Annual Report

on the

Ocean Observing System for Climate

FY 2006

Chapter II: The State of the Observing System

Office of Climate Observation, Climate Program Office

National Oceanic and Atmospheric Administration

Editor: Joel M. Levy, NOAA Office of Climate Observation

Annual Report On the Ocean Observing System for Climate FY 2006

Chapter II:

Introduction

a. The Sustained Ocean Observing System for Climate System Management

b. FY 2006 OCO Annual Report: Chapter 2 Projects and Authors

01. Tide Gauge Stations

a. Global Sea Level Observations
The University of Hawaii Sea Level Center

b. National Water Level Program Support Towards Building a Sustained Ocean Observing System for Climate

02. Drifting Buoys

a. The Global Drifter Program

b. Surface Drifter Program

03. Tropical Moored Buoys

a. Tropical Moored Buoy Array Program

b. Tropical Atmosphere Ocean (TAO) Array

c. Tropical Atmosphere Ocean (TAO) Refresh

04. Ocean Reference Stations

a. Ocean Reference Stations

b. Western Boundary Time Series in the Atlantic Ocean

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

d. Progress Report: Southern Ocean Modern Observations/Weddell Sea Moorings November 2006

e. Monitoring the Indonesian Throughflow in Makassar Strait
f. Meridional Overturning Variability Experiment
g. Integrated Boundary Current Observations In The Global Climate System
h. High Resolution Climate Data From Research and Volunteer Observing Ships
i. Assimilation, Analysis and Dissemination of Pacific Rain Gauge Data: PACRAIN

05. Ships of Opportunity

a. High Resolution XBT Transects: Progress Report
b. Ship of Opportunity Program (SOOP): Volunteer Observing Ships: Expendable Bathythermograph and Enviromental Data Acquisition Program
c. Ships of Opportunity

06. Argo Profiling Floats

a. The Argo Project

07. Ocean Carbon Networks

a. Global Repeat Hydrographic/CO2/Tracer Surveys in Support of CLIVAR and Global Carbon Cycle Objectives: Carbon Inventories and Fluxes
b. Surface Water pCO2 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
d. Optimal Network Design to Detect Spatial Patterns and Variability of Ocean Carbon Sources and Sinks from Underway Surface pCO_2 Measurements

08. Arctic Ocean Obs System

a. The Arctic Research Program, Fiscal 2006

09. Product Delivery, Analysis/Reanalysis

a. A Web Site for NCEP's Global Ocean Data Assimilation System: Data Link, Model Validation and Ocean Monitoring Products
b. In Situ and Satellite Sea Surface Temperature (SST) Analyses
c. Investigating some practical implications of uncertainty in observed SSTs
d. Development of Global Heat and Freshwater Anomaly Analyses
e. Preparation of Ocean Heat and Freshwater Content Variability Estimates
f. Evaluating the Ocean Observing System: Performance Measurement for Heat Storage

g. A fifty-year analysis of global ocean surface heat flux to improve the understanding of the role of the ocean in climate
h. Climate Variability in Ocean Surface Turbulent Fluxes
i. Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses
j. Evaluating the Ocean Observing System: Surface Currents
k. Quarterly reports on the state of the ocean: Meridional heat transport variability in the Atlantic Ocean
l. National Water Level Program Support Towards Building a Sustained Ocean Observing System for Climate.
m. Satellite Altimetry
n. Reconstruction of Past Sea Level Change from a Combination ofSatellite Altimeter and Tide Gauge Measurements
o. Global Carbon Data Management and Synthesis Project
p. Determination of the information content in long-occupied Voluntary Observing Ship (VOS) Expendable Bathythermograph (XBT) transects
q. Arctic Ice Thickness: State of the Arctic Report
r. Observing System Research Studies
s. Simulation of the ARGO Observing System

10. Data & Assimilation Subsystems

a. The Observing System Monitoring Center
b. World Ocean Database Project
c. Enhanced Ocean Climate Products from NCEP
d. Ocean Data Assimilation Research at GFDL
e. Ocean Data Management at NCDC
f. U.S. Research Vessel Surface Meteorology Data Assembly Center

Introduction:

a. The Sustained Ocean Observing System for Climate System Management
b. FY 2006 OCO Annual Report: Chapter 2 Projects and Authors

The Sustained Ocean Observing System for Climate System Management

Mike Johnson
Office of Climate Observation

Project Summary

Introduction

The Office of Climate Observation (OCO) is a project office established in 2003 under the auspices of the Climate Program Office (CPO) to manage the ocean sub-capability of the Climate Observations and Analysis Program. NOAA's Climate Goal, via the OCO, provides 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).

