to monitor, understand and predict ENSO in real time.

2.4. Estimation of Atlantic MOC with GODAS

The Atlantic Meridional Overturning Circulation (MOC) has been selected as one of the metrics for the CLIVAR Ocean Synthesis Evaluation Project. Here we present the capability of GODAS in simulating MOC and its sensitivity to data assimilation schemes. We estimated MOC using (a) the operational GODAS that assimilates temperature down to 750m, (b) the deep ocean GODAS, identical to the operational GODAS except it assimilates temperature down to 2200m, and (c) the Argo GODAS which assimilates the Argo salinity in addition to in situ temperature above 750m.

The averaged (1982-2004) MOC in the operational GODAS is 17 Sv at 26N, consistent with other observed analyses and model simulations. The averaged (1982-2004) MOC in the deep GODAS is 26 Sv. The larger MOC is associated with a northward density gradient between 1000-2000m depth. The averaged (2001-2006) MOC in the Argo GODAS is about the same as that of the operational GODAS. The AMOC in the deep GODAS has two upward trends, one during the first 5 year starting from the operational GODAS in January 1979 and another during 2000-2005 when the Argo temperature started to be assimilated. Therefore, it is important to constrain the model with observed temperature and salinity in the deeper ocean for a period of more than 5 years to allow the model to adjust to an equilibrium state.

2.5. Validation of heat content variability in GODAS

Since heat content variability in the top 300m in the tropical Pacific is closely linked to ENSO variability, its simulation by GODAS has been carefully validated using the TAO temperature and Altimetry sea level data. However, heat content variability beyond the tropical Pacific has not been systematically validated. Here we present a comparison of heat content variability simulated by GODAS, two other ocean analyses, and Altimetry sea level. The annual mean heat content analysis from the NOAA's National Oceanographic Data Center (NODC) in 1979-2003 (http://www.nodc.noaa.gov), the monthly mean heat content analysis from Coriolis in 2002-2008 (http://www.coriolis.eu.org), the Altimetry sea surface height analysis from AVISO in 1993-2008 (http://www.aviso.oceanobs.com) were used in our comparison. In addition, the monthly mean climatology from the World Ocean Atlas (WOA) 2005 was used.

The inter-annual and monthly variability between GODAS and the other analyses only match in regions with a large number of observations. Although the number of observations has increased from 1979 to 2003, the spatial correlation between NODC heat content and GODAS doesn't increase much over the years. There is a clear relationship between the number of observations and the agreement in heat content between GODAS and the NODC/Coriolis analyses. GODAS does not show the warming of the global oceans over the past 30 years, which is evident in NODC and supported by the satellite Altimetry since 1993.

2.6. BAMS Annual Climate Review Report

The PI has been invited by Dr. Richard Reynolds to contribute to the section of the 2007 BAMS Annual Climate Review Report on sea surface temperature.

3. REFERENCES

Levinson, D. H. and others, 2008: State of the climate in 2007, 3.1 Sea Surface Temperatures in 2007. *Bull. Amer. Meteor. Soc.*, **89,** p37-39.

Enhanced Ocean Climate Products from NCEP

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1. PROJECT SUMMARY

The operational GODAS exists in three versions. There is a standard version that lags the current date by 14 days and a second version that is initialized by the standard GODAS and is brought forward to lag the current date by one day. This 1-day lag version of GODAS was in parallel testing at this time last year and has since then been successfully transferred to operations. A third, deep version of GODAS, also in parallel testing last year, has also become operational. The operational versions of GODAS are based on MOMv3. A version of GODAS, based on MOMv4, was a new development last year. It has been successfully incorporated with the CFS and is a part of the Coupled Forecast System Reanalysis and Reforecast (CFSRR) which is currently underway at NCEP.

2. ACCOMPLISHMENTS

2.1. The Operational GODAS

The standard operational GODAS assimilates observations in a window extending from 2 weeks prior to 2 weeks after the analysis date, weighting observations closer to the analysis date more heavily. The purpose of this strategy is to increase the number of observations going into the analysis, but it means that the standard GODAS analysis lags the calendar date by 14 days. To satisfy a need for a more current analysis, both for monitoring changes in the ocean state and for initializing forecasts with the CFS, there is a second operational GODAS analysis lag that is initialized by the standard analysis and then runs forward using an asymmetrical observation window. This asymmetrical analysis has been upgraded in operations to have a 1-day lag with respect to the calendar date, replacing the former 7-day lag version.

The standard GODAS assimilates observations only in the upper 750 meters which does not take full advantage of the deeper Argo profiles. So in FY08 we successfully made operational a deep version of GODAS that assimilates observations down to 2200 meters. Any change to the standard GODAS must not alter the calibration of the CFS forecasts. However, the deep GODAS is free of that constraint and the goal is to upgrade that version on a more frequent basis.

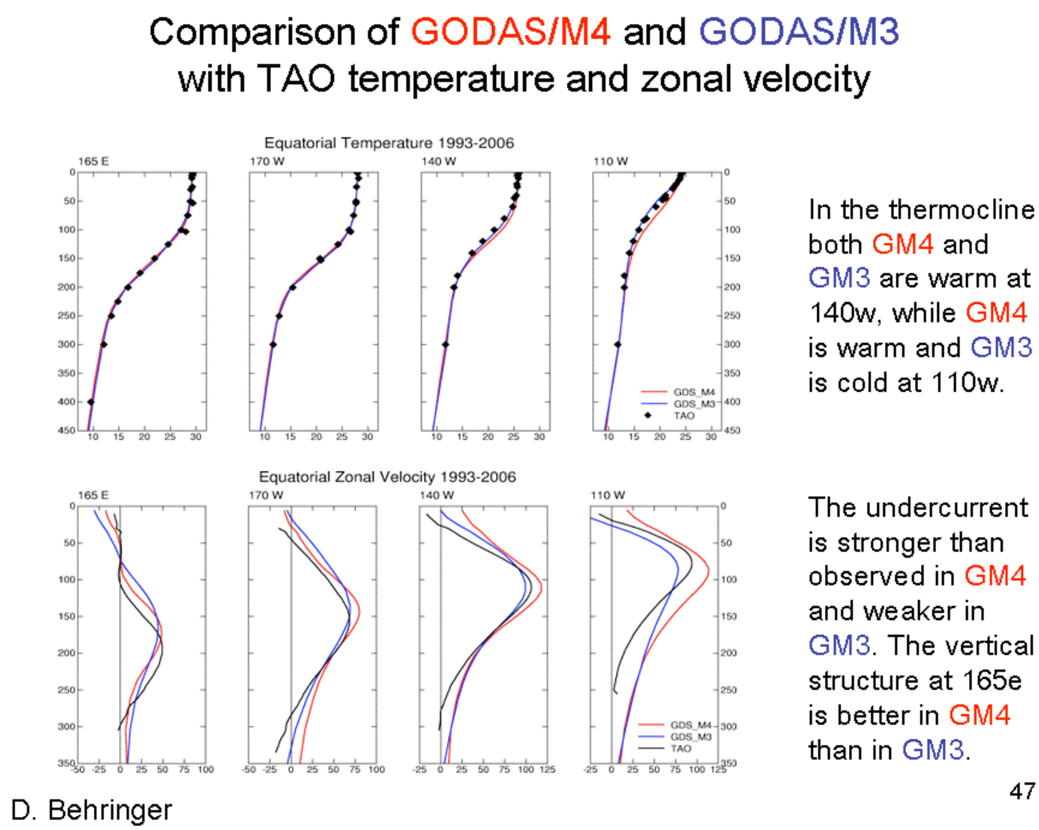
2.2. The MOMv4 version of GODAS

During FY08 the new version of GODAS based on GFDL's MOMv4 was integrated with the CFS and is now part of the Coupled Forecast System Reanalysis and Reforecast (CFSRR) which is currently underway at NCEP. This version of GODAS uses the tripolar grid of MOMv4 and is a fully global system that includes an Arctic Ocean and an ice model.

Also during FY08 the MOMv4 GODAS was further modified to allow the choice of either assimilating surface data (e.g. the Reynolds SST OI) or relaxing to it. It is also possible with the new GODAS to assimilate the different types of observations simultaneously (as is done in current operations), to assimilate them sequentially or to choose some configuration in between. This increased flexibility will make it easier to balance the constraints imposed by different data sets and to fine tune the system.

3. FY08 PUBLICATION

Huang, B., Y. Xue, and D. W. Behringer, 2008. Impacts of Argo salinity in NCEP Global Ocean Data Assimilation System: The tropical Indian Ocean. *J. Geophys. Res.*, 113, C08002.



Ocean Data Assimilation Research at GFDL

Tony Rosati and Brian Gross
NOAA Geophysical Fluid Dynamics Laboratory, Princeton NJ

1. PROJECT SUMMARY

Estimating the state of the Earth System is critical for monitoring our planet's climate and for predicting changes to it on time scales from months to decades. Toward these ends, the vast number of atmospheric observations and the growing number of ocean observations must be combined with model estimates of the state of the Earth System by means of data assimilation systems. This project explores the development of new data assimilation techniques using state-of-the-art ***coupled*** climate models and applies these techniques to detecting climate change, improving forecasts on seasonal to interannual time scales while providing estimates of their uncertainty, and improving our understanding of predictability at decadal time scales in order to provide a foundation for the development of a NOAA capability for decadal forecasts. This capability will provide the Nation's decision and policy makers with the best possible climate information on critical problems such abrupt climate change, changes in hurricane activity, drought, and sea-level rise.

2. ACCOMPLISHMENTS

2.1. Objective analysis of monthly temperature and salinity for the world ocean

Global data management systems (data mirroring and quality control systems) have been continuously maintained and updated (Figure 1). As for the application of Argo profiling data, objective analysis for the world ocean and the basin-scale sea level budget studies have been carried out as well as the investigation of reanalysis data from the GFDL coupled data assimilation system.

Figure 1. Data process for the GFDL coupled data assimilation system.

A new world ocean atlas of monthly temperature and salinity, based on individual profiles for 2003-2007 (WOA21c), is constructed and compared with the World Ocean Atlas 2001 (WOA01), the World Ocean Atlas 2005 (WOA05) and the data assimilation analysis from the Coupled Data Assimilation (CDA) system developed by the Geophysical Fluid Dynamics Laboratory (GFDL). First, we established a global data management system for quality control (QC) of oceanic observed data both in real time and delayed mode. Delayed mode QC of Argo floats identified about 8.5% (3%) of the total floats (profiles) up to December 2007 as having a significant salinity offset of more than 0.05. Second, all QCed data were gridded at 1° by 1° horizontal resolution and 23 standard depth levels using six spatial scales (large and small longitudinal, latitudinal, and cross-isobath) and a temporal scale. Analyzed mean temperature in WOA21c is warm with respect to WOA01 and WOA05, while salinity difference is less evident. Consistent differences among WOA01, WOA05, and WOA21c are found both in the fully and sub-sampled dataset, which indicates a large impact of recent observations on the existing climatologies. Root mean square temperature and salinity differences and offsets of the GFDL's CDA results significantly decrease in the order of WOA01, WOA05, and WOA21c in most oceans and depths as well. This result suggests that the WOA21c is of use for the collocated assessment approach especially for high-performance assimilation models on the global scale.

2.2. Basin patterns of global sea level changes

Based on independent observations, we estimate the sea level budget and linear trends for individual ocean basins and the world ocean during 2004-2007. Even though it is confirmed that the seasonal variation of global sea level is balanced by the different sea level components, basin scale sea level budgets show very different characteristics. Sea level budgets over the South Pacific and Antarctic Ocean maintain a good balance both on seasonal to interannual time scales. Meanwhile, only the satellite altimeter data exhibits a large 4-year trend over the South Indian Ocean (Figure 2). This basin significantly impacts the magnitude of the disagreement for the global sea level budget. Large differences among the 3 different gravity fields related to the hydrologic signals in the Atlantic and Indian Ocean could be one of the major causes of the imbalance in the global sea level budget.

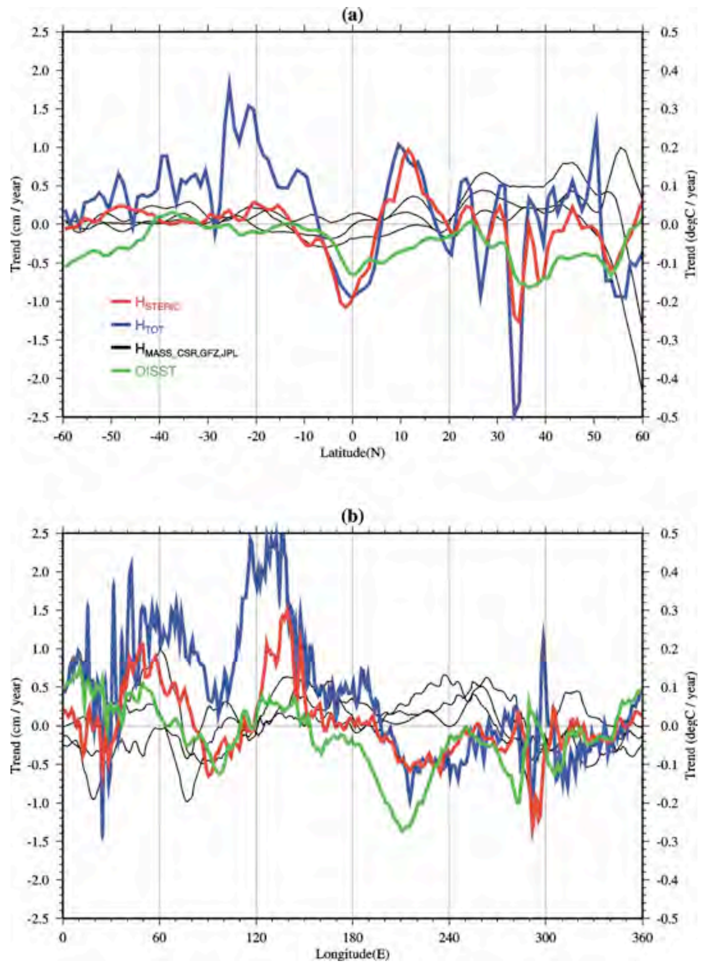


Figure 2. (a) 4-year linear trends of zonally averaged sea level from steric heights (H_{STERIC} in red), altimetric heights (H_{TOT} in blue), 3 different gravity fields ($H_{MASS\_CSR,}$ $H_{MASS\_GFZ,}$ H_{MASS_JPL} in black), and OISST (green). (b) Lower panel indicates the meridionally averaged results.

2.3. Validation for the GFDL Coupled Data Assimilation (CDA) system

We investigated the monthly mean analyses (SST, SSH, heat contents, zonal wind stress, 850hPa zonal wind speed, surface zonal current, vertical velocity, and sea ice mass) derived from the GFDL's CDA system from January 1979 to December 2008. GFDL's CDA analyses for 30 years are consistent with observation especially for the global temperature related fields. They also depicted the basin scale special features very well (ENSO (Figure 3), PDO, North America western coast upwelling, Atlantic hurricane non local anomalies, Indian Ocean dipole mode, and the Arctic sea ice coverage variation).

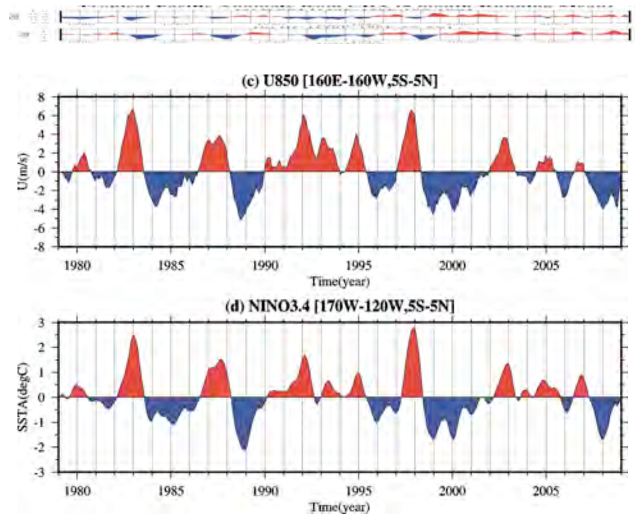


Figure 3. Time series of the equatorial Pacific (a) SST, (b) heat contents (upper 300 m temperature average), (c) zonal wind speed at 850 hPa, and (d) NINO3.4 SST anomalies simulated by the GFDL coupled data assimilation system.

2.4. Assimilation with Multi-Model Ensembles

Some new and exciting work has begun on a multi-model ensemble assimilation scheme. Both GFDL's CM2.0 and CM2.1 coupled models are used in a unified ensemble system in which the filtering process is based on the error statistics from both models' ensemble integrations. The system construction is complete but the analysis is ongoing. The idea here is that often the ensemble forecasts tend to look more like each other than reality. The goal is that the ensemble spread should span the possible solution space and to include the true solution. Some initial OSSE imperfect twin studies using this system uncovered some inconsistent constrains in the upper and deep ocean due to model biases and the nature of the low frequency of the deep ocean circulation. Although this issue may not be important for seasonal initialization it will most likely be for decadal initialization.

The impact of the ensemble circulation-dependent inflation filter (EcdiF) on oceanic climate detection is examined in 'biased' oceanic data assimilation (ODA) perfect model experiments. Two coupled GCM's CM2.0 and CM2.1 are used. Synthetic-observations are produced by projecting the CM2.0's simulation onto the ARGO network and they are then assimilated into the CM2.1 model. Because of the model bias and limitation of finite ensemble's representing the low frequency variability of the deep ocean, a standard ensemble filter fails to construct the proper watermass structure and develops spurious velocities. An EcdiF uses a pre-computed anomaly's variance to inflate the covariance for improving the consistency of the upper/deep ocean's data constraints.

2.5. Detection of Multi-Decadal Oceanic Variability

The impact of oceanic observing systems, external radiative forcing and oceanic initial conditions on the long time variability of oceanic heat content and salinity has been studied by the assimilation of synthetic oceanic "observations" in the context of a "perfect" IPCC AR4model. The 20th-century temperature (XBT) and 21st-century temperature and salinity (Argo) "observations" are drawn from the model projection on the 20th-century historical greenhouse gas and natural aerosol (GHGNA). These model observations are assimilated into the coupled model based on temporally-varying and fixed-year GHGNA records and different oceanic initial conditions. Both the 20th-century XBT and 21st-century Argo observations adequately capture basin scale heat content variability. Argo salinity observations appear to be necessary to reproduce the North Atlantic thermohaline variability. The addition of historical radiative forcing does not make a significant contribution to the detection skill. The initial conditions spun up from the temporally-varying GHGNA radiative effects produce better detection skill than the ones spun up from a fixed-year GHGNA value due to the relaxed assimilation shocks for the deep oceans that have been forced by the historical changes in radiative forcing. These results suggest that the 20th-century temperature observations be sufficient for the state estimate of the tropical ocean due to the strong TS relationship from air-sea interactions. Argo salinity observations are very important for global state estimation, particularly in high latitudes. An assimilation adequately spun up by external radiative forcing may reduce the error of the state of the art that combines a coupled model and observed data.

3. PUBLICATIONS

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Simulation of the Argo Observing System

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1. PROJECT SUMMARY

The Argo array currently consists of 3000 instruments that make vertical profiles of temperature and salinity every 10 days over the depth range of 1500 meters. The array has been brought to full strength, and a comprehensive assessment of the limitations of the Argo observing system is urgently needed.

The main goal of our study is to examine how well the Argo observing system determines the state of the global upper ocean. We sample and reconstruct oceanic fields from ocean general circulation models (OGCMs), in gradually more realistic sequence of simulations. By quantifying errors in the reconstructed fields, we estimate accuracy of the Argo observing system, and therefore directly address NOAA's Program Plan for *Building a Sustained Ocean observing System for Climate*.

This project is conducted at the University of Washington, Seattle, Washington.

2. ACCOMPLISHMENTS

In close collaboration with Drs. Wei Cheng and D.E. Harrison, we have been looking at the expected performance of the Argo observing system for the ocean. We have used a global coarse-resolution OGCM and a regional eddy-resolving OGCM to produce fields that we have sub-sampled in ways similar to how the Argo float array samples the ocean. We have then compared the fields reconstructed from this "Argo data set" with the complete model fields.