It is the job of OCO to advance the multi-year *Program Plan for Building a Sustained Ocean Observing System for Climate*. 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.

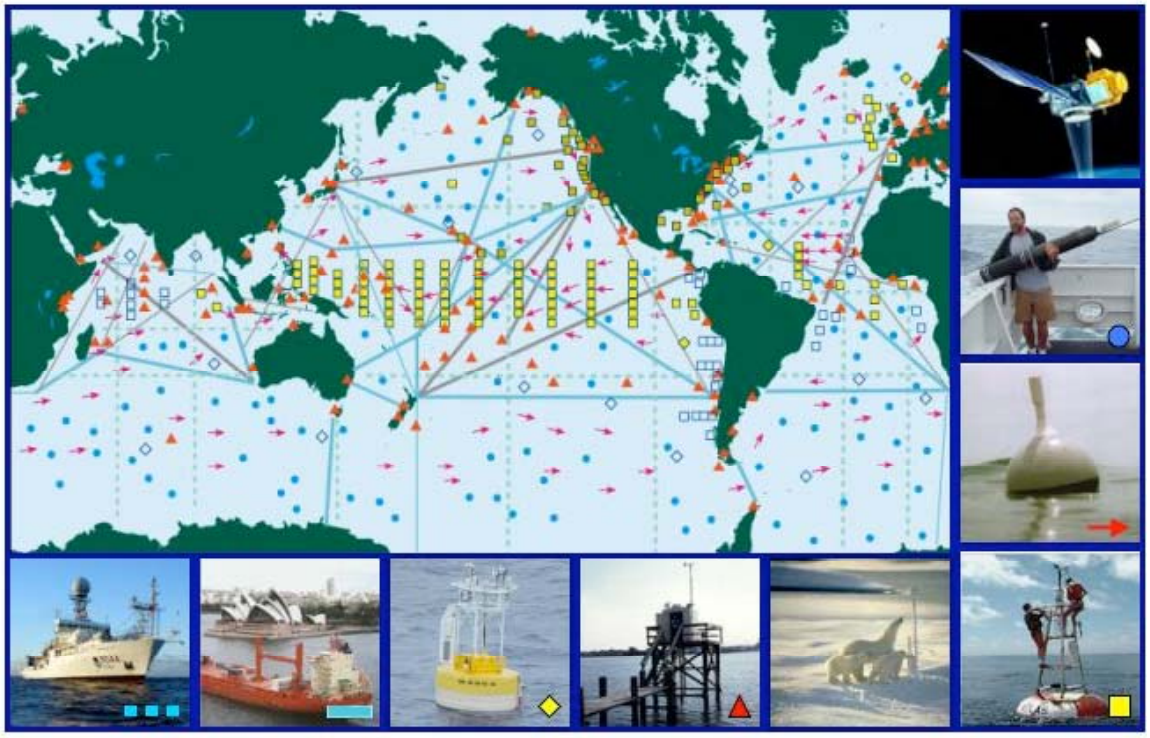

Figure 1. The Networks that make up the Sustained Ocean Observing System for Climate are (from lower left to upper right): Dedicated Ships, Ships of Opportunity, Ocean Reference Stations, Tide Gauge Stations, Arctic Observing Systems, Tropical Moored Buoys, Surface Drifting Buoys, Argo Profiling Floats, 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 Product Delivery.

Responsible Institutions

The "Networks" are managed by 19 distributed centers of expertise at the 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.

The 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), NCDC, NODC, NGDC, CO-OPS, NMAO, NDBC, NCEP, FSU (Florida State University), and CLS America. The contributions of these centers are summarized by the project managers in their individual reports.

Across NOAA there are 45 Federal employees, and 105 non-Federal employees working to implement the system. Within the OCO project office there are four Federal employees, and four non-Federal; one of the OCO Federal employees is detailed to the JCOMM Secretariat at the international GOOS Project Office at IOC/UNESCO in Paris.

Partnerships are central

A global observing system by definition crosses international and institutional boundaries, with potential for both benefits and responsibilities to be shared by many. In addition to the work specifically supported through the OCO program, NOS, NMFS, and NWS maintain observational infrastructure for ecosystems, transportation, marine services and coastal forecasting that do or have potential to contribute to climate observation. NOS sea level measurements in particular provide one of the best and longest climate records existent. NESDIS data centers are essential. NMAO ship operations are necessary for supporting ocean work. NESDIS and NPOESS continuous satellite missions are needed to provide the remote sensing that complements the *in situ* measurements. All of the OCO contributions to global observation are managed in cooperation internationally with the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). The National Science Foundation has initiated their Ocean Observatories Initiative, which will potentially provide significant infrastructure in support of ocean climate observation. The ongoing NSF-NOAA cooperative project for CLIVAR-ocean carbon surveys has proved to be an interagency-international-interdisciplinary success. The Office of Naval Research maintains a GODAE data server at Monterey that is critical to global data access. The UNOLS fleet provides ship support for ocean operations. NASA's development of remote sensing techniques is key. The ocean climate research being conducted by the CPO science programs, other NOAA programs, NASA, NSF, and the Navy provides the advancements in knowledge that are essential for continuous system improvement.

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 56% of what is needed in the ice-free oceans and 11% in the Arctic. 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 the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). These specific GCOS-92 actions now provide an excellent roadmap to guide observing system workplans. GCOS-92 is accessible via link from the OCO web site: www.oco.noaa.gov -- click on "Reports & Products." All of 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 nearly half of the total international effort in 2006.

FY 2006 Accomplishments

The international global ocean climate observing system overall advanced from 55% complete in FY 2005 to 56% complete in FY 2006.

The OCO program was reviewed 10-12 May 2006 in Silver Spring. The Annual System Review brought together 115 project managers, data users, advisors, and program managers both from NOAA and from other partner institutions to discuss system-wide issues and engage in program strategic planning. Several international program managers and technical coordinators associated with the JCOMM Observations Coordination Group (OCG) and the JCOMM Observing Platform Support Centre (JCOMMOPS) attended the meeting, bringing international expertise and advice to the OCO program. External review of the program was provided by the Climate Observing System Council (COSC).

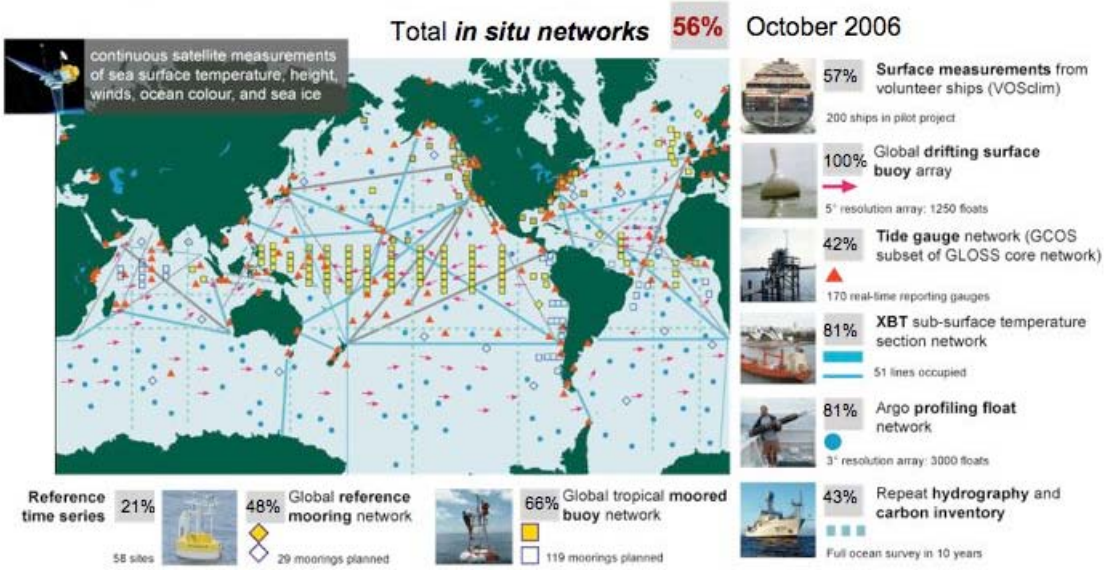

Figure 2: A schematic of the initial composite ocean observing system, including the current status against the targets of JCOMM and the GCOS Implementation Plan (GCOS-92).