The activities during the FY 2008 were focused on the analysis of the effects of float movements and of changing the number of floats, as well as on the role mesoscale variability. We carried extensive analysis in the Antarctic Circumpolar Current (ACC) and high-latitude North Atlantic. We have completed preparation of one manuscript describing the results, and are on advanced stages of preparation of the second paper. Our findings, which these two manuscripts describe, are summarized below.

2.1. Coarse-resolution studies

The global ocean model used in this study has 2^{o} resolution in both latitude and longitude. The atmospheric forcing used to drive the model is derived from observation-based estimates. Daily values for the 2-meter air temperature and humidity, 10-meter wind speed, and zonal and meridional components of the wind stress are taken from years 1979-2001 of the NCEP-NCAR reanalysis. Climatological monthly values are used for all other atmospheric variables and freshwater fluxes. The simulated ocean state is as realistic as can be expected in a coarse-resolution model. However, because of the coarse resolution, the intensity of the boundary currents is underestimated and the mesoscale eddies are not resolved. The effects of the oceanic velocities on the Argo array in reality are expected to be even stronger than in this model.

In these simulations, 3,000 Argo floats are advected with the GCM-simulated velocities at 1500m depth during most of the time. Every 10th day, a simulated float surfaces, while taking the temperature and salinity (T/S) profile; it then spends 8 hours at the surface, where the float is advected by the surface currents. A float becomes “lost” if it enters a shallow region. Resulting data are used to reconstruct temperature and salinity of the ocean, using objective analysis. The simulations are carried for five years.

a) Reconstruction of the oceanic state

We have analyzed the expected accuracy of the Argo system in reconstructing such important oceanographic variables as temperature, salinity, upper ocean heat content (UOHC), calculated over the top 800 m) and mixed layer depth (MLD). For each of the variables, the analysis is carried for:

(i) the annual-mean values;
(ii) the amplitude of the annual cycle: the absolute value of the difference between the August and February values;
(iii) the amplitude of the interannual difference: the absolute value of the difference between the annual means for year 5 and year 1.
(iv)

The first two or these variables characterize the climatology averaged over 5 years of GCM data. The second and third variables quantify the amplitude of the variability on annual and interannual time scales.

We analyze the **reconstruction errors**, the difference between the actual GCM-simulated and reconstructed fields.

Reconstruction errors in the vertical profiles of temperature and salinity decrease with depth, in concert with decreasing spatial gradients and temporal variability in the actual fields (Figure 1). The errors in temperature exhibit a maximum at approximately 100-150m, where the average errors in the annual mean reach 0.6 degrees in ACC and 0.3 degrees elsewhere. Average errors below 1000m are very small, less than 0.1 degrees.

The reconstructed climatology of UOHC is close to the actual GCM-simulated values over most of the ocean (Figure 2). The errors are particularly small for the annual-mean values and the magnitude of the annual cycle. However, the reconstruction errors are more significant in the regions of high gradients and intense currents, particularly in ACC and high-latitude North Atlantic. The largest errors in these regions are found in the magnitude of the interannual difference, which suggests that the detection of interannual trends from the Argo data alone can be problematic.

Similar to UOHC, the reconstruction errors in MLD are significant (Figure 3) in ACC and the high-latitude North Atlantic. MLD is highly sensitive to the near-surface values of temperature and salinity, and even small errors in these variables result in large errors in MLD. Errors in the magnitude of the annual cycle are particularly large.

b) Effects of float movements

Movements of the Argo floats by oceanic currents have complicated effects on the overall accuracy of the Argo system. The resulting redistribution of floats acts to increase the spatial sampling coverage of the Argo system, by providing observations from more points in the domain. The float movements, however, negatively impact the reconstruction of the time variability in sampled fields, by decreasing the time a float spends near any particular location. Significance of both effects increases in the regions of high gradients and strong currents, such as ACC.

The effects of float movements are studies in two sensitivity experiments. In the first experiment ("**parked floats**" case), the advection of the floats is turned off. The reconstruction errors are noticeably decreased in most of the domain (Figure 4a). In particular, the float movements are the main cause of the increased errors in the magnitude of the interannual difference of UOHC in ACC and high-latitude North Atlantic.

In the second experiment ("**random position**" case), the float advection is replaced by random redistribution of floats every time the sampling takes place. The reconstruction errors decrease (Figure 4b), demonstrating potential significance of an increase in spatial sampling coverage, caused by rapid redistribution of floats.

c) Effects of the changed number of floats

Two additional experiments estimate effects of the density of spatial sampling coverage. In the first experiment, the number of floats is doubled, and the average spacing between floats is decreased from 300 to 215 km. The reconstruction errors become smaller. The remaining errors in ACC and high latitudes suggest that even the doubled sampling coverage is not sufficient for accurate reconstruction in those regions.

In the second experiment, the number of floats is halved. The errors increase significantly (30-40 per cent), demonstrating the potential decrease in the reconstruction skill due to the floats gradually reaching the end of their lifetime.

2.2. Eddy-resolving simulations of the North Atlantic

To investigate the effects of mesoscale variability on the accuracy of the Argo system, we carried our analysis in a high-resolution regional model of the North Atlantic. High horizontal resolution ($1/8^o$ resolution in latitude/longitude) permits simulation of mesoscale eddies. The model has 30 levels in the vertical. The topography is estimated from the Scripps $1^o x 1^o$ dataset; the total depth of the ocean is 3,000 meters. Initially, 250 Argo floats are evenly distributed in the model domain; the floats are then advected by

GCM-simulated currents. For the analysis, we used 9 years of high-resolution data from the model.

In our **control** simulation, the Argo floats are advected by the full velocities. In agreement with our previous coarse-resolution experiments, the regions of the fast advection correspond to the largest systematic biases in the reconstructed fields. In particular, in the vicinity of the North Atlantic Current, the reconstructed MLD is shallower than in the original GCM data. The reconstruction errors in UOHC are also substantial in most of the subpolar gyre (Figure 5a).

Next, we analyze the effects of mesoscale variability on the expected accuracy of the Argo system. In our second experiment ("**time-mean**" case), the mesoscale variability is removed from both the velocities and temperature/salinity fields. As Figure 5b demonstrates, the mesoscale variability explains a substantial part of the reconstruction errors in the control experiment, particularly in the subpolar gyre.

If the mesoscale variability is removed from the velocities and not from the temperature and salinity ("**mean-advection**" case), the errors are very similar to those in the time-mean case. We conclude that the high-frequency variability in velocities (and float movements) is the main cause of the increase in reconstruction errors due to eddies. The mesoscale variability in temperature and salinity has secondary importance.

To further quantify effects of advection, we conduct the fourth experiment, in which the magnitude of mesoscale variability is amplified by a factor of 2.5. This amplification factor was chosen to bring the variance in the simulated sea-surface height closer to the observed one. As a result of the amplification, the biases in the simulated fields increase everywhere in the domain, with the largest change within the Labrador Current, and near the Cape Hatteras.

2.3. Significance of results

Our study helps to identify the regions, in which the reconstruction of oceanic variables from the Argo data set can be less reliable than in the rest of the World Ocean. The results also demonstrate several important effects of oceanic advection on the accuracy of the reconstruction. As shown by our coarse-resolution global simulations, float movements represent a major source of reconstruction errors in ACC and the high-latitude North Atlantic, particularly in the year-to-year variability. Our eddy-resolving simulations further suggest that the mesoscale variability in velocities and float movements act to increase reconstruction errors in the North Atlantic.

The results emphasize the need for additional, dense spatial sampling in ACC and the high-latitude North Atlantic, as well as in the regions characterized by intense mesoscale variability. Combining Argo data with other in situ measurements less affected by oceanic currents, such as XBTs and mooring data, will also help to improve accuracy of the reconstruction of oceanic variables.

3. PUBLICATIONS

Kamenkovich, I., W. Cheng, E.S. Sarachik, and D.E. Harrison, “Simulation of the ARGO observing system in a global ocean model”. *J. Geophys. Res.*, submitted.

Kamenkovich, I., W. Cheng, E.S. Sarachik, and D.E. Harrison, “Effects of mesoscale variability on the accuracy of the ARGO observing system”, to be submitted.

4. FIGURES

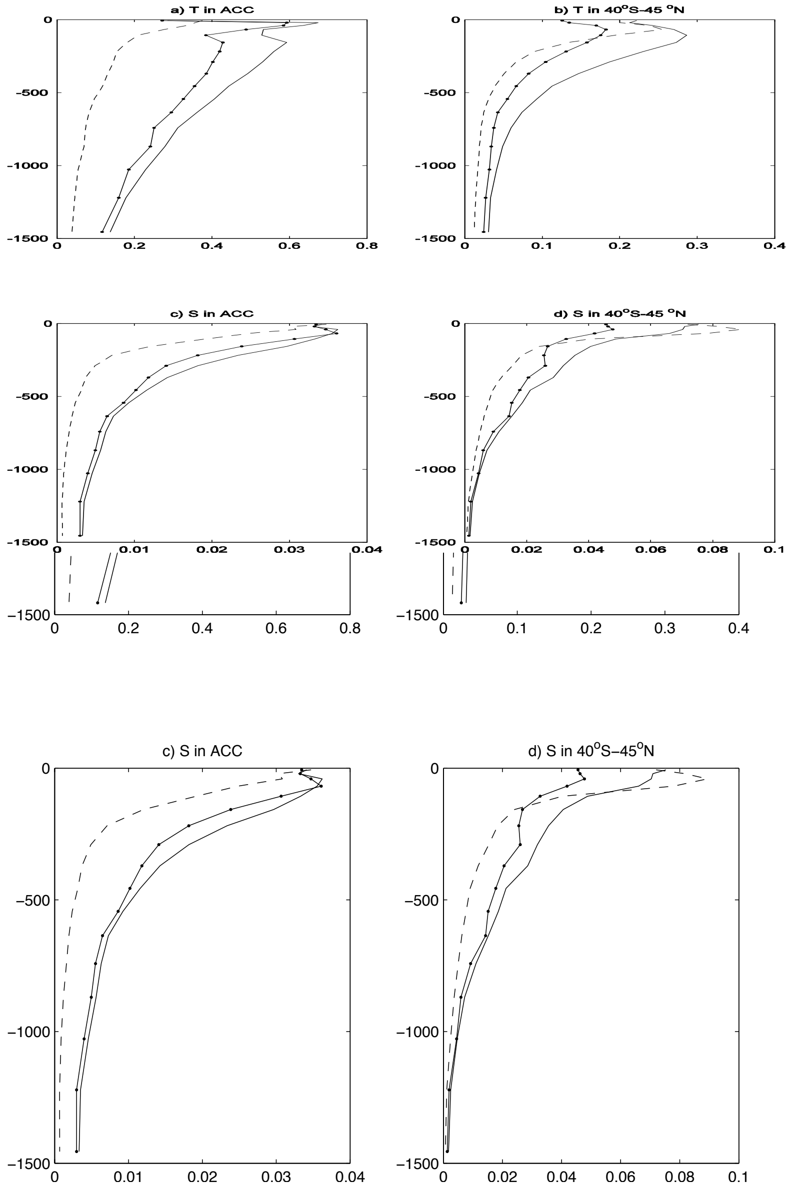

Figure 1. Area averaged magnitude (absolute value) of reconstruction errors in temperature (top row) and salinity (bottom row) as functions of depth. The values in the left column (panels a,c) are computed within ACC (south of 40°S); in the right column (panels b,d) – in the mid- and low latitudes (between 40°S and 45°N). The solid lines show errors in the annual means, dashed – in the magnitude of the annual cycle; dots –in the magnitude of the interannual difference.

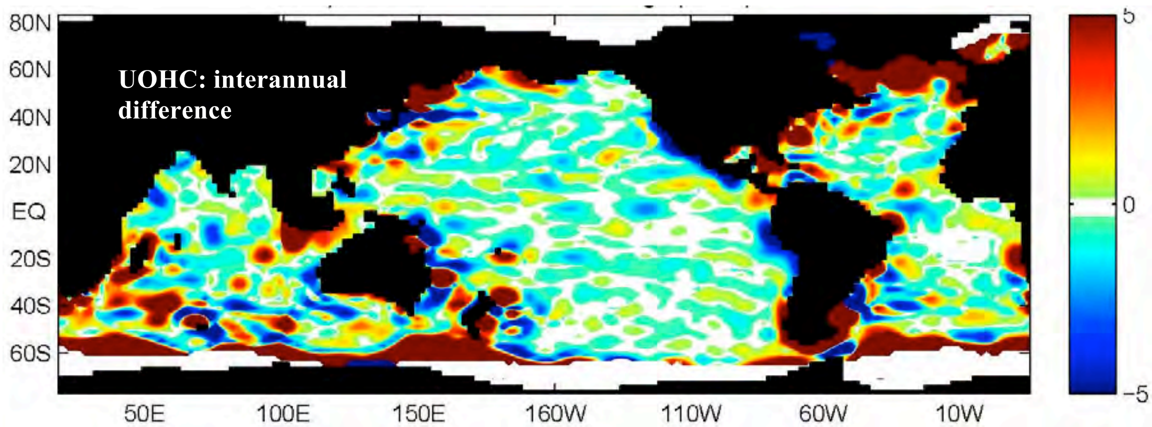

Figure 2. Accuracy of the reconstruction of UOHC in the standard 5-year simulation. Reconstruction errors are shown for the amplitude of the interannual difference (in flux units, contour interval is $0.25Wm^{-2}$). Values under ice are not shown.

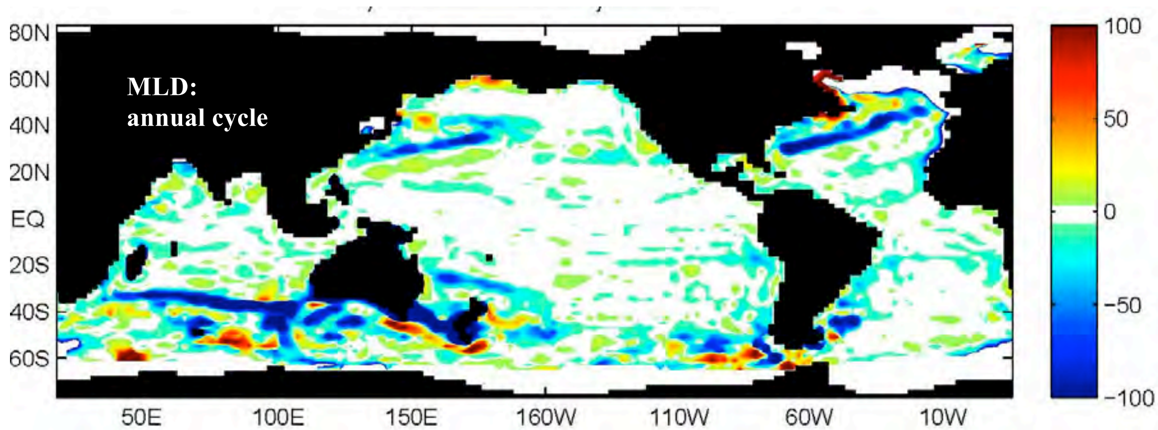

Figure 3. Accuracy of the reconstruction of the mixed layer depth in the standard 5-year simulation. Reconstruction errors are shown for the amplitude of the annual cycle. Contour interval is 5m. Values under ice are not shown.

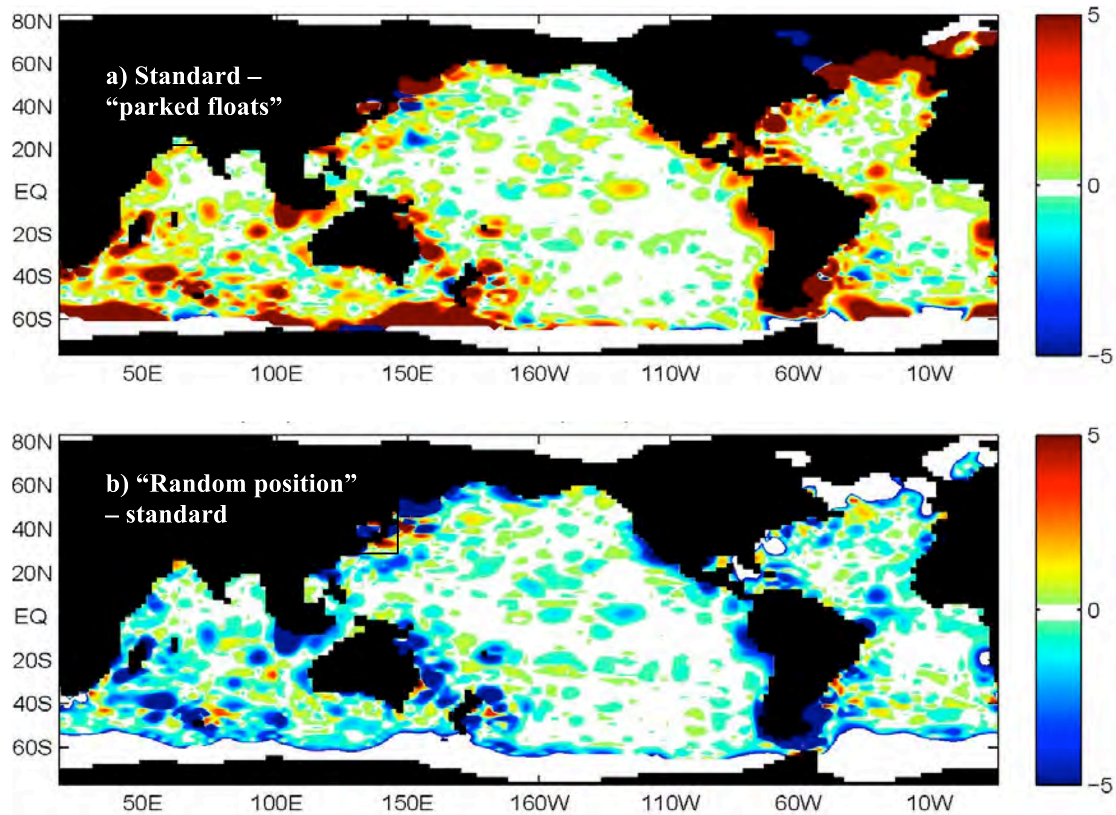

Figure 4. Effects of float movements on the reconstruction of the magnitude of interannual difference. Shown are the differences in the magnitude of reconstruction errors between the standard and “parked floats” cases (top panel) and the “random position” and standard cases (bottom panel). The contour interval is 0.25Wm^{-2}. Values under ice are not shown.

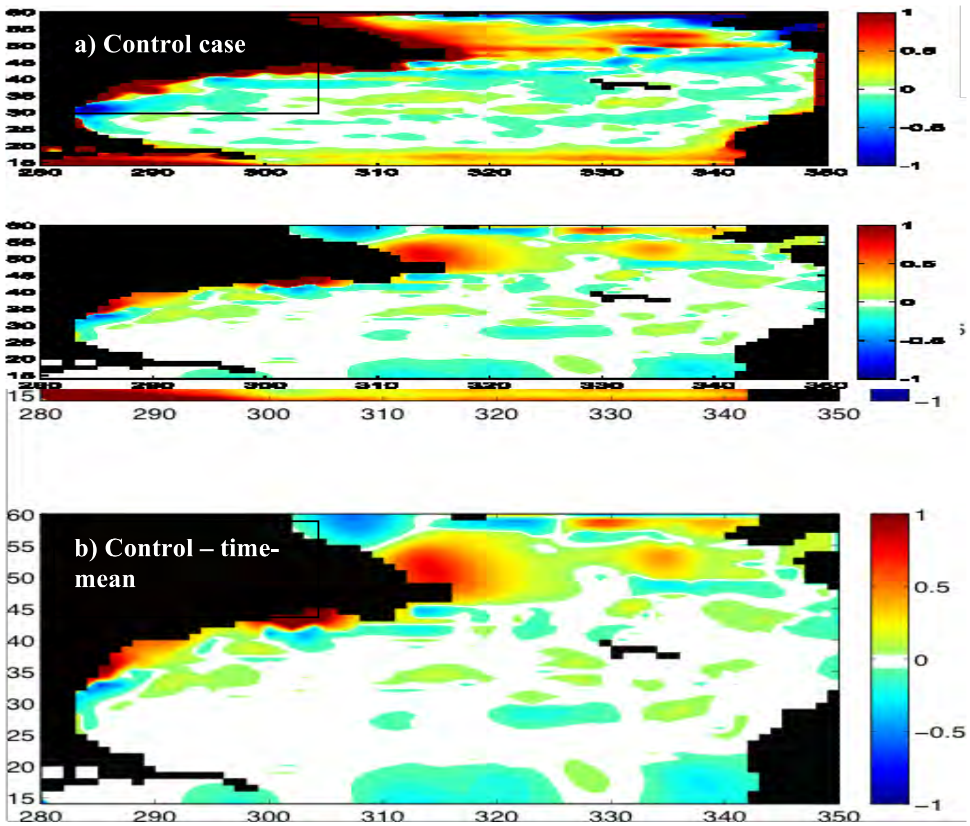

Figure 5. Reconstruction errors and importance of mesoscale eddies for reconstruction of UOHC in the eddy-resolving North Atlantic simulations. Top panel: reconstruction errors in the control case. Bottom panel: the difference in the error magnitudes between the control case and the experiment with the time-mean fields. Units are degrees C (heat content per unit area is divided by $3.4x10^9 Jm^{-2}deg^{-1}$).