The annual reports of the Project Managers detail the specific advancements of the individual networks. Highlights for 2006 include:

- *Documenting long-term trends in sea level change*: Following the tragic Indian Ocean tsunami of 24 December 2004, tide gauge station upgrading to real-time reporting continued to be the top priority for the sea level program, so that the climate stations contribute to the international tsunami warning system as well as to the climate reference network.

- *Documenting the ocean-atmosphere exchange of heat and fresh water*: The Global Drifting Buoy array was maintained at its design goal of 1250 buoys in sustained service. FY2006 was the first full year of operations at the system design level. The Tropical Moored Buoy network was expanded in the Atlantic Ocean; the U.S. added two new stations in the PIRATA North East Extension off the west coast of Africa. In cooperation with Chile, the Stratus Ocean Reference Station project installed a U.S. surface meteorology sensor suite on the Chilean tsunami warning buoy; this was the first multi-use ocean station established through cooperation of the international OceanSITES program and the international tsunami warning systems.
- *Documenting the ocean's storage and global transport of heat and fresh water*: The Argo array continued its rapid progress toward global coverage, passing the milestone of 2500 active floats in service. Transition of the MOVE array from Germany (research investigation) to U.S. support (sustained time series) was initiated. Transition of the Indonesian Through Flow monitoring system from NSF to NOAA funding was initiated. Development of the California Current near-real-time monitoring system was initiated.
- *Documenting ocean carbon sources and sinks*: Two carbon dioxide monitoring systems were added to the Ocean Reference Stations at the Hawaii Ocean Time-series site and the Bermuda Test bed site.
- *System management and product delivery*: The reporting of oceanic essential climate variables was advanced, with the Bulletin of the American Meteorological Society (BAMS) annual *State of the Climate* special edition publishing eight articles on the state of the ocean. The test Version 2.00 Beta of the Observing System Monitoring Center web tool was made available to the international community via the JCOMMOPS web site as well as the OCO web site.

Global Ocean Observing System Budget Allocation ($K)					
Network	**FY 02**	**FY 03**	**FY 04**	**FY 05**	**FY 06**
Tide Gauge Stations	670	710	970	1196	1177
Drifting Buoys	1699	2077	2769	3130	3427
Tropical Moored Buoys	3175	3175	3625	4360	3094
Ships of Opportunity	1960	1903	2487	2907	2776
Argo Profiling Floats (gliders)	271	275	273	249	247
Ocean Reference Stations	1712	2082	2998	2995	3958
Ocean Carbon Networks	1478	2204	2875	3521	3482
International Arctic Ocean Observing System	337	337	337	397	310
Dedicated Ship Time	0	626	523	92	542
Data & Assimilation Subsystems	1286	1323	1487	1418	1331
Service Argos Data Processing	813	480	1525	1408	448
Product Deliver, Analysis/Reanalysis	578	638	896	1982	2048
Institutional Infrastructure	626	653	1269	1356	711
IOOS Global Systems Total (OCO managed)	**14605**	**16483**	**22034**	**25011**	**23551**
Partner Programs					
Argo Program (managed separately)	6978	9706	9811	9491	9758
Arctic Program (managed separately)	1600	4322	3651	4928	4927
TAO/PIRATA, NWS operations (managed separately)	0	0	0	0	3200
OCO Funding Distribution					
NOAA				13944	12388
External				9043	10301
CLS America				1408	448
Community Support (workshops, panels, JCOMM, CLIVAR, GOOS)				616	414
Total Global Systems, OCO managed				**25011**	**23551**
OCO Income Budget Lines					
OAR Laboratories & Cooperative Institutes				5613	5389
OAR Climate & Global Change Program				4886	4619
OAR Climate Observations & Services				14156	9871
NWS TAO/PIRATA					2695
Other (one-time supplemental funding)				356	977
Total				**25011**	**23551**