Observing System Research Studies

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1. PROJECT SUMMARY

This project supports the design, evaluation and development of the global ocean observing system for climate through a variety of research and leadership activities. These activities include data set preparation/dissemination, data analysis and modeling studies. The goal is to expand our knowledge of what we know and can rationalize, and what we cannot know or rationalize, from the observing system as deployed at present and from the historical data set that has been produced over past decades. It also supports the evolution of the observing system through evaluation of alternative observing strategies and evaluation of the differences between available ocean analysis products (taken as one measure of the uncertainty in the analysis products). A primary objective is identifying ocean and climate state indices that are of societal relevance, and understanding the limits on the accuracy of our estimates of these indices resulting from the observing system's limitations.

Finally it supports the goals of the Office of Climate Observations and NOAA's Climate Goal through the PI's activities as Chair of the OCO Climate Observing System Council, and of the Ocean Observations Panel for Climate (co-sponsored by the GOOS, GCOS and WCRP) and other national and international leadership activities involved with sustained ocean observing. The PI is also a member of the JCOMM Management Committee and works with its Program Areas to progress the development and delivery of global ocean services.

No data are collected through this project; the Ten Climate Monitoring Principles are not relevant to the activities undertaken.

Initial focus has been on SST variability since it is agreed to be the most important variable for climate impacts. Substantial work has been done also on subsurface ocean temperature conditions since these are important to future projections of climate and sea level changes. Work has been done with all of the variables of the global ocean observing system, and shall continue in FY09 as described below.

2. ACCOMPLISHMENTS

6 Papers are in print or have appeared in the literature since start of FY08.
3 Papers are currently in the review process.
3 research projects have made significant progress.

3. PUBLICATIONS

Carson, M. and D.E. Harrison, 2008: Is the upper ocean warming? Comparisons of 50-year trends from different analyses. *J. Climate*, 21(10), 2259–2268.

Carson, M. and D.E. Harrison, 2008: Upper Ocean Warming: Spatial patterns of Trends and interdecadal variability. NOAA Tech. Memorandum OAR-PMEL-138, NTIS: PB-2008107952, 31pp.

Chiodi, A.M. and D.E. Harrison, 2007: Mechanisms of summertime subtropical Southern Indian Ocean sea surface temperature variability: On the importance of humidity anomalies and the meridional advection of water vapor. *J. Climate*, 20(19), 4835–4852.

Chiodi, A.M. and D.E. Harrison, 2008: Hurricane Alley SST variability in 2005 and 2006. *J. Climate*, 21(18), 4710–4722.

Chiodi, A.M. and D.E.Harrison, 2008: Characterizing the interannual variability of the equatorial Pacific: an OLR Perspective. NOAA Tech. Memorandum OAR PMEL-140. NTIS:PB-2008112890, Seattle, WA 30pp.

Harrison, D.E. and A.M. Chiodi, 2009: Pre and post 1997/1998 westerly wind events and equatorial Pacific cold tongue warming. *J. Climate*, 22(3), 568–581.

4. SUBMITTED PAPERS

Carson, M. and D.E. Harrison, 2009: Regional Interdecadal Variability in bias-corrected Ocean Temperature Data. *J. Climate*, submitted.

Chiodi, A.M. and D.E. Harrison, 2009: An OLR-based index for North American seasonal climate anomalies. *J. Climate*.

Chiodi, A.M. and E.D. Harrison, 2009: Characterizing ENSO variability in the equatorial Pacific: An OLR perspective. *J. Climate*.

Larkin, N.K. and D.E. Harrison, 2009: The 1997–98 El Niño and the post-WWII composite event. *J. Climate*.

5. IN PROGRESS

Harrison, D.E., R.D. Romea, G. Vecchi, and A. Chiodi: Effects of surface forcing on the seasonal cycle of the eastern equatorial Pacific. Intended *J. Phys. Oceanogr*.

Chiodi, A.M., and D.E. Harrison: The annual range of Southern Hemisphere SST; Comparison with surface heating and possible reasons for the high-latitude fall off. Intended *J. Climate*.

6. BRIEF DESCRIPTION OF RESEARCH RESULTS

Ocean heat content is an ocean index that is straightforward to define and is relevant to assessment of climate variability and change. Its trends are of particular interest to society, as a test of global climate models and as a major component of sea level variability and rise. We have continued to probe the historical ocean data set and determine the extent to which accurate long term trend estimates of world ocean heat content can be made. Work completed early in FY08 showed that because so much of the world ocean has not been observed adequately to permit a meaningful trend estimate to be made, differences in the interpolation techniques used to produce a global "data set" have very substantial effects on the inferred global 50year trend. This questions the usefulness of recently published estimates of long term heat content trends. Recent work shows that expendable bathythermograph data introduce a decadally-varying temperature bias compared to other instruments in the historical data set that measure pressure and temperature concurrently. The effect of this bias on regional interdecadal temperature variability has been shown to be smaller that the remaining interdecadal temperature variability. This confirms that the regional ocean temperatures have undergone substantial changes over recent decades, and suggests that such changes are likely to continue to at least partially obscure longer-term subsurface trends in the near future. This work emphasizes the need for obtaining and maintaining global coverage of *in situ* observations in order to accurately determine long-term world ocean trends.

Indices for characterizing the ENSO-state of the planet are also important. As we have noted previously, the 'operational' El Niño index introduced by NOAA several years ago has many practical shortcomings and its use has led to confusion in many nations about what weather to expect. We continue to explore ENSO indices, and their strengths and weaknesses. In FY08 we showed that outgoing longwave radiation (OLR) information can be used to give rather unique perspective on recent El Niño behavior. This OLR perspective has a distinctly event-like character, not seen the indices most-commonly used describe the anomaly state of the tropical Pacific, such as Niño 3.4 region SSTA or the Southern Oscillation Index. This makes determination of "event-status" based on OLR less ambiguous than using other commonly used ENSO indices, which show a continuous interannual distribution of neutral-to-secondary-to-large anomalies. In OLR, the most commonly agreed upon warm-events stand out. OLR also offers a more dynamically-direct connection to the global seasonal weather anomalies caused by ENSO, which are of the more general societal concern that specific tropical Pacific conditions. Examination of NCEP/NCAR reanalysis atmospheric geopotential height anomalies confirms that significant and robust atmospheric circulation anomalies are driven over the North Pacific and North America in years distinguished by eastern central pacific OLR variability. Groups of years considered "El Niño" based on some other ENSO indices, but not particularly distinctive based on OLR behavior, do not show such anomalies. This work suggests that eastern central Pacific OLR information be used, both operationally and historically, to identify the El Niño events that are most likely to have substantial and predictable effects on N. American weather. Two papers on this work have been submitted for publication

It is important for the broader community to understand the anomaly patterns associated with any given ocean/climate index. Because ENSO is of such widespread societal interest, we updated the Harrison and Larkin (1986) global marine surface composite for El Niño events, based on the "conventional" El Niño classification list (which the OLR index also seems to identify). This paper, which was co-authored with Dr. Sim Larkin of the US Forest Service, has been submitted for publication, and is available for downloading to researchers and others.

Work was done to complete and bring to publication in respected journals some work ongoing from FY07. For example, we showed that the surface heat flux contribution of meridional advection of surface humidity can dominate interannual surface heat flux variability in subtropical Indian Ocean regions that are thought to affect southern Africa weather. This is contrary to previous suggestions that zonal wind speed effects on surface heat flux dominate in these regions. Results also show that surface heat flux dominates the effects of ocean heat flux convergence on interannual timescales in the subtropical regions of interest, contrary to some earlier hypotheses. The meridional-moisture-advection type of surface heat flux variability shown to be important in this case is caused by the Mascarene High in sea level pressure preferentially locating itself either near the coast of Madagascar or Western Australia. The case with the Mascarene High near Madagascar is conducive to the type of SST anomalies associated with increases in rainfall over southern Africa. This work makes the case that more must be learned about this type of basin scale atmospheric behavior in order to improve seasonal weather forecasting efforts in this region.

We also showed that it is possible to understand the differences in tropical North Atlantic SST anomalies in the 'hurricane alley' formation regions between 2005 (lots of hurricanes) and 2006 (few hurricanes) by considering differences in the large scale atmospheric circulation over the region, and the resulting changes in air-sea heat fluxes. It is not necessary to invoke changes in the atmospheric loading of aerosols off of West Africa to rationalize the observed SSTA patterns. It is necessary, however, to consider the effects of sub-seasonal atmospheric variability on the surface fluxes to accurately model the observed 2005 to 2006 SSTA difference. Results show low-wind, clear sky conditions associated with atmospheric anticyclones are conducive to forming shallow ocean-mixed-layers that warm rapidly; up to a degree per day, which is much more than expected from seasonal-climatology or monthly-mean conditions. Though strong cooling also occurs as the heat in these shallow surface layers are mixed to deeper depths, a substantial amount of this warming remains in the longer-term average and can be attributed to non-linear effects that warm the ocean more than would be expected from knowledge of monthly or seasonal mean conditions alone. This suggests that this sub-monthly atmospheric variability, or its effects, will have to be predicted to improve interannual SST predictions in these regions. This is somewhat of a break from traditional forecasting efforts in which seasonal mean conditions are predicted knowledge of the seasonal-mean base state. These papers show once again how important accurate knowledge of air-sea fluxes is for understanding (and predicting) SST anomalies of climate relevance; the observing system activities that serve to help us evaluate operational air-sea flux estimates are very important.

Trying to find indices that can help us forecast the onset, characteristics and strength of El Niño events is also of national interest. One obvious route is indices of equatorial Pacific surface zonal winds. To construct useful indices we must understand the space and time characteristics of winds in this region. We showed that there has been a change in the wind patterns associated with westerly wind events over the tropical Pacific since the major 1997-98 El Niño event, and that these seem sufficient to explain why we have been having more “Dateline El Niño” than “conventional El Niño” events since then. We used numerical ocean model experiments to obtain the latter conclusion. This work suggests a new index that takes into account the basin scale wind anomaly conditions present during a westerly wind event might be developed for tracking the likelihood of an El Niño appearing in any given year. Presentation of this work at national scientific conferences has been successful in generating considerable interest in the phenomena documented by this study among the research and forecasting/monitoring communities.

Progress has been made on a paper that determines the effects of the various components of surface forcing on the seasonal cycle in the eastern equatorial Pacific. Traditionally, much attention has been paid in the literature to the importance of the component of the seasonal cycle driven by meridional wind variability. Preliminary results show that zonal wind variability is at least as important and that accurate knowledge of both wind components and surface heat flux is necessary for ocean models to accurately resolve many aspects of the observed seasonal cycle. Progress has also been made on a paper that examines the reasons for the observed fall-off of seasonal range of surface SST with latitude. Preliminary results show that ocean mixed layer depth estimates available from the World Ocean Database 2005 can be used to reasonably predict the observed zonal mean SST seasonal range structure in the ice-free latitudes of the Southern Ocean. Using World Ocean Database 2001 data instead results in a much different answer at high latitude because this region of the world ocean was sampled considerably less during the pre-ARGO years. This shows the importance of the increased sampling provided by the ARGO program to our understanding of this fundamental feature of Earth’s climate.

7. OBSERVING SYSTEM MEETINGS/WORKSHOPS LED OR ATTENDED

4-6 Oct GCOS/IPCC Lessons-learned Syd
16-19 Oct GCOS SC Paris
31 Oct GOOS outreach Lon
29-30 Nov Autumn COSC
Jan 3 IOC on OceanObs/Info09
Jan 9-11 POGO9 Bermuda
Jan 28-Feb 1-3rd Reanalysis Wkshp Tokyo
March 13-14 GSOP-III Southampton UK
March 24-26 CWG Review Princeton NJ
April 7 pre-GSSC GOOS wkshp Paris
April 8-10 GSSC Paris
April 10-11 PICO Paris
April 8-12 El Niño Definition mtg. UHawaii
April 21-25 AOPC Geneva
May 5-9 WCRP Modeling Summit ECMWF
May 6-9 CLIMAR-III Gydnia Poland
May 19-23 Gijon ICES/PICES/IOC
Jun 2-4 IGST DC
June 9-13 OOPC 13 Buenos Aires
June30-4July GCOS Geneva
July 7-8 OSMC PMEL
Aug 26-28 PMEL Lab Review
Sept 3-5 DC OCO Annual Review

10. Data Management

The Observing System Monitoring Center (OSMC)

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[3]NOAA National Geophysical Data Center, Boulder CO

1. PROJECT SUMMARY

The Observing System Monitoring Center (OSMC) is an information gathering, decision support, and display system for the National Oceanic and Atmospheric Administration's (NOAA) Office of Climate Observations (OCO) located in Silver Spring, MD. The OSMC permits the many "networks" of *in situ* ocean observing platforms -- ships, floats, tide gauges, etc. -- to be viewed as a single system. It is a key integrating component for the management of a sustained Ocean Observing System for Climate.

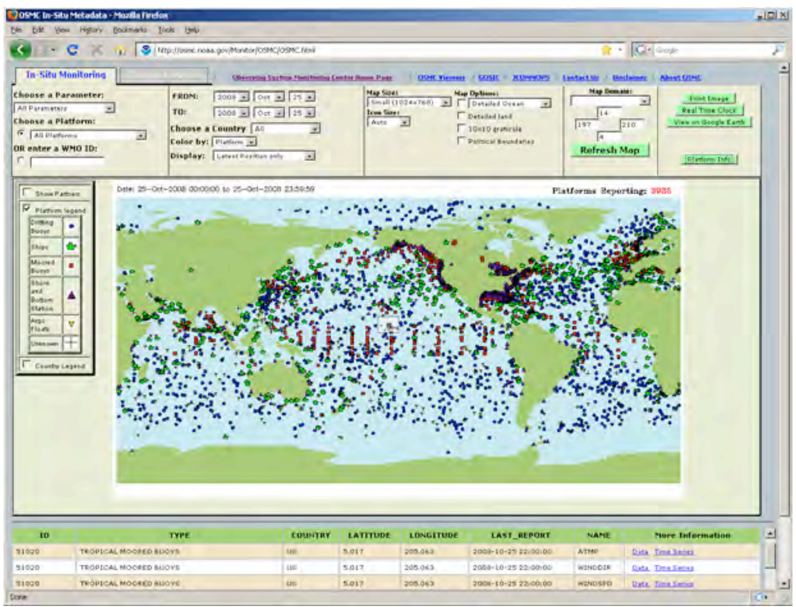


Figure 1. Screen snapshot of OSMC interface.

The OSMC system displays the current and historical status of the global observing system for *in situ* ocean surface meteorological and oceanographic measurements (Figures 1, 2). It provides dynamically generated maps to visualize the coverage of observations.

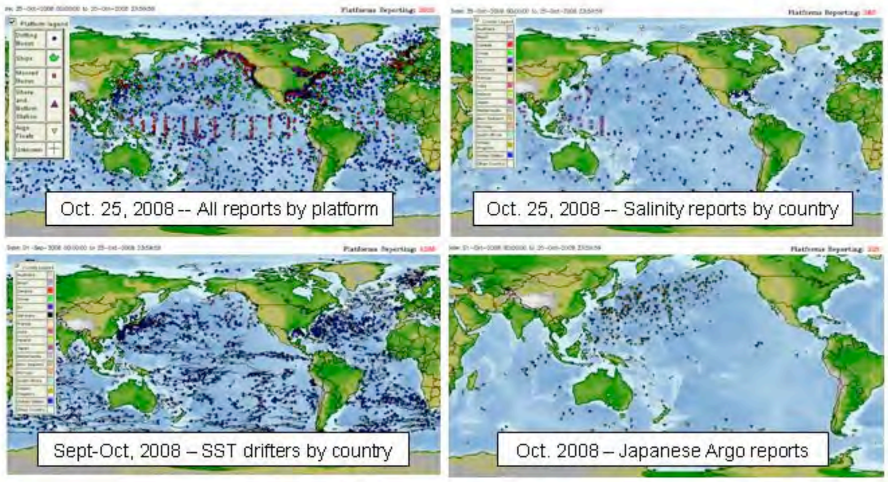


Figure 2. Sample OSMC maps.

The selection of observations may be constrained by observing platform, by parameter (temperature, sea level height, etc.), and by contributing nation. Maps may be requested for various time intervals – daily, weekly, monthly or arbitrary. With a click the user can "drill down" to see the metadata that describes a given observation.

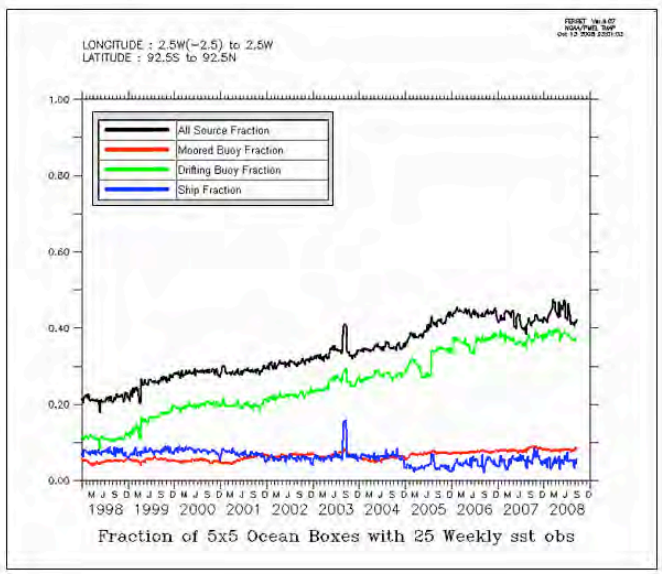


Figure 3. Progress in implementation of the ocean observing system.

Other viewers in the OSMC also provide time series showing trends in observing system coverage (Figure 3); they provide tabulated summaries, showing the counts, continually updated, of observations by ocean basin and platform type, and the contributing nation (Figure 4); and they provide visualizations of the observations on a globe with Google Earth® (Figure 7).

Number of Observing System Platforms Reporting

	Argo Floats	CMAN	Drifting Buoys	Moored Buoys	Ships	Unknown	Undefined	Sum
10-26-2008	121	349	1177	413	0	0	0	2060
10-25-2008	272	353	1179	414	524	49	330	3121
10-24-2008	297	358	1187	419	630	54	406	3351
10-23-2008	275	356	1191	414	606	54	392	3288
10-22-2008	266	357	1239	415	630	56	406	3369

*A count is defined as a platform reporting any type of observation on a particular day.

Figure 4. One of many OSMC table-based summaries.

The OSMC also offers analysis capabilities, developed through collaborative interaction with the Climate Observing System Council (COSC) and NOAA observing system scientists. These analysis capabilities help managers to assess the adequacy of the observations to compute critical ocean state fields, such as sea surface temperature. Figure 5 shows a 5x5 degree gridded analysis of a simple metric for the adequacy of the sampling of SST – the percentage of weeks in which at least 25 observations are made in a grid box during the 9 month period beginning Jan. 1, 2008.

The OSMC system is available on-line at http://www.osmc.noaa.gov. It is provided as a resource to other NOAA centers, national research partners, and international partners.

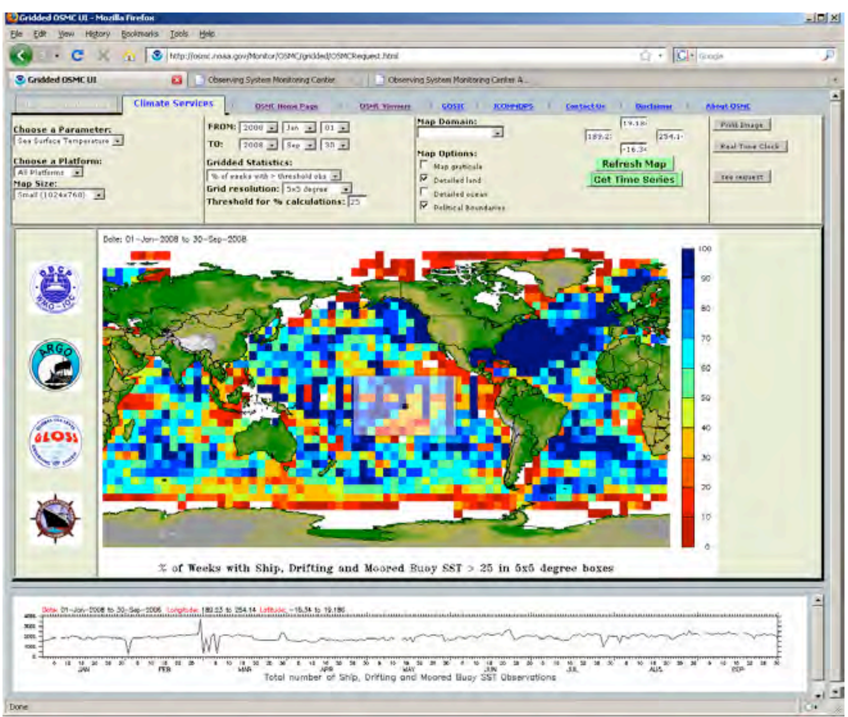


Figure 5. Analysis interface of the OSMC.

The OSMC project is a joint development effort between the Pacific Marine Environmental Laboratory (PMEL) in Seattle, Washington; the National Data Buoy Center (NDBC) at Stennis

Space Center in Mississippi; and the National Geophysical Data Center (NGDC) in Boulder, Colorado. The project is aligned to take advantage of the strengths of each organization. PMEL (an ocean/climate research laboratory) is responsible for the user interface/graphics/analysis tools; NDBC (an operational organization) is responsible for the data; and NGDC (a data center) provides technical consulting and development services on the use of data bases and standard services.

The OSMC is being designed in close cooperation with the JCOMM in situ Observing Platform Support Centre (JCOMMOPS). The development of the OSMC represents an important step towards the fulfillment of commitments to the Ten Climate Monitoring Principles.

2. PROGRESS

The following milestones track the progress made on OSMC during fiscal year 2008. "Group" lists only those accomplishments or events that involved the entire collaborative group.

2.1. Group Accomplishments (PMEL, NDBC, NGDC)

- The OSMC collaboration released the OSMC system through the publicly accessible OCO Web site. The OSMC site was advertised to the Climate Observing System Council (COSC), JCOMMOPS and OCO partners nationally and internationally.
- Outreach to the community regarding the value of the OSMC and the role of the community as participants in the OSMC occurred at multiple venues including:
    - "Monitoring and Analyzing the Global Ocean Observing System with the Observing System Monitoring Center", 88th Annual AMS meeting, Jan. 2008
    - "An Integrated View of the Ocean Observing system" presented at the 2nd Joint GOSUD/SAMOS Workshop, Seattle WA, June 10-12, 2008
    - "The OSMC-IOOS Collaboration Plan", at the IOOS Program Office Integrated Products Team Workshop, Silver Spring, July 7-8, 2008
    - "The Observing System Monitoring Center (OSMC) -- Steps Towards Climate Data Integration", at the Office of Climate Observations annual review, Silver Spring, September 3-5, 2008
- The OSMC development group and the operational OSMC continued to support OCO needs for materials and information needed for numerous initiatives, briefings, presentations, and ad-hoc requirements.
- An OSMC technical development meeting was held February 12-13 in Boulder to address database design issues associated with "duplicates" (multiple reports of the same observation internal to GTS and through delayed mode data sources).

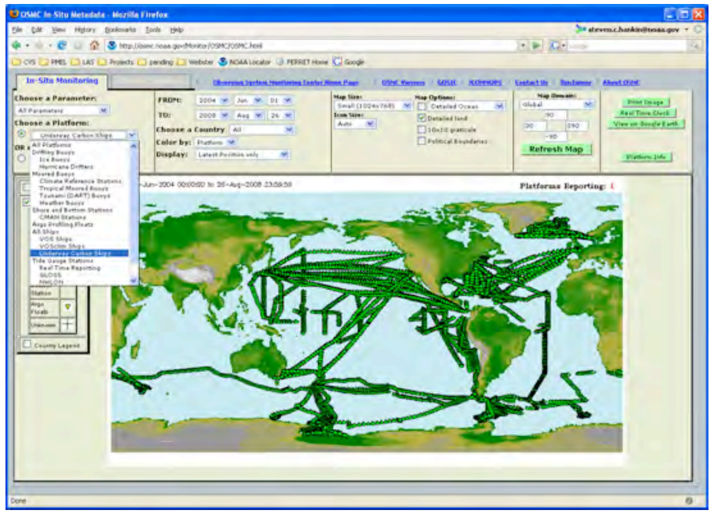


Figure 6. Carbon underway observations through the OSMC.

- The full OSMC group met for an OSMC all-hands meeting July 17-18, Seattle in which progress was assessed, strategic plans and priorities were decided upon, and technical issues that had been identified through weekly telcons were addressed. Among the many outcomes of this meeting were concrete plans for the incorporation of non-GTS data sources into the OSMC. The strategy to be followed will utilize the Climate System Markup Language (CSML) standard as an intermediate metadata representation for all non-GTS platforms.
- NDBC and PMEL worked together to arrange the first transfer of metadata from carbon observations into the OSMC database. Due to limitations in the quality and completeness of the metadata in the Takahashi collection the carbon observing system in the OSMC appears as a single monolithic (virtual) cruise as shown in Figure 6. The FY09 OSMC tasks describe the refinement of this initial step.
- Using graphical techniques prototyped by NGDC, the Google Earth® displays of OSMC metadata were improved as shown in Figure 7. The new style uses "placemarks" instead of an image. The platform icons on Google Earth® are clickable to retrieve metadata and data plots. We believe that Google Earth® can provide an excellent interface for those who wish to use the OSMC to monitor polar observations.

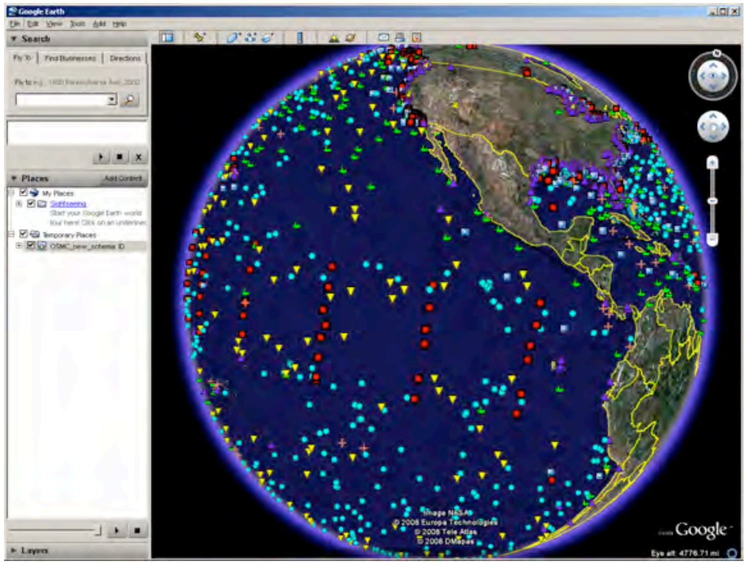


Figure 7. Google Earth® viewer showing ocean observations.

- Under the joint IOOS-OSMC tasks that were identified in May with joint funding from the IOOS Program Office NDBC and PMEL worked together to add IOOS as a new program type in the OSMC. This work has been partially completed. IOOS is the first program encountered in the OSMC that supports multiple platform types. Incorporating IOOS into the OSMC has revealed the need to generalize the concept of a "program" as modeled in the OSMC database.

2.2. PMEL ACCOMPLISHMENTS

- PMEL met its on-going project leadership responsibilities for the OSMC collaboration: organizing meetings and telcons; overseeing the tracking of bug fixes, milestones, and deliverables; coordinating plans of high level strategy; helping to ensure that group-wide communications continue to flow smoothly. PMEL also continued to provide the primary (though by no means sole) point for coordination of OSMC developments and outreach with projects such the Integrated Ocean Observing System (IOOS); the NOAA Data Management Committee (DMC); the NOAA "GEO-IDE" data integration framework; and NOAA science programs.
- In December 2007 OSMC version 3 was officially announced and made available from NDBC. It contains the following new features that PMEL developed or contributed to:
    - Through mouse-click "drill down" the OSMC interface provides plots of profiles, time series, and trajectories of ships and drifters. Figure 8 illustrates a TAO mooring time series.

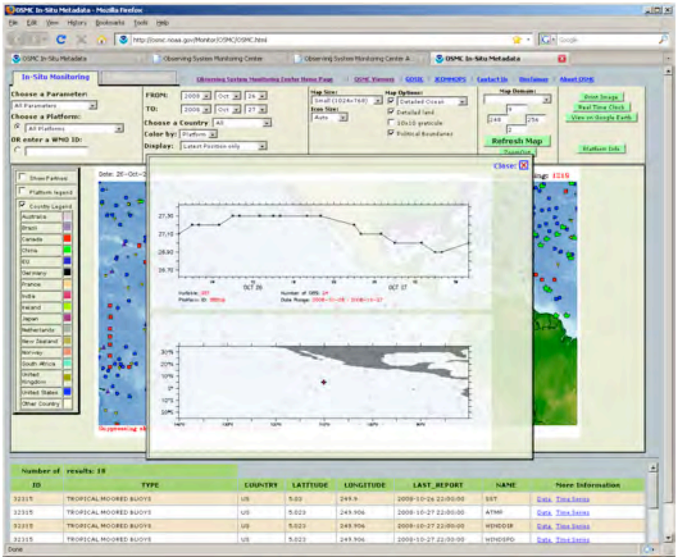


Figure 8. Data visualizations through "drill down".

- In Figure 9 we see Reynolds error bias fields as an underlay, providing perspectives on the adequacy of the *in situ* observing system.

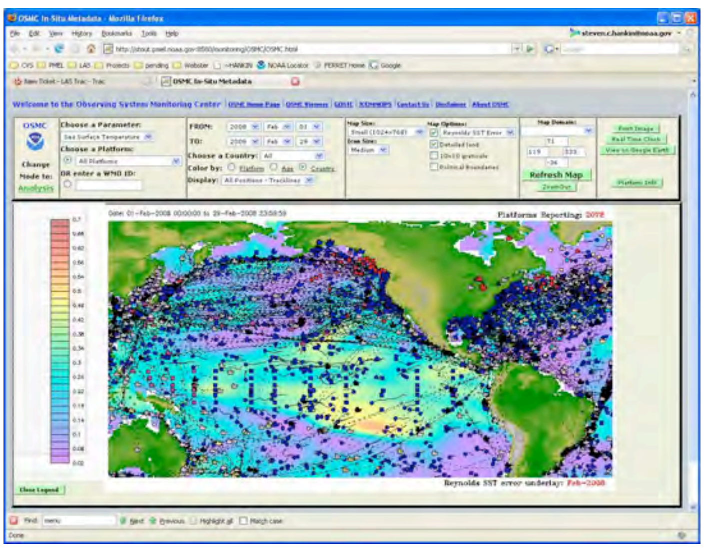


Figure 9. Observations overlaying Reynolds bias estimates.

- Improved the appearance and usability of the user interface through the use of a "tabbed" layout
- Improved click-and-drag selection, preserving aspect ratio
- The ability to color by parameter values as shown in Figure 10

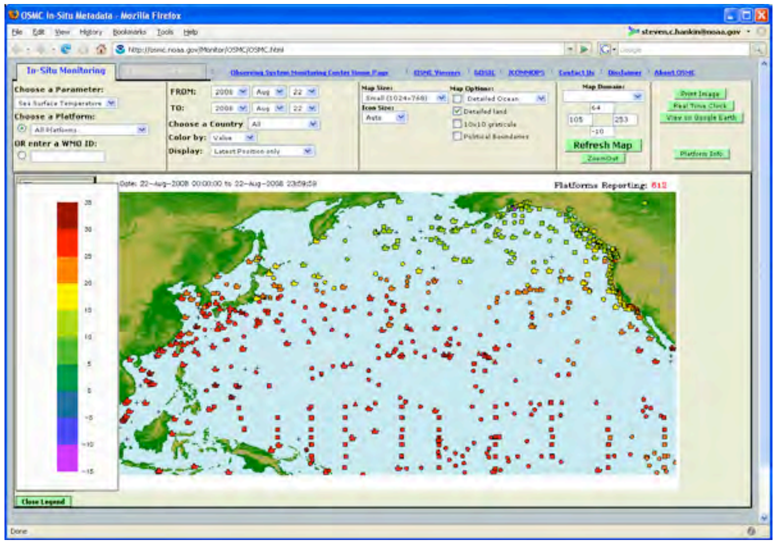


Figure 10. SST observations colored by value.

- Auto-sizing of icons was added based upon the density of information that is being displayed. The user can optionally over-ride this.
- OSMC color schemes were altered to more closely match those in use at JCOMM-OPS.

- A prototype viewer for collections of time series was developed as shown in Figure 11. This is a step towards the integration of U. Hawaii Seal Level and OceanSites time series. The prototype was efficiently developed using LAS for visualizations and the Google Web Toolkit® (GWT) for interface development. The code for this system was offered to U. Hawaii to speed along their system upgrades.

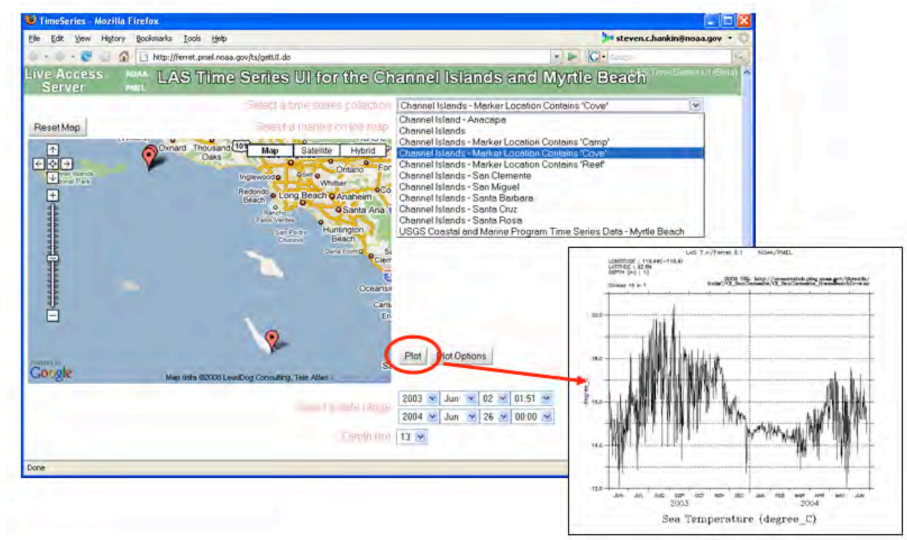


Figure 11. Prototype Web viewer for time series collections.

- A desktop Google Gadget® was created allowing OSMC users to customize their desktops with small OSMC viewers as shown in Figure 12.

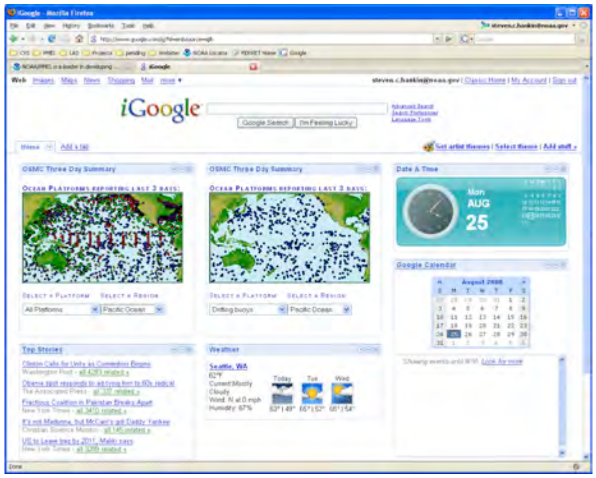


Figure 12. OSMC as a Google Gadget®.

- The following platform types and parameters were added or better differentiated in the LAS viewer
  - IOOS-managed platforms
  - VOSclim
  - Ice buoys
  - Tropical moored buoys
  - Weather buoys
  - Wave Height (new parameter)
  - Ocean CO_2

2.3. NDBC ACCOMPLISHMENTS

- Continued to update the OSMC Oracle database and NetCDF files with data from the following sources:
  - GODAE data files (Met and Profiles)
  - GTS feed from NWSTG (over 4,800 unique GTS headers)
  - WMO Allocation table (Country info)
  - WMO Pub 47 data (meta-data)
  - JCOMOPS WMO Platform Cross-Reference (meta-data)
  - NDBC Platform Data
  - VOS Clim Ships
- During fiscal year 2008 NDBC processed approximately 20 million observation records from the NDBC GTS feed and approximately 20 million more observation records from the GODAE feed. This represents a 17% increase in GODAE observations processed over 2007. (Note direct GTS processing at NDBC started in June 2007 so we could not calculate an annual increase from this feed.)
- During fiscal year 2008 added 3,240 new platforms to the OSMC database, an 11.8% increase.

- Data Enhancements:
  - Started ingesting XBT profile data
  - Ingested the Takahashi carbon data
  - Identified 154 ice buoys
  - Added wave height data
  - Added over 400 Realtime and NWLON Tide Gauges
  - Developed a CREX decoder for ingesting of tide elevation series data
  - Added additional headers (based on the GTS/GODAE comparison) to the GTS feed and started ingesting the data into the OSMC database.
  - Identified and resolved issues related to GODAE synthetic data (i.e. ZSAL).
- Database enhancements:
  - Working with NGDC and PMEL to identify Version 4 schema enhancements which includes the following:
    - Support for platform operational status information
    - Multiple URLs related to a platform
    - Storage of GTS header/type information
    - Storage of Quality Assurance data
    - Sensor/Instrument information
    - Add Program information, so that platform types are not used incorrectly.
    - Address duplicate resolution via an updated view
  - Developed routines to populate the Version 4 schema with a month of data to support the data/database analysis effort
  - Developed data migration scripts for the Version 4 schema
  - Inserted LOCATION parameter records for platforms not reporting parameter values
  - Identified duplicates and devised a set of rules for handling the duplicates along with detailed examples
  - Identified latitude and longitude precision differences between the GODAE (2 positions) and NDBC (3 positions) data feeds. This was impacting the C-MAN locations, which are fixed platforms.
  - Updated dew point difference to dew point temperature for impacted GODAE observations
  - Created new table space for indexes to improve database performance
- OSMC operational environment:
  - Performed OSMC server upgrades and security patches as required
  - Procured a replacement server and disk array to address performance issues.
- Integrated Ocean Observing System (IOOS) Support:
  - Identified IOOS platforms
- Miscellaneous Support:
  - Researched FNMOC QC flags
  - Researched the decoding and storing of GTS message header/type information to assist in future problem resolution.
  - Performed various analysis related to JCOMOPS/OSMC count differences
  - Implemented Webalizer web stats for the OSMC site
  - Coordinated with GODAE when unexpected data outages occurred

- Continued to research observations received on GODAE and not received via GTS. As of September 2008, there were 1,800 platforms that made 99,585 observations that reported on GODAE and not GTS from June 2007 to September 2008. Note: less than 65 of these platforms contained more than 100 observations for the period.
    - Assisted in the development of SQL queries in support of the user interface
- OSMC/DIF Accomplishments
    - Working to serve Sea Surface Temperature obs from OSMC via DIF developed SOS and will complete by 1st week of November 2008.
    - Enhanced contents of OSMC database to identify those observations which "belong" to IOOS.
    - Successfully registered the SOS with Compusult registry and working to ingest metadata into the OSMC database.
    - Provided NGDC with SOS database schema and provided several NDBC samples of the query code.
    - Developed a CREX decoder to ingest more observations into the OSMC database which will be served up into SOS.