Table 1: System Funding Record

Project	Authors	Web Site
Tide Gauge Stations		
1. Global Sea Level Observations	Mark Merrifield	http://ilikai.soest.hawaii.edu/uhslc/products.html http://ilikai.soest.hawaii.edu/RSL/
2. 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/
Drifting Buoys		
1. The "Global Drifter Program" - Drifter Measurements of Surface Velocity, SST, SSS, Winds and Atmospheric Pressure	Peter Niiler	http://www.aoml.noaa.gov/phod/soto/gsc/index.php http://www.aoml.noaa.gov/phod/dac/drifter_bibliography.html
2. Surface Drifter Program	Silvia Garzoli, Rick Lumpkin	http://www.aoml.noaa.gov/phod/dac/gdp.html http://www.aoml.noaa.gov/phod/ graphics/dacdata/forecast90d.gif
Tropical Moored Buoys		
1. 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/ http://www.pmel.noaa.gov/pirata/ http://www.pmel.noaa.gov/tao/ http://www.clivar.org/organization/indian/ http://www.clivar.org/organization/indian/ www.pmel.noaa.gov/tao/disdel/disdel.html
2. Tropical Atmosphere Ocean (TAO) Array	Landry Bernard, Michael McPhaaden	http://www.tao.noaa.gov/ http://www.pmel.noaa.gov/tao/
3. Tropical Atmosphere Ocean (TAO) Refresh	Landry Bernard	No url in report.
Ocean Reference Stations		
1. Ocean Reference Stations	Robert A. Weller, Albert J. Plueddemann	http://www.oceansites.org/ http://uop.whoi.edu/projects/WHOTS/whots.htm
2. Western Boundary Time Series in the Atlantic Ocean	M. Baringer, C. Meinen, and S. Garzoli	http://www.aoml.noaa.gov/phod/wbcts/ http://www.aoml.noaa.gov/phod/floridacurrent/
3. Flux Mooring for the North Pacific's Western Boundary Current: Kuroshio Extension Observatory (KEO)	Meghan F. Cronin, Christian Meinig, Christopher L. Sabine	http://www.pmel.noaa.gov/keo/ http://www.pmel.noaa.gov/keo/data.html
4. Southern Ocean Modern Observations/ Weddell Sea	Arnold Gordon, Bruce Huber	No url in report.

4. Southern Ocean Modern Observations/ Weddell Sea Moorings	Arnold Gordon, Bruce Huber	No url in report.
5. Monitoring the Indonesian Throughflow in Makassar Strait	Arnold Gordon	No url in report.
6. Meridional Overturning Variability Experiment	Uwe Send	No url in report.
7. Integrated Boundary Current Observations in the Global Climate System	Uwe Send, Russ Davis, Daniel Rudnick, Peter Niiler, Bruce Cornuelle, Dean Roemmich	No url in report.
8. High Resolution Climate Data From Research and Volunteer Observing Ships	C. W. Fairall	http://www.etl.noaa.gov/et6/air-sea/ http://www.esrl.noaa.gov/psd/psd3/air-sea/oceanobs/ http://www.esrl.noaa.gov/psd/psd3/wgsf/ ftp://ftp.etl.noaa.gov/et6/archive/ ftp://ftp.etl.noaa.gov/user/cfairall/wcrp_wgsf/flux_handbook/
9. Assimilation, Analysis and Dissemination of Pacific Rain Gauge Data: PACRAIN	Mark L. Morrissey, Susan Postawko, J. Scott Greene	http://www.evac.ou.edu/pacrain http://pacrain.evac.ou.edu/ http://www.evac.ou.edu/srdc http://sparce.evac.ou.edu/ http://www.pi-gcos.org/
Ships of Opportunity		
1. High Resolution XBT Transects	Dean Roemmich, Bruce Cornuelle, Janet Sprintall, Glenn Pezzoli	http://www-hrx.ucsd.edu http://www.brest.ird.fr/soopip/
2. Ships of Opportunity Program (SOOP): Volunteer Observing Ships: Expendable Bathythermograph and Environmental Data Acquisition Program	Molly O. Baringer, Gustavo J. Goni, Silvia L. Garzoli	http://www.aoml.noaa.gov/phod/hdenxbt/ http://www.aoml.noaa.gov/phod/hdenxbt/ http://www.aoml.noaa.gov/phod/xbt.php http://www.aoml.noaa.gov/phod/trinanes/SEAS/ http://seas.amverseas.noaa.gov/seas/
2. Ships of Opportunity	Robert A. Weller	http://uop.whoi.edu/vos/ http://frodo.whoi.edu ftp.whoi.edu/pub/users/fbahr/VOS
ARGO Profiling Floats		
1. The Argo Project -	Dean H. Roemmich, Russ E. Davis, Stephen C. Riser, W. Brechner Owens, Robert L.	www.argo.ucsd.edu http://www.usgodae.org/ http://www.ifremer.fr/coriolis/cdc/argo.htm http://www.argo.ucsd.edu/FrBibliography.html

Ocean Carbon Networks		
1. 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 Johnson, Molly Baringer, John Bullister, Calvin W. Mordy, Jia-Zhong Zhang	http://ushydro.ucsd.edu/index.html
2. 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/explorer_realtime.php http://www.pmel.noaa.gov/co2/uw http://www.ldeo.columbia.edu//CO2 http://cdiac3.ornl.gov/underway/servlets/dataset
3. APPENDIX. Underway CO_2 Measurements aboard the RVIB Palmer and Data Management of the Global VOS Program	Taro Takahashi	www.ldeo.columbia.edu/CO2
4. High-Resolution Ocean And Atmosphere pCO_2Time-Series Measurements	Christopher L. Sabine, Francisco Chavez, Nicholas Bates	http://www.pmel.noaa.gov/co2/moorings/ http://www.oceansites.org/OceanSITES/
5. Optimal network design to detect spatial patterns and variability of ocean carbon sources and sinks from underway surface pCO_2 measurements	Joellen L. Russell, Colm Sweeney, Anand Gnanadesikan, Richard A. Feely, Rik Wanninkhof	No url in report.
Arctic Ocean Observing System		
1. The Arctic Research Program, Fiscal 2006	John.Calder, Kathleen Crane, Jacqueline Grebmeier, M. Zhdanov, A. Ostrovskiy, Jackie Richter-Menge, James Overland, Igor Polyakov, Ignatius Rigor, Taneil Uttal, Tom Weingartner and Terry Whitledge	www.arctic.noaa.gov
Analysis		

1. 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/
2. In Situ and Satellite Sea Surface Temperature (SST) Analyses	Richard W. Reynolds	http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/ ftp://eclipse.ncdc.noaa.gov/pub/OI-daily/ http://nomads.ncdc.noaa.gov:8085/thredds/catalog.html http://nomads.ncdc.noaa.gov:8085/las/servlets/dataset
3. Investigating some practical implications of uncertainty in observed SSTs	Lisa Goddard	No url in report.
4. Development of Global Heat and Freshwater Anomaly Analyses	Gregory C. Johnson, John M. Lyman, Josh K. Willis	http://oceans.pmel.noaa.gov/
5. Preparation of Ocean Heat and Freshwater Content Variability Estimates	Sydney Levitus	No url in report.
6. Evaluating the Ocean Observing System: Performance Measurement for Heat Storage	Claudia Schmid, Gustavo Goni	www.aoml.noaa/gov/phod/soto/
7. A Fifty-Year Analysis of Global Ocean Surface Heat Flux	Lisan Yu and Robert A. Weller	http://oaflux.whoi.edu
8. Climate Variability in Ocean Surface Turbulent Fluxes	Mark A. Bourassa, Shawn R. Smith, Eric Chassignet	http://www.coaps.fsu.edu/RVSMDC/SAC/index.shtml http://www.coaps.fsu.edu/RVSMDC/FSUFluxes/
9. 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.html http://www.cpc.ncep.noaa.gov/products/janowiak/us_web.shtml
10. Evaluating the Ocean Observing System: Surface Currents	Rick Lumpkin and Gustavo Goni	http://www.aoml.noaa.gov/phod/trinanes/java.html http://www.aoml.noaa.gov/phod/soto/gsc/index.php
11. 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/index.php
12. National Water Level Program	Stephen K. Gill, Chris Zervas,	http://tidesandcurrents.noaa.gov http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml

Support Towards Building a Sustained Ocean Observing System for Climate	Lori Fenstermacher	http://tidesandcurrents.noaa.gov/sltrends/sltrends_global.shtml http://opendap.co-ops.nos.noaa.gov/content/
13. Satellite Altimetry	Laury Miller	http://www.oscar.noaa.gov http://www.beringclimate.noaa.gov
14. Reconstruction of Past Sea Level Change from a Combination of Satellite Altimeter and Tide Gauge Measurements	R.S. Nerem	No url in report.
15. Global Carbon Data Management and Synthesis Project Project 1: CLIVAR/ CO_2 Repeat Hydrography Program CO_2 Synthesis Science Team (R. Feely) Project 2: An End-to-end Data Management System for Ocean pCO_2 Measurements (S. Hankin) Project 3: Understanding the Temporal Evolution of the Global Carbon Cycle Using Large-Scale Carbon Observations (C. Sabine)	Christopher L. Sabine, Richard A. Feely, Steven C. Hankin, Rik Wanninkhof, Tsung-Hung Peng, Alex Kozyr, Robert Key, Frank Millero, Andrew Dickson,	http://cdiac.ornl.gov/oceans/RepeatSections/repeat_map.html http://cdiac.esd.ornl.gov/oceans/home.html http://cdiac.ornl.gov/oceans/glodap/Glodap_home.htm http://ioc.unesco.org/ioccp/Hydrography/Hydro_Map.htm http://www.aoml.noaa.gov/ocd/gcc/a16s/ http://whpo.ucsd.edu/data/co2clivar/pacific/p16/p16n_2006a/index.htm http://cdiac.ornl.gov/oceans/VOS_Program/VOS_home.html http://cdiac.ornl.gov/oceans/Moorings/moorings.html
15. Determination of the information content in long-occupied Voluntary Observing Ship (VOS) Expendable Bathythermograph (XBT) transects	Gustavo Goni, Robert L. Molinari	No url in report.
16. 16. Arctic Ice Thickness: State of the Arctic Report	Jacqueline A. Richter-Menge, Jim Overland	http://www.arctic.noaa.gov/ http://www.crrel.usace.army.mil/sid/IMB/index.htm
17. Observing System Research Studies	D.E.Harrison	No url in report.
18. Simulation of the ARGO Observing	I.V. Kamenkovich,	No url in report.

18. Simulation of the ARGO Observing System	I.V. Kamenkovich, Edward S. Sarachik	No url in report.
Data and Assimilation		
1. Observing System Monitoring Center (OSMC)	Steven Hankin, Kevin J. Kern, Ted Habermann	http://osmc.noaa.gov/OSMC/
2. World Ocean Database Project	Sydney Levitus, Tim Boyer, Harnan Garcia, John Antonov, ARicardo Locarnini	No url in report.
3. Enhanced Ocean Climate Products from NCEP	Stephen J. Lord	No url in report.
4. Ocean Data Assimilation Research at GFDL	Tony Rosati, Brian Gross	http://nomads/nomads/forms/assimilation.html
5. Ocean Data Management at NCDC	Huai-Min Zhang	http://www.ncdc.noaa.gov/oa/rsad/blendedseawinds.html http://nomads.ncdc.noaa.gov:8085/las/servlets/dataset?catitem=731 http://las.pfeg.noaa.gov/las6_5/servlets/dataset?catitem=20
6. U.S. Research Vessel Surface Meteorology Data Assembly Center	Shawn R. Smith, Mark A. Bourassa, Eric Chassignet	http://samos.coaps.fsu.edu/ http://www.coaps.fsu.edu/RVSMDC/html/data.shtml http://www.coaps.fsu.edu/RVSMDC/marine_workshop3/
Education		
1. Education Initiatives sponsored by the	Diane Stanitski	www.adoptadrifter.noaa.gov

01. Tide Gauge Stations:

a. Global Sea Level Observations
   The University of Hawaii Sea Level Center

b. National Water Level Program Support Towards Building a Sustained Ocean Observing System for Climate

Global Sea Level Observations
The University of Hawaii Sea Level Center

Mark A. Merrifield
University of Hawaii Sea Level Center
Honolulu, HI

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, sampled at least every hour, that are available in near-real time usually via geostationary satellites. 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 50 stations, including 7 stations with colocated GPS for monitoring land motion at the tide gauge. 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 particularly important 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 selected 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 and WOCE, and currently is a designated CLIVAR data assembly center and a GLOSS data archive center.