2.4. NGDC Accomplishments

Task 1. Map Interfaces / Spatial Queries:
The application of COTS internet mapping tools to OSMC tailed off considerably during FY2008 as the project focused on maps provided by LAS and the NGDC team focused on database performance and design as well as access to OSMC using various standards.

Task 2. Database Performance and Design:
During the first half of the year we developed a number of queries for comparing the GODAE and direct GTS feeds and for identifying and counting observations from hierarchical platform types. These queries were examined using Oracle optimization tools and it was demonstrated that this analysis and subsequent changes to the queries led to significant improvements in database performance.

The OSMC Team as a whole spent a considerable amount of time developing and optimizing a variety of queries against various database designs during the year. The OSMC database design work addressed several major themes. The evolution of the database design is chronicled in the three Appendices 1-3. Appendix 1 shows the design at the beginning of the year (Version 3.0). This design is the basic parameter/value design that has been developed by NGDC throughout the OSMC Project. The main feature was the inclusion of separate observation value and parameter tables which allowed addition of new observation types or parameters to the database without altering the fundamental design.

Appendix 2 shows Version 3.5 of the database design, also referred to as the "location" design because the location was separated from the observation value. This design also included the capability to relate multiple URLs to platforms and to track time periods during which platforms were observing particular parameters.

This design was motivated by the requirement for identifying various kinds of duplicate observations. The systematic understanding and recognition of these duplicates was a major focus of the OSMC Team early in the year. Michelle provided an analysis which included examples of many types of duplicates. After much discussion by the entire team (see Appendix 4 Table) it was concluded that the Version 3.5 design could accommodate all of these duplicate types without additional, duplicate specific tables.

Version 3.5 was populated with several months of data at NDBC as a test to ensure that the queries required for OSMC could be run against the database. These results of these tests were positive. At the same time, new project requirement emerged which necessitated more additions to the design (see discussion of Version 4 below). It was agreed that further implementation work for Version 3.5 would be incorporated into the migration to Version 4 (see Appendix 3).

The next major step for the OSMC database design is reflected in Version 4, which includes sensors, programs, messages, and profiles for the first time. This design has been motivated significantly by detailed input from Derrick about the observing systems and the messages that are the primary source of information for OSMC and about requirements for monitoring details of the performance of the observing system using spatial tools. This design addresses a variety of new requirements:

1. GTS messages / bulletins information
2. Sensors in addition to platforms
3. Spatial queries for XBTs.

Climate Science Markup Language and Other Access Standards:

Our progress on Climate Science Markup Language was affected by delays in hiring a replacement for Nancy Auerbach, who moved to Australia. We now have hired David Neufeld as part of the OSMC project. David comes with extensive experience in geospatial data access and management. His initial focus has been on familiarizing himself with various CSML tools that are being developed by CSML experts at the Natural Environment Research Council and the Reading e-Science Centre in England in Python and Java. We have made progress with the Java version of the CSML tools and have succeeded in using those tools to read gridded data from netCDF files and to present those data as CSML. We have also developed a CSML service for tide gage time series data from the Alaska Tsunami Warning Center. These data are very similar to tide gage data included in OSMC, so that experience helps build our expertise for OSMC datasets. We are working with CO-OPS who will be using this service to ingest these data.

We have also made progress in using the open-source data access tool, Featureserver, with the OSMC database. This tool can be used to access data from a variety of data sources in different formats or in different databases. We have succeeded in accessing Oracle Spatial data sources and now need to customize that work to account for the OSMC Database Design.

IOOS-DIF Access to the OSMC:

NDBC has developed a Sensor Observation Service that is providing data in the IOOS/DIF format using a database design similar to the original OSMC database that existed when NGDC joined the project. We have started work to make it possible to serve those data using the OSMC Database as a data source. This can be done using a set of views that mimic the

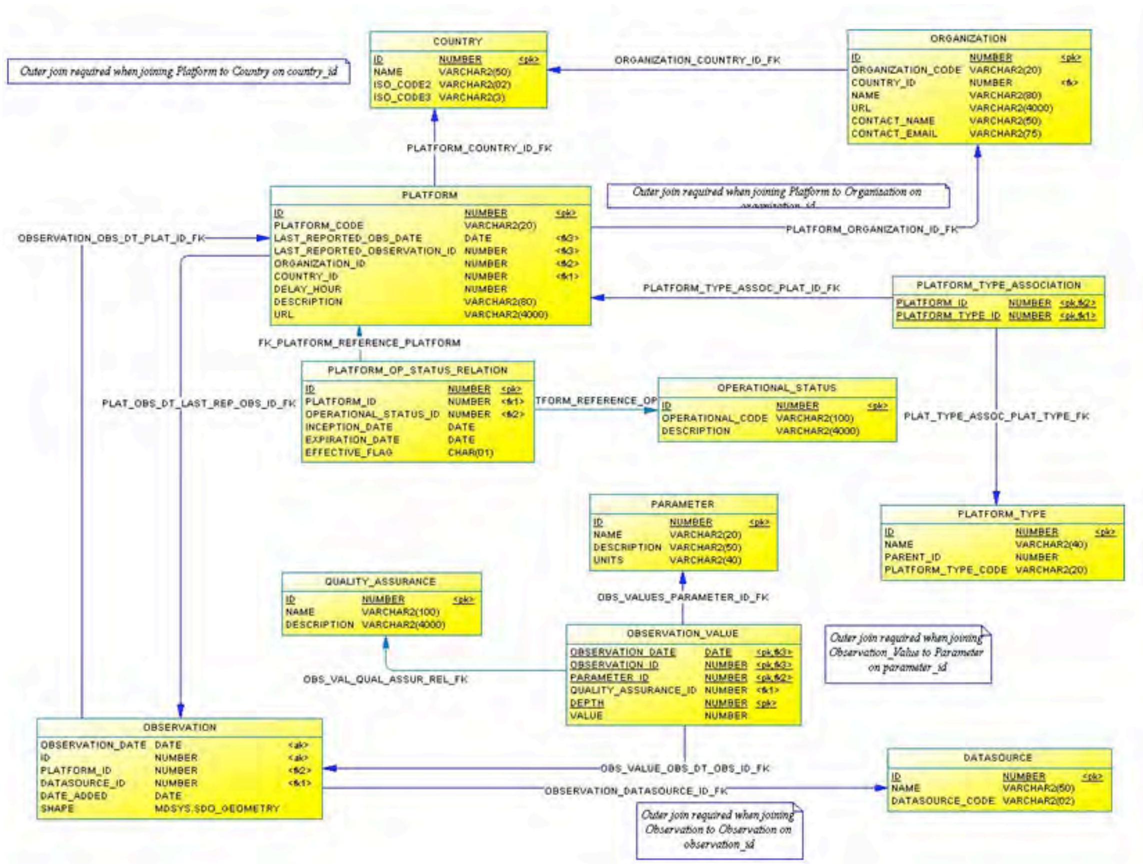
NDBC database design. We have received information from NDBC about their design and the four queries that they use to support the SOS: getCapabilities, describeSensor getObservation, and Bounding Box. We have proposed a view that supports the GetCapabilities request.

Other Tasks and Action Items:

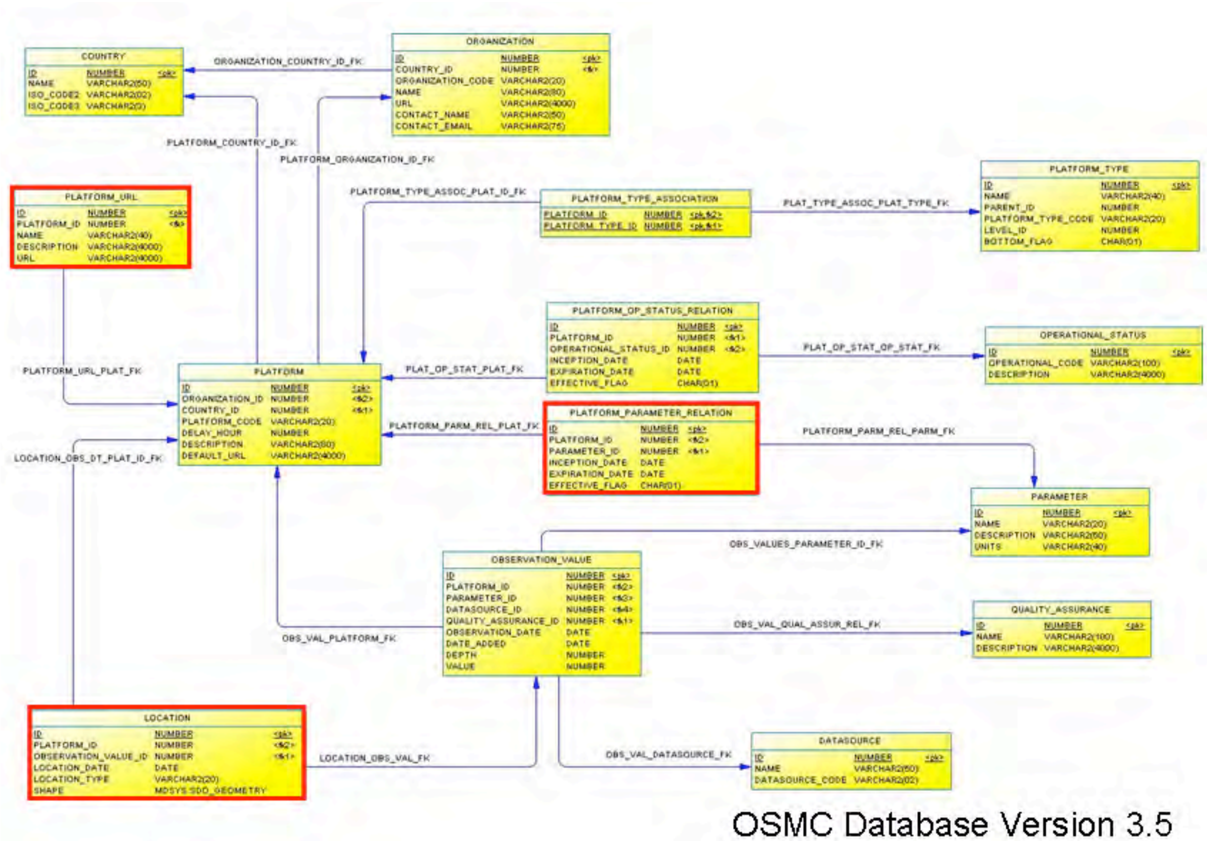
1. Developed Java programs to generate NetCDF observation count summary files using the new database schema. Counts are aggregated by platform type, parameter.
2. Refined the requirements for the XBT reporting facilities. Determined that database changes will be necessary to complete this task and incorporated those changes into Version 4 of the database design.
3. Developed views required to generate IOOS-DIF services for OSMC data.

3. APPENDIX

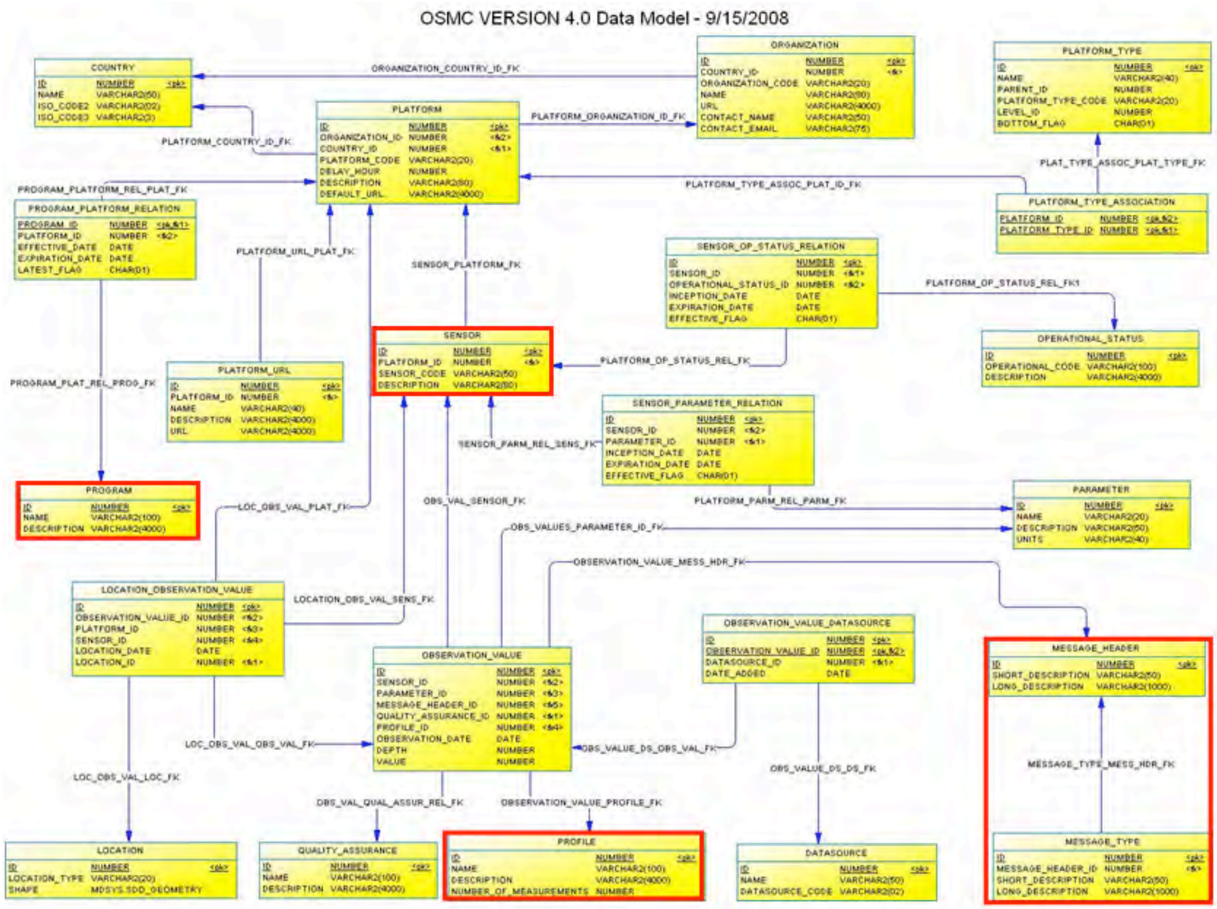
3.1. OSMC Version 3.0 design schematic



3.2. OSMC Version 3.5 design schematic



3.3. SMC Version 4.0 design schematic



3.4. OSMC Design requirement for Version 4.0

Source	Description	Query Strategy
Steve's List from email "Re: OSMC - 'Duplicate' Observations" on 5/22/2008	REPORTS on the same OBSERVATION_EVENT may come from multiple SOURCEs	These are multiple rows in the OBSERVATION_VALUE table with equal PLATFORM_IDs, PARAMETER_IDs. OBSERVATION_DATEs, but different DATASOURCES
Steve's List from email "Re: OSMC - 'Duplicate' Observations" on 5/22/2008	REPORTS on the same OBSERVATION_EVENT may come at multiple delivery times (DATE_ADDED?) from the same SOURCE	This one is pretty similar to the last, but the DATE_ADDED is different and the DATASOURCE is the same
Steve's List from email "Re: OSMC - 'Duplicate' Observations" on 5/22/2008	REPORTS on the same OBSERVATION_EVENT may differ in the list of PARAMETERS they contain	Not sure I would call this a duplicate. It is more like an OBSERVATION_VALUE that gets added to a set of OBSERVATION_VALUES in an OBSERVATION.
Steve's List from email "Re: OSMC - 'Duplicate' Observations" on 5/22/2008	REPORTS on the same OBSERVATION_EVENT may differ in the VALUES of the PARAMETERS they contain	These are observations that do not agree: multiple OBSERVATION_VALUES for the same PARAMETER, PLATFORM, DATASOURCE (?).
Steve's List from email "Re: OSMC - 'Duplicate' Observations" on 5/22/2008	REPORTS on the same OBSERVATION_EVENT may differ in LAT/LONG (SHAPE) they contain	Multiple LOCATIONS with the same OBSERVATION_VALUE_ID
Michelle's Cases from the "Duplicate Report" of May 12, 2008	UNION	This case represents the same OBSERVATION_VALUES reported at two times. My inclination would be to reject the later OBSERVATION_VALUES in this case. If we keep them they could be found by the different DATE_ADDED values.
Michelle's Cases from the "Duplicate Report" of May 12, 2008	BEST_UNION	These are two OBSERVATION_VALUES from the same platform and time but for two different parameters at two different locations. The LOCATION_DATE and PLATFORM_ID fields in the LOCATION table allow us to describe this and to find how many occurrences we have of the same platform being at two locations at the same time.
Michelle's Cases from the "Duplicate Report" of May 12, 2008	CONFLICT_UNION	In this case we have two datasources reporting different parameters for the same platform and time, but at different locations.
Michelle's Cases from the "Duplicate Report" of May 12, 2008	BEST	Same OBSERVATION_VALUE from two datasources at different locations.
Michelle's Cases from the "Duplicate Report" of May 12, 2008	BEST	Same/different OBSERVATION_VALUEs from two datasources at different locations.
Michelle's Cases from the "Duplicate Report" of May 12, 2008	CONFLICT	Different LOCATIONS for different datasources.

3.5. Acronyms

ArcIMS	Arc Internet Map Server
DDL	Data Definition Language
ESRI	Environmental Systems Research Institute
FTE	Full Time Equivalent
FY	Fiscal Year
GEO-IDE	NOAA's Global Earth Observation Integrated Data Environment
GIS	Geographic Information Systems
GODAE	Global Ocean Data Assimilation Experiment
JCOMMOPS	Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology Observing Platform Support
LAS	Live Access Server
NDBC	National Data Buoy Center
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
MS	Microsoft
OCO	Office of Climate Observations
OSMC	Observing Systems Monitoring Center
PMEL	Pacific Marine Environmental Laboratory
PP&I	Program, Planning & Integration
SDE	Spatial Database Engine
WMS	Web Map Service
WFS	Web Feature Service

OceanSITES:
Global Data Assembly Center

Bill Burnett
NOAA National Data Buoy Center, Stennis Space Center MS

1. INTRODUCTION

OceanSITES is the international project working towards the coordination and implementation of a global system of sustained multi-disciplinary timeseries observatories. Timeseries fill a unique gap in the sampling provided by other elements of the global ocean observing system, enabling co-located observations of many variables and processes in strategic or representative locations over long periods of time, with high temporal resolution, from (and including) the ocean surface to the seafloor.

The scientific applications of such data are to monitor, detect, understand, and predict changes and related processes in the physical climate state of the ocean, the carbon cycle, and the ecosystem. Operational applications include detection of events, initialization and validation of assimilation products, delivery of constraints or reference data for forecasts (especially biogeochemical and ecosystem relevant ones). In addition there are a variety of technical applications, such as calibration and validation of data and products from other observing system elements.

OceanSITES, through its international steering team, has developed a rationale for timeseries observations and for needing a coordinated global network, and has defined a pilot project consistent with the needs and expectations of the sponsoring bodies GOOS, CLIVAR, and POGO. A major requirement for sites in the project is an open data policy. A global timeseries data management system is under construction via a subgroup of the OceanSITES steering team, including a data format coherent with other past and present efforts.

The in situ, time series-based OceanSITES program represents the logical next step in completing the Global Ocean Observing System. As such, the program now is an official component of the global system organized under JCOMM, and is also one of its action groups under DBCP. Much of the technology is available and many elements are in place already. The main challenge is coordination and assuring sustainability of the system, via common advocacy, recruiting a user base, and sharing the operation among communities and countries.

1.1. National Data Buoy Center (NDBC) GDAC Status

Starting in 2000, NDBC began obtaining and distributing observations from “partners.” These partners are designated as U.S. Integrated Ocean Observing System (IOOS) data providers. NDBC receives these marine meteorological, oceanographic (physical) and water quality observations in real-time, quality controls the observations and distributes the data via the Global Telecommunications System (GTS)/web services. NDBC also serves as the Data Assembly Center (DAC) for the Tropical Atmosphere Ocean (TAO) Pacific array and the tsunameter array which covers the Pacific, Atlantic and Gulf of Mexico. NDBC also quality controls and maintains data from 60 oil and gas platforms located in the Gulf of Mexico. Thus, NDBC is well suited to serve as a Global Data Assembly Center (GDAC) for OceanSITES, as well as an OceanSITES DAC.

NDBC supports these ~700 platforms by collecting, quality controlling and disseminating the observations in real-time and in delayed mode. Using the NDBC Observing System Monitoring Center (OSMC), OPeNDAP servers and ftp site – NDBC will act as a DAC for physical observations (marine weather and oceanographic – and possibly for biogeochemical variables) for a number of PIs in the United States. NDBC will also serve as the second OceanSITES GDAC and synchronize their OceanSITES files with Coriolis. NDBC proposed a form, similar to the form used to maintain the metadata from the 60 oil and gas platforms, to help maintain all the OceanSITES platforms.

1.2. Tasks proposed

This document describes three tasks in support of OceanSITES, enabling rapid and efficient progress on the data management, quality control, and data dissemination, as well as initiating work towards the generation of products and indicators resulting from this global timeseries network.

2. PROGRESS

The following milestones track the progress made on OceanSITES during fiscal year 2008.

Establishment of an OceanSITES GDAC at NDBC

Overview

The international CLIVAR/GOOS/JCOMM sponsors a coordination project called OceanSITES, a global network of ocean timeseries (or reference) sites located around the world's oceans. The NOAA/NDBC Integrated Ocean Observing System Data Assembly Center (IOOS DAC) and OceanSITES have agreed to make the NDBC IOOS DAC a Global DAC (GDAC), providing a shared and more secure capability together with the Ifremer/Coriolis GDAC in France. These GDACs will provide quality assurance/quality control, provide virtual access to the data, maintain a global timeseries dataset and synchronize catalogues on a periodic basis. The definition and structure of the data system is shown below.

Today NDBC is meeting the U.S. NWS's need for data in the marine environment by assembling and quality checking data from other U.S. government agencies, academia and industry as part of the U.S. Integrated Ocean Observing System (IOOS), a component of the Global Ocean Observing System (GOOS) and the Global Earth Observation System of Systems (GEOSS). The NDBC IOOS DAC is already providing real-time quality control of observations from Woods Hole OceanSites platforms, http://www.ndbc.noaa.gov/station_page.php?station=32st0, as well as operating the Tropical Ocean Atmosphere (TAO) Data Assembly Center. The NDBC IOOS DAC website provides a one-stop shop for real-time and delayed mode, quality controlled observations for 160 NDBC platforms, 190 NOS water level stations, 220 partner platforms, 55 TAO buoys, 25 NERRS water quality stations and 39 DART tsunami stations.

3. 2008 NDBC ACCOMPLISHMENTS

- **Coordination**: NDBC coordinated with Coriolis personnel to define equipment, hardware, software and telecommunication requirements for the secondary GDAC.
  - Attended the OceanSITES Data Management Team Meeting and the Science Team Meeting in Vienna, Austria - April, 2008.
    - Briefed NDBC's Data Assembly Center and contribution to the Integrated Ocean Observing System (IOOS).
    - Proposed alternative method towards disseminating OceanSITES observations (via OPeNDAP vice FTP).
    - Proposed new metadata sheet (derived from Gulf of Mexico Oil and Gas platform metadata sheet) to be used as the metadata sheet that validates all OceanSITES platforms.
    - Collaborated with Coriolis and other Data Management Members on the format for data distribution.
    - Updated the OceanSITES Users Manual.
  - Coordinated teleconference calls with Coriolis to discuss OceanSITES data management team structure and dissemination of OceanSITES data.
  - Numerous e-mails with Coriolis and Data Management Team personnel on format and dissemination of OceanSITES data.
  - Obtained primary server for the OceanSITES data files.
  - Defined communication requirements to share OceanSITES data with other GDAC on a daily basis.
  - Proposed and agreed to method for sharing files with Coriolis.
  - Worked with Coriolis and SIO to update the DAC format checker.
  - Wrote and edited the 2008 Data Management Team Report

- **Quality Control:** NDBC IOOS DAC continued to integrate additional OceanSITES into their IOOS infrastructure. Observations approved by the Principle Investigator (PI) were released through to the GTS and made available via the OceanSITES ftp server and OPeNDAP server.
  - Developed a local OceanSITES "server" according to specifications approved by the data management group
  - Serves as the DAC for the four Woods Hole Stations
  - Serves as the DAC for the four TAO flux sites
  - Serves as the DAC for the two Scripps sites – and possibly more if wave observations are included.

- **Observing System Monitoring Center (OSMC):** NDBC coordinated efforts with the OSMC project to ensure that the OSMC provides OceanSITES observations and leverages the OPeNDAP/DODS services developed through the OSMC framework.

NDBC will additionally provide all OceanSITES observations through their OPeNDAP server in the approved OceanSITES netCDF formats.

- Continued to update the OSMC Oracle database and NetCDF files with data from the following sources:
  - GODAE data files (Met and Profiles)
  - GTS feed from NWSTG (over 4,800 unique GTS headers)
  - JCOMOPS WMO Platform Cross-Reference (meta-data)
  - NDBC Platform Data
- Worked with Coriolis and SIO to identify enhancements which includes the following:
  - Support for OceanSITES platform operational status information
  - Multiple URLs related to a platform
  - Storage of GTS header/type information
  - Storage of Quality Assurance data
  - Sensor/Instrument information
  - Add Program information, so that platform types are not used incorrectly
  - Address duplicate resolution via an updated view

- **Standardization:** FTP servers at NDBC and Coriolis are online and synchronize available data daily. This data is available from both NDBC and Coriolis. Both GDAC's will develop similar portals to implement viewing services for the global timeseries datasets.
  - Implemented new schema to conduct daily checks with Coriolis GDAC server to update new GDAC observations and format information.
  - Began replicating OceanSITES platforms with Coriolis (GDAC to GDAC) in July 2008 – via ftp//data.ndbc.noaa.gov/data/oceansites and ftp://ftp.ifremer.fr/ifremer/oceansites
  - Finalized the OceanSITES Global Data Assembly Center form for collecting and maintaining information for OceanSITES data access and data distribution in October 2008.
  - Working with primary OceanSITES PIs to begin updating the metadata forms and will post information on OceanSITES website.

U.S. Research Vessel Surface Meteorology Data Assembly Center

Shawn R. Smith, Mark A. Bourassa and Eric Chassignet
Center for Ocean-Atmospheric Prediction Studies, The Florida State University, Tallahassee FL

1. PROJECT SUMMARY

The central activity of the U.S. Research Vessel Surface Meteorology Data Assembly Center (DAC) is the continued development of the Shipboard Automated Meteorological and Oceanographic System (SAMOS) initiative (http://samos.coaps.fsu.edu/). The SAMOS initiative focuses on improving the quality of and access to surface marine meteorological and oceanographic data collected *in-situ* by automated instrumentation on research vessels and ships of opportunity. The DAC activities focus primarily on NOAA Strategic Plan Goals 2 and 3 by providing high quality weather and near surface ocean data for use in validating satellite products, global air-sea flux analyses, and model fields. Research vessels are mobile observing platforms that are an essential component of the global ocean observing system. These vessels travel to remote and hard to observe ocean locations that are far from normal shipping lanes.

The rationale for this activity centers on the desire to understand the physical and thermodynamic interaction between the ocean and atmosphere. This interaction is key to our understanding of how marine weather systems evolve, how these systems impact the ocean, and how the oceans impact the weather. On longer time scales, understanding the interaction between the ocean and atmosphere is necessary to assess our changing global climate system. The role of the DAC is providing the high quality marine meteorological and surface ocean measurements to the research and operational community so that they can address these ocean-atmospheric interactions. High quality observations are essential to our scientific understanding of the ocean-atmosphere interactions.

The DAC was established at the Florida State University specifically to coordinate the collection, quality evaluation, distribution, and future archival of SAMOS data. SAMOS are typically a computerized data logging system that continuously records navigation (ship's position, course, speed, and heading), meteorological (winds, air temperature, pressure, moisture, rainfall, and radiation), and near ocean surface (sea temperature and salinity) parameters while a vessel is at sea. Measurements are recorded at high-temporal sampling rates (typically 1 minute or less). The DAC collaborated with the Woods Hole Oceanographic Institution (WHOI) to design a ship-to-shore-to-user data pathway for U.S. research vessel SAMOS data. In the past, the data flowed from ship to shore only in a delayed-mode with a 3 month to 2-year lag between collection and availability to the user community. The new data pathway supports automated data transmission from each ship to the DAC on a daily basis. A "preliminary" version of the SAMOS data are available on-line within 5 minutes of receipt by the DAC. The preliminary data undergo common formatting, metadata enhancement, and automated quality control. Visual inspection and further scientific quality control result in a "research" quality SAMOS product that are nominally distributed with a delay of 10 days from the original data collection date. All quality-evaluated research vessel data from the SAMOS initiative and past DAC programs are freely available to the user community (http://www.coaps.fsu.edu/RVSMDC/html/data.shtml), and we continue to work with several world data center archives (e.g., National Oceanographic Data Center, National Center for Atmospheric Research) to ensure long term stewardship of these data.

2. ACCOMPLISHMENTS

Over the past year, our efforts have focused on the continued development of the SAMOS Initiative. In collaboration with partners at NOAA's Office of Marine and Aviation Operations (OMAO), Raytheon Polar Services (RPS), and the United States Coast Guard (USCG), the number of vessels participating in SAMOS has increased from 12 to 17. We continue to actively recruit new vessels to participate in the SAMOS initiative. Data from all 17 vessels are routinely pushed through our automated (preliminary) data quality evaluation (DQE). In the past year our research quality processing (including visual DQE) has been operationally applied, but a backlog of SAMOS data still needs to complete the research processing. Many upgrades have been made to both our public access web site and our internal data base tools. Throughout the year, DAC personnel have been actively promoting the SAMOS Initiative at both national and international meetings.

Deliverables for FY 2008 included:

1. Continue routine quality evaluation of meteorological data for 12 SAMOS vessels currently contributing to the DAC
2. Recruit additional research vessels to the SAMOS initiative (focus will be on NOAA and UNOLS vessels)
3. Improve and enhance metadata collection from participating research vessels
4. Implement additional data quality evaluation techniques.
5. Create and distribute turbulent air-sea fluxes for vessels contributing to SAMOS
    - Subtask1: Compare SAMOS fluxes with available NWP products
6. Continue liaison activities with U.S. and international government agencies, archives, climate programs
    - Subtask1: Establish data exchange with GOSUD
    - Subtask2: Implement data exchange with NODC and NCAR archives
    - Subtask3: Produce subset of SAMOS observations for ICOADS
7. Expand user options on the SAMOS web site to ease user access to observations and metadata

The following accomplishments address the deliverables. Also noted are impediments to achieving the deliverables.

2.1. Vessel recruitment [Deliverable 2]

Recruitment of additional vessels to participate in the SAMOS Initiative was very successful during the reporting period. Five new vessels were recruited (Table 1) in the past year. These vessels now routinely contribute SAMOS observations when they are at sea. Collaboration with NOAA OMAO resulted in four new recruitments. The *Oceanus*, operated by WHOI, is the first UNOLS vessel to be recruited since 1995. We also have been in communication with Eric Schulz from the Australian Bureau of Meteorology to recruit two Australian RVs. A data exchange framework is in place that will involve the Australian Bureau sending their meteorological data to the DAC in SAMOS format netCDF files. We will conduct automated QC of these files and will distribute them with other SAMOS data. Visual QC will only be done in Australia and we are working to establish a protocol to distribute their visually inspected data.

In addition, Co-PI Smith and Jeremy Rolph (our data quality analyst) attended the annual UNOLS RVTEC meeting November 2007 and participated in the 2nd Joint GOSUD/SAMOS workshop. These (and other) workshops provided and opportunity to recruit additional vessel operators. Most expressed interest in participating in SAMOS and have made verbal commitments, but initiating new data transfers is still difficult in these times of tight operational budgets for research vessels. Flat funding at the SAMOS DAC has also limited our ability to further increase the number of vessels contributing data to the DAC.

Table 1. Ships transmitting observations to SAMOS DAC during FY 2007 and FY 2008.

		Number of ship days with data	
Vessel	Operator	1/10/2006 – 30/9/2007	1/10/2007 – 30/9/2008
Atlantis	WHOI	291	294
David Star Jordan	NOAA		88
Fairweather	NOAA		79
Gordon Gunter	NOAA	4	44
Healy	USCG	62	162
Henry Bigelow	NOAA	70	139
Hi'ialakai	NOAA	107	196
Ka'imimoana	NOAA	61	197
Knorr	WHOI	252	305
Lawrence Gould	NSF/Raytheon	32	260
Miller Freeman	NOAA	190	187
Nancy Foster	NOAA	122	179
Oceanus	WHOI		115
Oregon	NOAA		84
Oscar Dyson	NOAA	170	211
Rainier	NOAA		107
Ronald Brown	NOAA	149	151
		1510	2798

2.2. Daily SAMOS data processing [Deliverable 1]

Preliminary processing of SAMOS observations received via daily email messages from participating research vessels is an ongoing operational activity at the DAC. During FY 2008, 2798 days of shipboard meteorology data were processed for the 17 recruited vessels (see Table 1). Preliminary processing (Figure 1) starts once the data file arrives at the DAC as an attachment to an email. Each email attachment is unpacked, the data provided are verified that they conform to the format and parameters expected for the individual vessel, and finally the data are blended with vessel specific metadata and are converted to a common netCDF format. The data for each day are then passed through an automated quality evaluation program and data quality statistics are calculated prior to the file being posted for users on the SAMOS web and ftp sites. The entire process from arrival at the DAC to distribution of the preliminary data files is fully automated. Preliminary files appear on the data distribution site within 5 minutes of their arrival at the DAC (typically shortly after 0000 UTC).

A comparison of the spatial distribution of data received, processed, and on-line for FY 2007 and FY 2008 is shown in Figure 2. The addition of 5 ships and more complete data from the 12 recruited in the previous year resulted in over 1200 more ship days of data than in FY 2007. We continue to track all stages of the quality processing of the ship data in the SAMOS SQL database and quality statistics are accessible via the SAMOS web site (http://samos.coaps.fsu.edu/html/data_availability.php).

2.3. Delayed-mode SAMOS processing [Deliverables 1 and 4]

Due to data logging problems on the ship or communication dropouts, some data arrive several days after they were collected. Often the data are noted to be missing by the analyst at the DAC and arrive after the analyst notifies the vessel technician at sea. In addition, data for a single day may be fragmented and may arrive in multiple files attached to a single email. As a result, the DAC developed a method to merge multiple files for a single observing day into a combined, delayed-mode data file. This merged file undergoes additional automated (e.g., duplicate removal) and visual data quality evaluation and is then released as a "research-quality" SAMOS data file for the particular observation day (Figure 1).

Currently the merge occurs 10 calendar days after the observation day (when the preliminary data should arrive at the DAC). Nominally, the data quality analyst at COAPS reviews the latest merged files and conducts a visual quality evaluation on a daily basis. The visual analysis is accomplished using SVIDAT, a graphical user interface developed by COAPS programmers. SVIDAT allows the analyst to review, add, or modify data quality flags on the merged files. Once the analyst is satisfied with the data quality, the file is saved and posted automatically to the SAMOS ftp and web sites. This process also updates all necessary tracking information in the ship database and creates the copies of the original, preliminary, and research quality files for delivery to the national archive centers.

The rapid increase in data volume flowing through the SAMOS DAC (over 1200 more ship days of data in FY 2008; Table 1) has overwhelmed the ability of our visual analyst to keep up with the delayed-mode visual inspection. The analyst has been working forward from September 2007 to complete the delayed-mode inspection and prepare the data for final archival at NODC. The number of ship days of data ready for archival are shown in Table 2. Comparing to Table 1, one can see that there are nearly 2000 more days to evaluate for 2008 (and new data arrives each day). Through separate funding at COAPS, we hired a temporary data analyst to help with this backlog; however, we anticipate that this will be sufficient to clear the backlog. Support for this analyst is temporary and without additional funding, this analyst will not be retained. Designing methods to streamline the QC system to further reduce visual inspection will be a priority for FY 2009. A new statistical technique for delayed-mode QC is currently under development.

2.4. Metadata enhancement [Deliverable 3]

The SAMOS DAC continues to work to improve access to the metadata (e.g., instrument heights, sensor locations, averaging methods, etc.) necessary for scientific application of these observations. This continues to be a struggle. It is easier to get the SAMOS data from recruited vessels, but some critical metadata is lacking. We have implemented a web-based metadata interface that allows the SAMOS data providers to update their metadata via a secure login for each operator and ship. We have provided demonstrations of this interface at RVTEC and the 2nd GOSUD/SAMOS workshop. Feedback from users has still been limited and we will continue to push forward with training on this interface.

Table 2. Data completing research quality processing at the SAMOS DAC and ready for archival at NODC for FY2007 and FY2008.

		Number of ship days ready for archival	
Vessel	Operator	1/10/2006 – 30/9/2007	1/10/2007 – 30/9/2008
Atlantis	WHOI	92	120
David Star Jordan	NOAA		4
Fairweather	NOAA		5
Gordon Gunter	NOAA		
Healy	USCG	30	6
Henry Bigelow	NOAA	9	34
Hi'ialakai	NOAA	23	49
Ka'imimoana	NOAA	11	77
Knorr	WHOI	29	129
Lawrence Gould	NSF/Raytheon		29
Miller Freeman	NOAA	28	71
Nancy Foster	NOAA	21	54
Oceanus	WHOI		
Oregon	NOAA		
Oscar Dyson	NOAA	27	59
Rainier	NOAA		2
Ronald Brown	NOAA	15	90
		285	729

Another new feature is date stamping all metadata within the SAMOS ship profile database. This allows metadata changes to be tracked and will ensure that the proper metadata is assigned to the SAMOS data files (even in the event of reprocessing earlier data to include late arriving reports).

The issue of metadata collection and access is a broad problem. Mr. Smith continues to serve on the Data Management Best Practices Subcommittee of the UNOLS council. The committee is reviewing data management practices (including metadata) for the UNOLS fleet and has developed a framework for required cruise level metadata from each vessel for each cruise. Adoption of this framework is still pending in the UNOLS council, but once it is accepted, the DAC will work with UNOLS to share cruise level metadata for all SAMOS vessels. Metadata related to specific instruments is even more of a challenge; so one outcome of the 2nd Joint GOSUD/SAMOS workshop was to establish a SAMOS task team to define an automated method to transfer instrument metadata from ship to shore on a regular schedule. This task team will be organized and will begin their work in late 2008. The team will consider the practical needs of vessel operators and the larger marine metadata initiatives of JCOMM, etc.

2.5. Liaison activities [Deliverable 6]

The SAMOS DAC serves as the project office for the entire SAMOS initiative. In this capacity, DAC personnel facilitate U.S. and international collaborations on topics ranging from data accuracy, data acquisition and exchange, training activities, and data archival. Major meetings include Ocean Sciences (March 2008) and CLIMAR-III (May 2008). We have forged new partnerships within the metadata community (NSF Legacy workshop, Sept. 2008), educators of marine technicians through the Marine Advanced Technology Education (MATE) center (MATE partner meeting, August 2008), and the coastal observing community (Northern Gulf Institute Meeting, May 2008).

Foremost of the liaison activities was convening the 2nd Joint GOSUD/SAMOS workshop in Seattle, Washington from 10-12 June 2008. This meeting was supported via additional OCO funding separate from our base support. UCAR JOSS arranged and the United States Coast Guard hosted the meeting. The workshop organizing committee (Shawn Smith, Mark Bourassa, Loic Petit de la Villéon, David Forcucci, and Phillip McGillivary) brought together a panel consisting of operational and research scientists, educators, marine technicians, and private sector and government representatives. Broad topic areas included new opportunities for international collaboration, emerging technologies, scientific application of underway measurements, and data and metadata issues. New sessions included a technician's round-table discussion and developing educational initiatives. Scientific discussion centered around the need for high-quality meteorological and thermosalinograph observations to support satellite calibration and validation, ocean data assimilation, polar studies, air-sea flux estimation, and improving analyses of precipitation, carbon, and radiation. Determining the regions of the ocean and observational parameters necessary to achieve operational and research objectives requires input by the scientific user community (e.g., via CLIVAR). This input will allow SAMOS and GOSUD to target their limited resources on vessels operating in the high priority regions. The vessel operators and marine technicians were very supportive of the activities of SAMOS and GOSUD. They requested a clear set of guidelines for parameters to measure, routine monitoring activities, and calibration schedules. The operators also desire additional routine feedback on data flow and data quality. A clear need for educational materials was noted by the technical community. The dissemination of best practices guides for existing techs and pre-cruise training for new techs were suggested. The result of the workshop was a series of action items and ten recommendations. The resulting action items will help address subtask 1 (initiating an exchange between GOSUD and SAMOS). The full workshop report, objectives, agenda, poster and oral presentations, and list of participants are available at http://www.coaps.fsu.edu/RVSMDC/marine_workshop4/.

2.6. Data archival [Deliverable 6, subtask 2]

Chris Paver from NODC visited COAPS in late August 2008 to learn about the SAMOS QC procedures and to establish an archival agreement with NODC. The meeting resulted in COAPS and NODC drafting a submission agreement that will guide the routine transmission of SAMOS data to NODC. Using an rsync protocol, NODC will be able to routinely receive a full set of SAMOS data for each participating vessel. The protocol ensures that a complete archive set for each ship will be provided to NODC once a full month of data has completed research quality QC at COAPS. The full archive set will include:

- the original ASCII formatted data from the vessel (as received via email)
- both preliminary and research quality controlled SAMOS netCDF files
- a file map showing the relationship between the original and netCDF files
- a variable map linking the original variable names (from the provider) to the variable names used in the netCDF file (operationally this is stored in our SQL database)
- documentation (readme, file naming, file format, and processing procedures)
- md5 check sum file

NODC will know the month of data is complete and ready for archival (and assignment of an NODC accession number) once the MD5 check sum file is available. The interval between updates for a given ship will nominally be monthly, once the backlog of research quality data is completed (see above). We are also exploring NODC providing off-site backup of all critical SAMOS codes and data in the event of a catastrophic event (fire, hurricane, etc.).

2.7. Data Distribution [Deliverable 7]

All near real-time (quick) and delayed-mode (research) data are available via the web (http://samos.coaps.fsu.edu/, under "Data Access") and ftp (samos.coaps.fsu.edu, anonymous access, cd /samos_pub/data/) sites. The SAMOS web site also includes an overview of the initiative, provides links to relevant literature and best practices guides, and access to past SAMOS workshops. The DAC provides access to the preliminary quality controlled data for all 17 ships currently recruited to the SAMOS initiative, and access to research quality data from September 2007 – February 2008 is new in FY 2008. A searchable metadata portal allows users to access ship- and parameter-specific metadata. An improved interface for digital photos and schematics of participating vessels is now available which includes pop-up descriptors of each graphic. The web site also provides access to recruitment materials for vessels, desired SAMOS parameters, accuracy requirements, and training materials.

The data distribution system is under constant development. A major new feature developed in FY 2008 is a user interface that allows selection by ship(s) and dates to create cruise track maps on Google Earth (http://samos.coaps.fsu.edu/html/ship_tracker.php). The cruise tracks are plotted by accessing data for each ship that has been sub-sampled at an hourly interval (from the original one-minute interval) and stored in the SAMOS SQL database. Currently the sub-sample is the one-minute value at the top of each hour, but this will be changed to a 10-minute average to support the ICOADS project sometime in FY 2009 (Deliverable 6, subtask 3). The track map provides cruise lines that are automatically color coded by ship. The mapping tool allows zoom and swapping from a satellite to a hybrid map available from Google Earth. Examples of the maps are shown in figure 2.

At present, none of the SAMOS data are distributed in real-time via the Global Telecommunications System (GTS). The primary reasons are based on cost and the desire to ensure that the SAMOS data can fulfill their primary goal as an independent validation source for models and satellite products. Over the past year, there has been growing interest (expressed at CLIMAR-III and the 2nd Joint GOSUD/SAMOS workshop) to place a subset of the SAMOS observations on the GTS (even in delayed mode). The DAC is exploring this option, but the practicalities of ensuring that a SAMOS report can be distinguished from a regular Voluntary Observing Ship report from the same vessel need to be carefully explored. A modeling center should be able to differentiate a quality-controlled SAMOS report collected using research quality sensors from the manual bridge observation for that vessel (and differentiate the metadata from both). Current GTS formats are not well suited to this task. A dialog has been implemented with the U. S. VOS coordinator, the SOT from JCOMM, and the ICOADS project to determine the best approach to placing SAMOS data on the GTS. A series of "masked" call signs is being considered by SOT for SAMOS (G. Ball, personal communication, 2008). The other reality is that placing SAMOS data on the GTS will require additional programming at the DAC to place data in the desired format (BUFR or SHIP), coordination with JCOMM-OPS to build the masked call sign list, and careful coordination with WMO concerning metadata issues. These all will take additional resources that are not available under our proposed flat budget.

2.8. Deliverable 5 pushed forward to FY 2008

Difficulties in obtaining the necessary metadata to accurately compute the turbulent fluxes and the backlog of data needing research quality QC have slowed progress on this task. We are making progress in both areas and anticipate preliminary flux work to begin in FY 2009.

3. FIGURES AND IMAGES

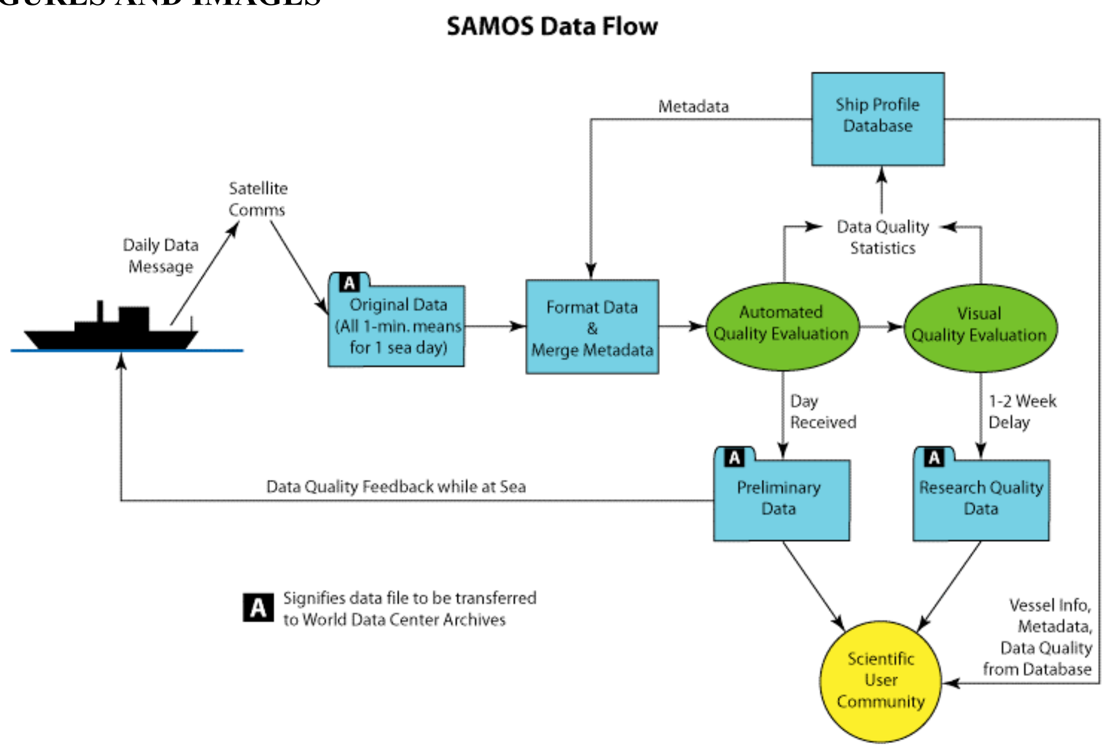


Figure 1. Operational data flow between research vessels at sea and the SAMOS DAC. Data transfers take advantage of 24/7 broadband satellite communications. Real-time data quality feedback to vessels at sea and their home institutions have proven successful to reduce the amount of poor quality data caused by sensor failures.

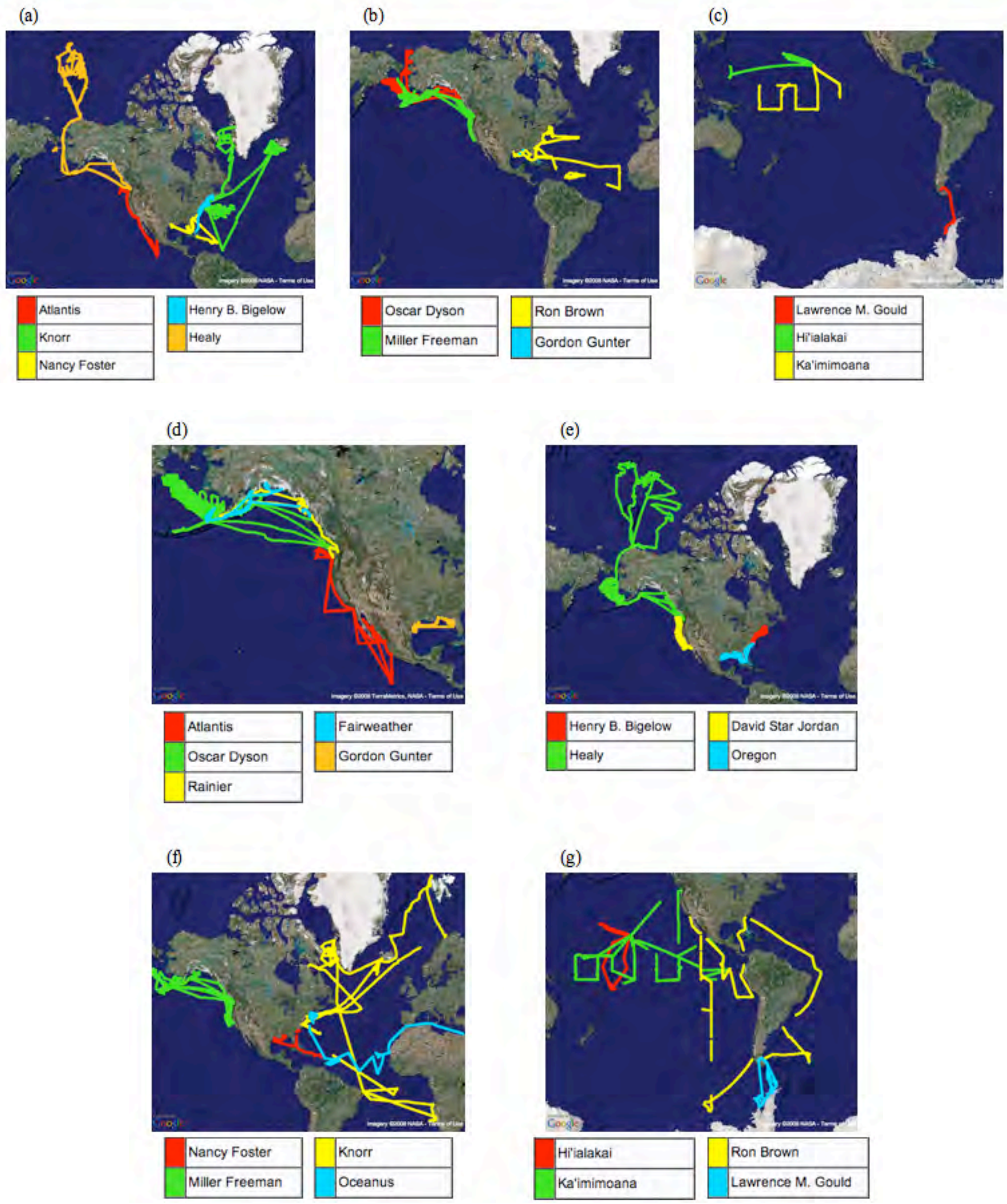


Figure 2. Cruise tracks comparing SAMOS data coverage for FY 2007 (a, b, and c) and FY 2008 (d, e, f, and g). The maps are created using Google Earth maps through an on-line application developed by the DAC. Any user can draw cruise maps for any available SAMOS data using the tool at: http://samos.coaps.fsu.edu/html/ship_tracker.php.

4. PUBLICATIONS AND REPORTS

4.1. Technical reports

Smith, S. R., and L. Petit de la Villeon, 2008: Report of the 2nd Joint GOSUD/SAMOS Workshop. Center for Ocean-Atmospheric Prediction Studies, Florida State University, 71 pp. [Available from COAPS, The Florida State University, Tallahassee, FL 32306-2840].

4.2. Conference proceedings/presentations

Smith, S. R., and J. Rolph, 2008: SAMOS Metadata: Architecture and Lessons Learned. Presentation, *NSF Legacy of Ocean Exploration Project Data Management Meeting*, LDEO, Palisades, NY, 3-5 September 2008.

Smith, S. R., G. Goni, L. Petit de la Villeon, and M. A. Bourassa, 2008: Sustained underway oceanic and atmospheric measurements from ships: A multi-user component of the ocean observing system. Short Abstract, *NOAA Climate Observation Division 6th Annual System Review*, Silver Spring, MD, 3-5 September 2008.

Smith, S. R., J. Rolph, and M. A. Bourassa, 2008: Activities of the Shipboard Automated Meteorological and Oceanographic System (SAMOS) Initiative Data Assembly Center. Short Abstract, *NOAA Climate Observation Division 6th Annual System Review*, Silver Spring, MD, 3-5 September 2008.

Smith, S. R., 2008: Obtaining quality data from an ocean observing system. Presentation, *2008 Marine Advanced Technology Education Partner Meeting*, Key West, FL, 11-13 August 2008.

Rolph, J., S. R. Smith, and M. A. Bourassa, 2008: Quality evaluation of marine meteorological observations. Short Abstract, *2nd Joint GOSUD/SAMOS Workshop*, Seattle, WA, 10-12 June 2008.

Smith, S. R., M. A. Bourassa, and J. R. Rolph, 2008: Data flow through the Shipboard Automated Meteorological and Oceanographic Systems (SAMOS) Data Assembly Center. Short Abstract, *2nd Joint GOSUD/SAMOS Workshop*, Seattle, WA, 10-12 June 2008.

Rolph, J., S. R. Smith, and M. A. Bourassa, 2008: Quality evaluation of marine meteorological observations. Short Abstract, *2008 Northern Gulf Institute Annual Conference*, Biloxi, MS, 13-14 May 2008.

Smith, S. R., M. A. Bourassa, and J. R. Rolph, 2008: The Shipboard Automated Meteorological and Oceanographic Systems (SAMOS) Initiative. Short Abstract, *Third JCOMM Workshop on Advances in Marine Climatology (CLIMAR-III)*, Gdynia, Poland, 6-9 May 2008.

Smith, S. R., M. A. Bourassa, S. D. Woodruff, S. J. Worley, E. C. Kent, and N. Rayner, 2008: A project to create bias-corrected marine climate observations from ICOADS. Short Abstract, *Third JCOMM Workshop on Advances in Marine Climatology (CLIMAR-III)*, Gdynia, Poland, 6-9 May 2008.

Woodruff, S. D., P. Brohan, E. C. Kent, S. J. Lubker, R. W. Reynolds, S. R. Smith, and S. J. Worley, 2008: ICOADS: Data Characteristics and Future Directions. Short Abstract, *Third JCOMM Workshop on Advances in Marine Climatology (CLIMAR-III)*, Gdynia, Poland, 6-9 May 2008.

Smith, S. R., J. Rolph, and M. A. Bourassa, 2008: The Shipboard Automated Meteorological and Oceanographic System (SAMOS) Initiative. Short Abstract, *2008 Ocean Sciences Meeting*, Orlando, FL. 2-7 March 2008.

Smith, S. R., 2007: Metadata automation: Survey Results and Ideas. Presentation, *UNOLS Research Vessel Technical Enhancement Committee 2007 Annual Meeting*, Moss Landing, CA, 6-8 November 2007.

Smith, S. R., and J. Rolph, 2007: The SAMOS Initiative. Presentation, *UNOLS Research Vessel Technical Enhancement Committee 2007 Annual Meeting*, Moss Landing, CA, 6-8 November 2007.

World Ocean Database Project

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1. PROJECT SUMMARY

The "World Ocean Database Project" has the goal of creating the most comprehensive, global, scientifically quality-controlled ocean profile-plankton database possible with all data in one common format. Releases of this database include *World Ocean Database 2005*, *World Ocean Database 2001*, *World Ocean Database 1998*, and *World Ocean Atlas 1994*. Data for 29 variables are available including temperature, salinity, oxygen, nutrients, and tracers among others. There are approximately 7.9 million temperature and 2.6 million salinity profiles included in the most release of this database (*World Ocean Database 2005* (WOD05)).

The utility of NODC profile databases is given in Figure 1 which documents that NODC databases and products based on these databases have been cited more than 5,531 times during the past 25 years.

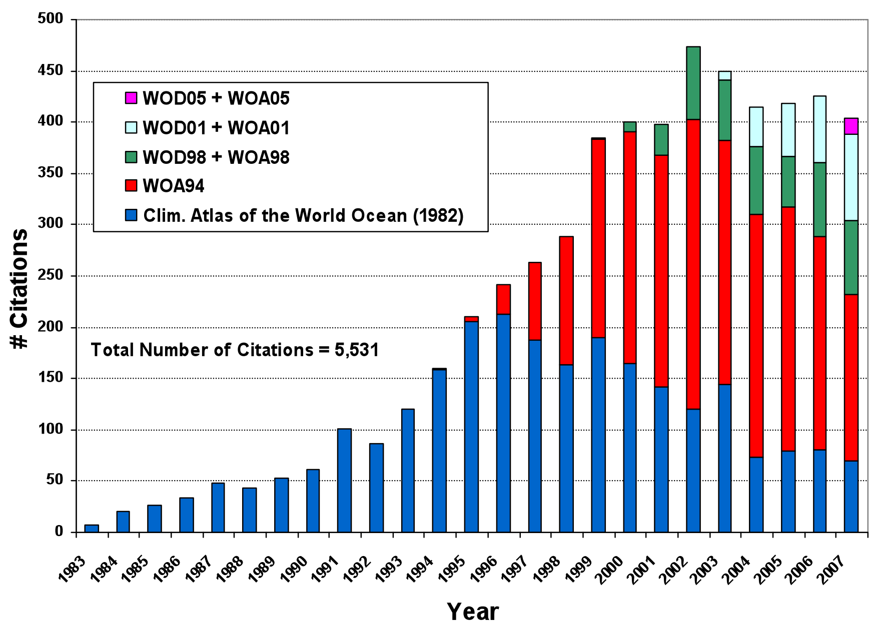

Figure 1. Time series of the number of citations as a function of year for NODC profile databases and products based on those databases.

NODC data and related products are used as initial and boundary conditions in ocean models and for ocean acoustic tomographic inversions and as "sea-truth" for verifying models among many other uses.

All data in the WOD series are available both on DVD as well as online. Figure 2 shows that more than 700 million ocean profiles have been downloaded during the past four years alone.

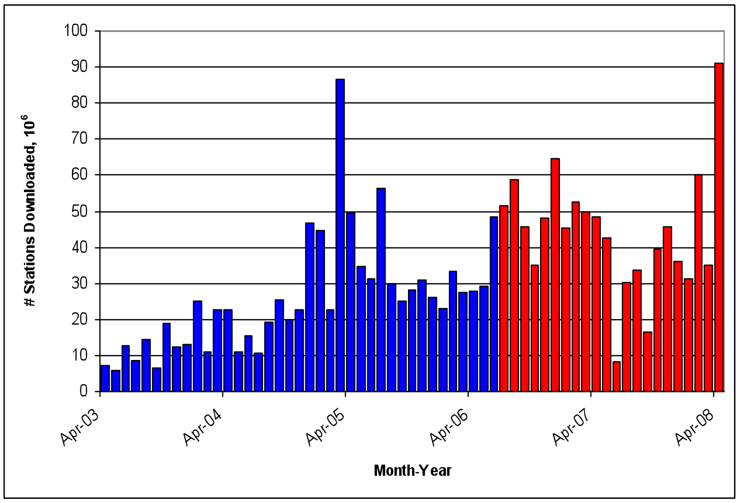

Figure 2. Number of casts in the World Ocean Database downloaded as a function of time.

2. ACCOMPLISHMENTS

We are completing data processing for *World Ocean Database 2009* (WOD09) in FY09 as planned. To date we have processed:

1) Ocean Station Data (Bottle): ~ 143,000 casts
2) Conductivity-Temperature-Depth: ~ 144,000 casts
3) Expendable Bathythermograph: ~ 70,000 profiles
4) Mechanical Bathythermograph: ~ 3,000 profiles
5) Profiling Float: ~ 297,000 casts
6) Moored Buoy: ~ 78,000 profiles
7) Drifting Buoy: ~ 13,000 profiles
8) Towed CTDs: ~ 41,485 casts

3. PUBLICATIONS AND REPORTS

Boyer, T. P., J. I. Antonov, H. Garcia, D. R. Johnson, R. A. Locarnini, A. V. Mishonov, O. K. Baranova, I. Smolyar, M. Zweng, 2006: World Ocean Database 2009, Chapter 1: Introduction, NOAA Atlas NESDIS 60, Ed. S. Levitus, U.S. Gov. Printing Office, Wash., D.C., in preparation.

Ocean Data Management at NCDC

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1. PROJECT SUMMARY

The project "Ocean Data Management at NCDC" directly supports the mission of NCDC (NOAA National Climatic Data Center): "To provide stewardship and access to the Nation's resource of global climate and weather related data and information, and assess and monitor climate variation and change." This in turn directly supports the NOAA Mission: "To understand and predict changes in Earth's environment and conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs."

NCDC plays an active and important role in the national and international climate change monitoring and assessment programs [e.g., the US Climate Change Science Program (CCSP) Syntheses]. Climate change monitoring and assessment require meteorological and marine data over both land and ocean. Changes of environmental variables at and near the marine surface are important since they occur over approximately 70% of the Earth's surface and contain important climate change signals. Due to the drastic property differences between water and air (e.g., density and heat capacity), huge amount of water, energy, momentum and gases (e.g., carbon dioxide) are constantly exchanged at the turbulent air-sea interface. These exchanges regulate the weather in the short term and the climate change in the long term. Thus, NCDC has been actively archiving, serving and utilizing the world's surface marine data, and it will need to continue to do so.

Modern day Global Ocean Observing System (GOOS) consists of multiple platforms and instruments (both in-situ and remote sensing). Each of these observations contributes to the understanding and assessment of climate change signals. However, individual instrument observations have limitations in coverage (in both time and space) and limitations on accuracy. To maximize benefits and integrally use all the available observations, it is necessary to blend them together to produce higher resolution and higher accuracy products. For example, research on global water and energy budgets and numerical weather and ocean forecasts demand increasingly higher resolution forcing data (better than daily and 50 km; e.g., WMO/TD-No. 1036, 2000; Curry et al. 2004). The recent international Global Earth Observation System of Systems (GEOSS) and Global Climate Observing System (GCOS) also called for optimal combinations of the above platforms for integrated global observing system and service.

There are typically three types of errors in observations and blended products: 1) random error; 2) sampling error; and 3) bias error. The bias error is the systematic difference between one instrument (or a set of instruments, e.g., in-situ observations) and another (e.g., remote sensing/satellite observations). The combined error for all terms should be reduced to a required accuracy for meaningful climate change diagnostics. In the satellite era, satellite observations provide dense data coverage, thus in-situ data play a minor role in the reduction of random and sampling errors and in increasing resolutions in blended products. However, in-situ observations provide the "ground-truth", thus play an essential role in correcting the systematic biases of indirect measurements (e.g., remote sensing/satellite observations that are calibrated to in-situ observations).

The overall objectives of this project are: 1) to ingest the world's marine observations into the NCDC archives; 2) to quality control the data for various applications (such as for Reanalysis); 3) to produce blended products for optimal use of all the observations; and 4) to improve services for a wide variety of user communities. The highlighted tasks and deliverables for this fiscal year are detailed in the next section.

2. ACCOMPLISHMENTS

2.1. ICOADS - Access to historical records; Expanded GIS functionality

As the result of a US project starting in 1981, available global surface marine data from the late 18th century to date have been assembled, quality controlled, and made widely available to the international research community in products of the Comprehensive Ocean-Atmosphere Data Set (COADS). A new name, International COADS (ICOADS), was agreed upon in 2002 to recognize the multinational input to the blended observational database and other benefits gained from extensive international collaboration. NCDC continued to ingest, archive, quality control and serve the ICOADS data (http://www7.ncdc.noaa.gov/CDO/CDOMarineSelect.jsp).

Improved data model has been developed to accommodate access for the entire ICOADS data archive (Figure 1). Additional quality control code is being applied prior to database loading. A prototype GIS system has been completed.

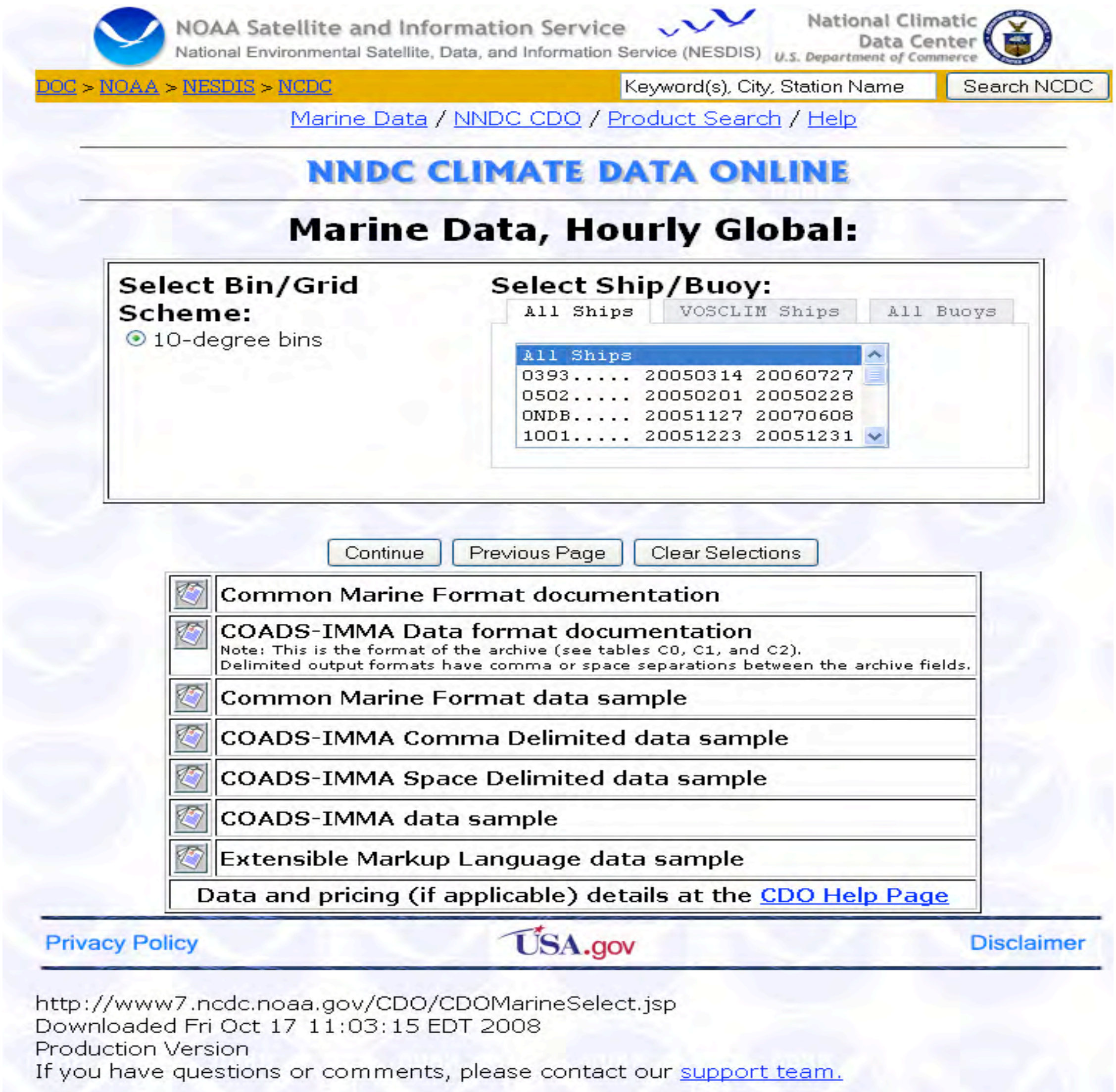


Figure 1. A screen capture of the Climate Data Online (CDO) for the global hourly marine observations.

2.2. VOSClim

VOSClim is an ongoing project within WMO/IOC JCOMM's Voluntary Observing Ships' Scheme. It aims to provide a high-quality subset of marine meteorological data, with extensive associated metadata, to be available in both real-time and delayed mode to support global climate studies. Data from the project are invaluable for climate change studies and research. In particular it is used to: 1) input directly into air-sea flux computations, as part of coupled atmosphere-ocean climate models; 2) provide ground truth for calibrating satellite observations, evaluating and validating NWP model and reanalysis results; and 3) provide a high quality reference data set for possible re-calibration of observations from the entire VOS fleet. As the VOSClim Data Assembly Center (VOSClim DAC), NCDC continued to ingest, archive, quality control and serve the ICOADS data.

Additionally, we maintained the VOSClim website. In doing this, we updated the monthly ship monitoring statistics and list of participating ships (Figure 2), and provided access to the VOSClim data. The data is provided through database access as well as ASCII text files supplied through pull down menus, as recommended by VOSClim partners and scientific users.

ASCII data access is considered of more utility for the current level of scientific and general users and therefore is a critical addition. Drop down menus for access to monthly data monitoring statistics are provided as well as links to ship photographs and other metadata information. There are currently 258 active VOSClim ships, which surpasses the initial project target of 200 participating vessels.

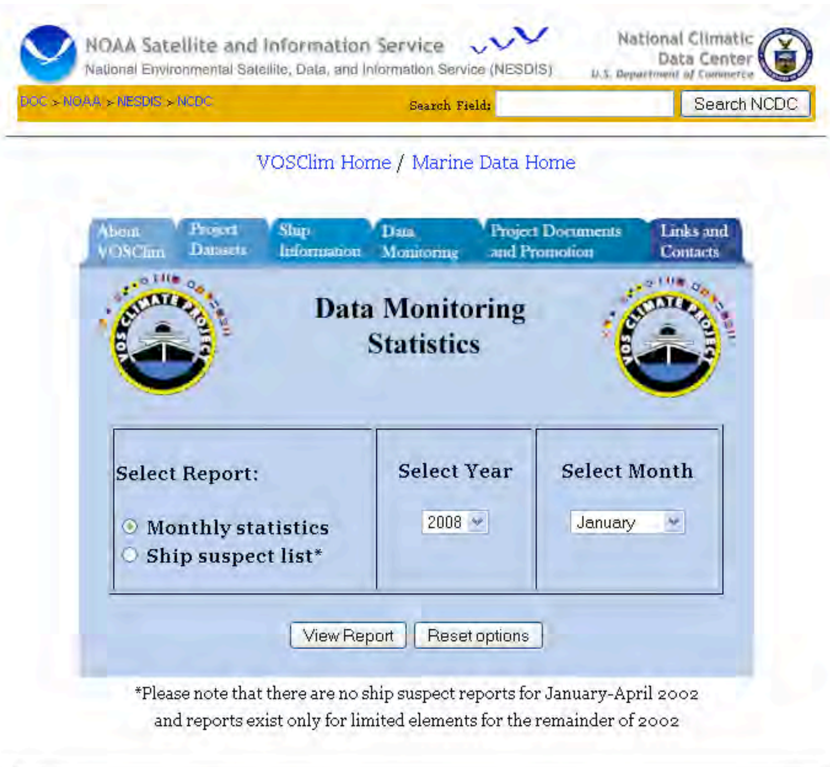


Figure 2. VOSClim's Data Monitoring webpage (http://www.ncdc.noaa.gov/oa/climate/vosclim/vosclim-stats.html).

Beginning in 2008, NCDC assumed duties previously provided by the Global Collecting Centers (GCCs) to collect VOSClim observations from global delayed-mode data files. Software was created at the DAC to parse the observations from the GCC quarterly data files and generate a report with statistics. The statistics are supplied each quarter to the GCC's for their annual report and the observations are made available through the VOSClim website.

2.3. Improvement of Blended High Resolution Sea Winds

The importance of production of air-sea interface products has been stipulated in the previous section (Project Summary). Our blended sea winds have been used by a wide variety of communities, including climate research, decision making & planning, wave hindcasting &

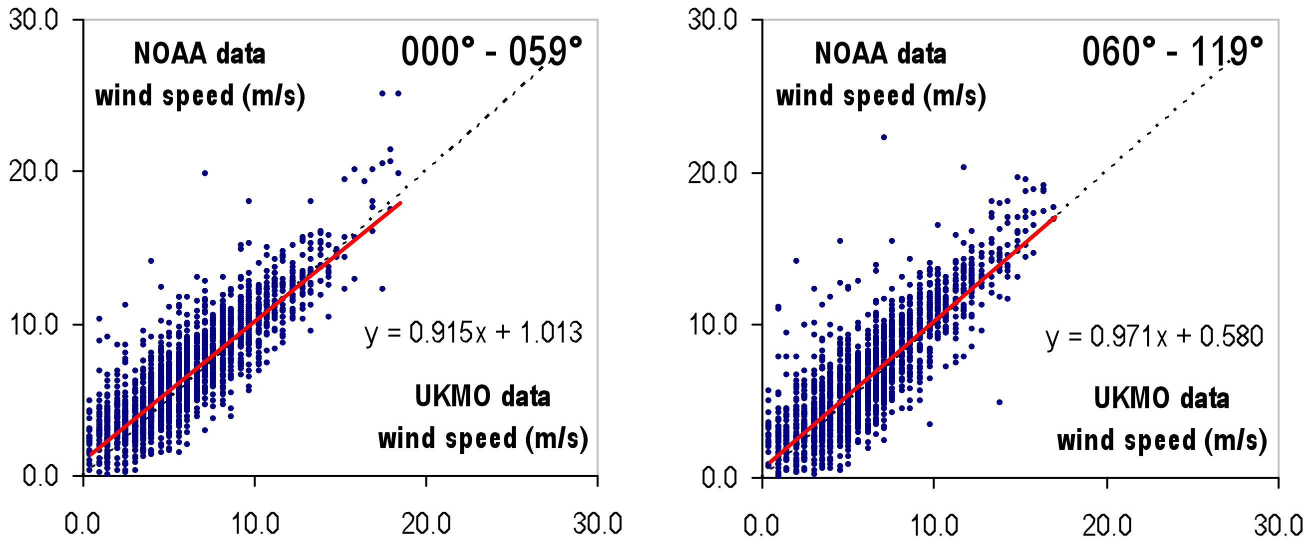
forecasting, ecosystems, marine resource management, marine transportation, wind/wave energy harvesting, and outreach & education. In this year, we have completed the following tasks:

a) Operational production and service of the blended 0.25°, 6-hourly sea winds

In the previous year, we had developed the procedures to generate the blended sea winds on a global 0.25° grid and 6-hourly time resolution. In the last year, we continued such products with an update frequency of about one month. We continued the data service via the interactive web interface (see links at http://www.ncdc.noaa.gov/oa/rsad/blendedseawinds.html).

b) Product evaluation for product improvement

In this year, the evaluation process for our blended products has been started. An example is shown in Figure 3 from the UK Met Office. Other evolutions have been started at the NOAA NCEP, the Scripps Institution of Oceanography of University of California at San Diego, the Aerospace & Marine International (UK) Ltd, and others.



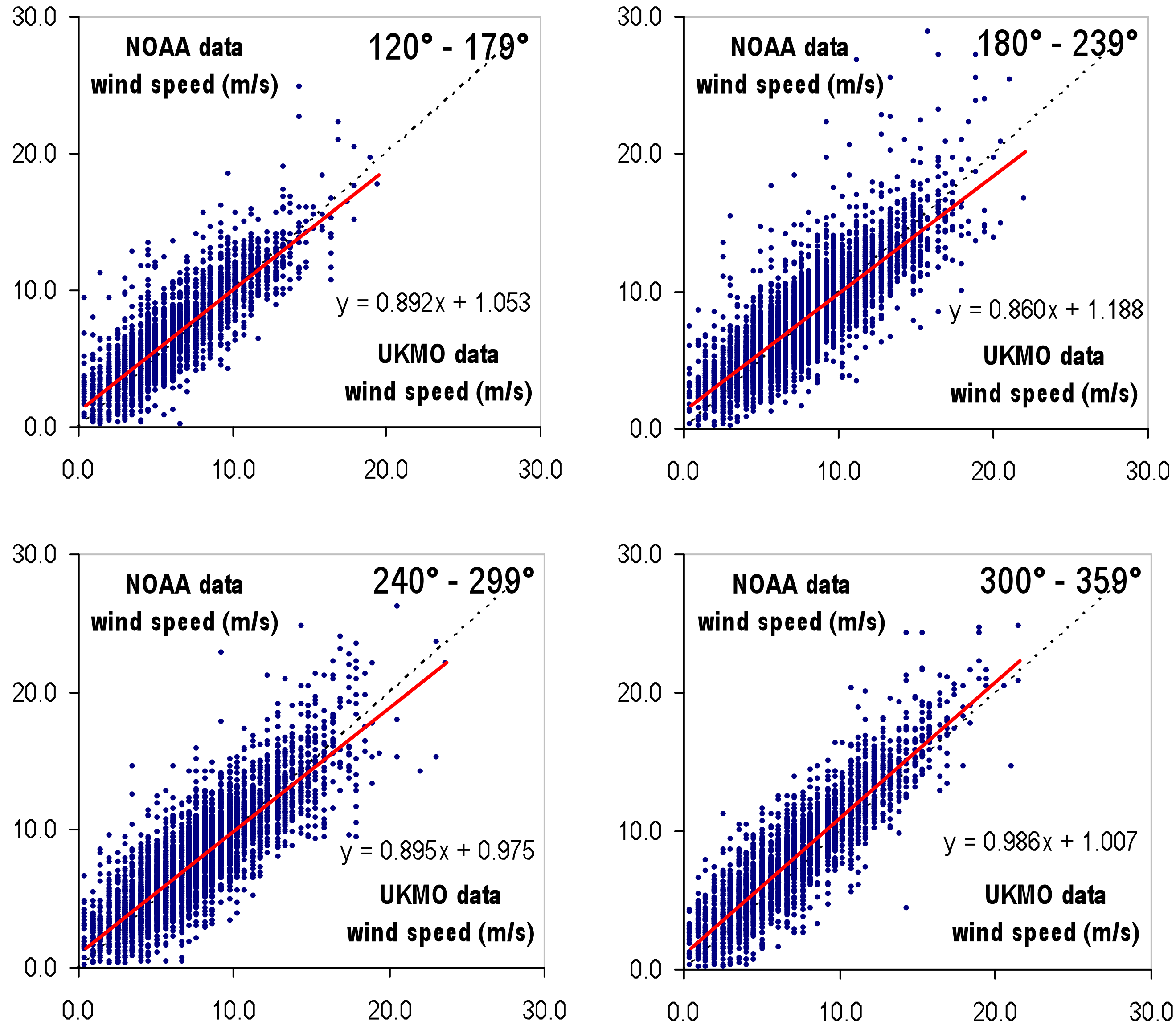


Figure 3. Comparison of directional wind speed data – UK Met Office Model predictions and NCDC Blended Sea Winds data from multiple satellites. Note the Met Office winds are at 20m and NCDC winds are at 10m above the mean sea level; better agreement could be achieved when the winds are corrected to the same height (from Richard Swift for UK Met Office Marine Data Analysis).

3. PUBLICATIONS AND REPORTS

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Anderson, D. and H.-M. Zhang, 2008: Shallow ocean overturning and the heat and carbon content of the Glacial Tropical Ocean. G*lobal and Planetary Change*, submitted.

Huai-Min Zhang, Richard W. Reynolds, Lei Shi, and John J. Bates, 2008: Blended High Resolution Sea Surface Flux Parameters from Multiple Satellites. *FLUXNEWS – Newsletter of the WCRP Working Group on Surface Fluxes*, Issue 5, Jan 2008, pp. 25-27.

Zhang, H.-M., R. W. Reynolds, G. Rutledge, R. Mendelssohn, F. Schwing, L. DeWitt, and D. Swank, 2008: Multi-Satellite Blended Surface Marine Products and Their Applications. *ASLO/AGU/TOS/ERF 2008 Ocean Sciences Meeting - From the Watershed to the Global Ocean*, 2-7 March 2008, Orlando, Florida, USA.