ACCOMPLISHMENTS

Tide Gauge Operations

The UHSLC assists with the operation and maintenance of 48 international 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 2-6 minute averaged data; however, we are in the process of switching all stations over to 15-minute transmissions of 1-minute averages, with even higher rates at major tsunami generation zones. Of the 50 UHSLC stations, 40 contribute to the GLOSS Core network, and 34 to the GCOS network. 7 are equipped with co-located GPS, and 14 are within 10 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 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.

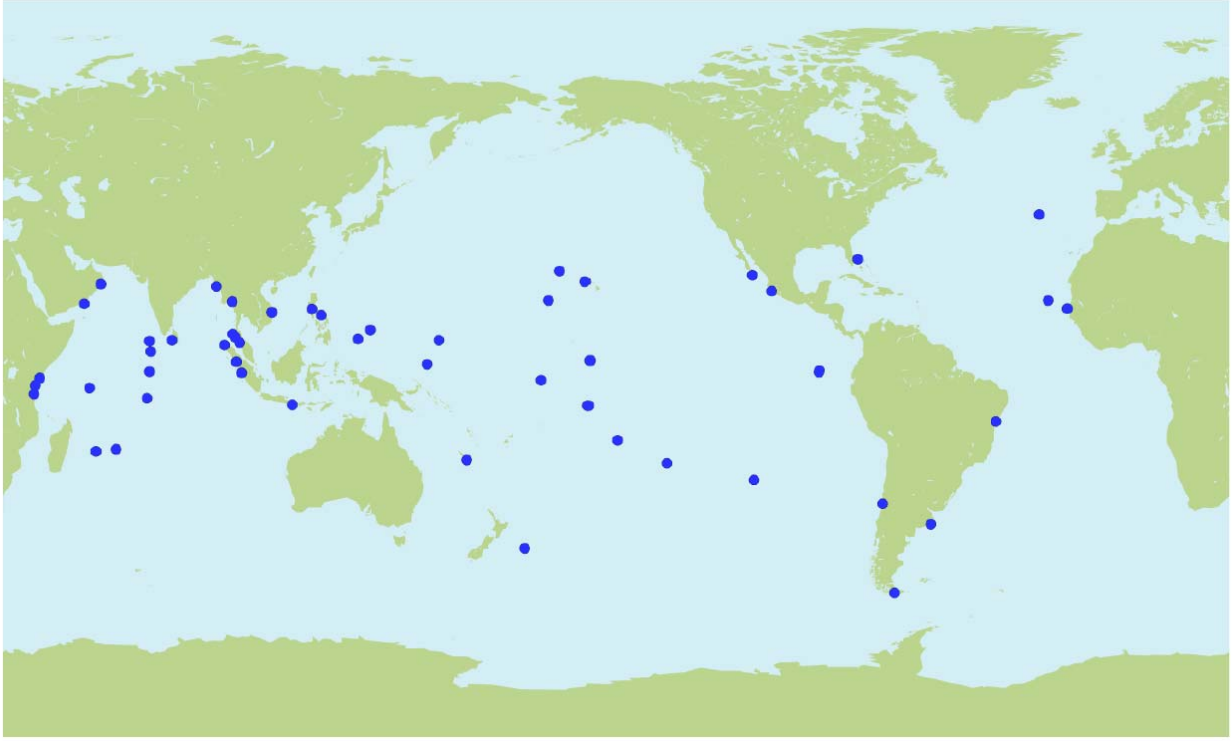

Figure 1. Tide gauge stations operated and maintained with assistance from the UHSLC.

New station installations and upgrades of existing OCO stations during October 2005-November 2006 were made primarily in the Indian Ocean in support of the implementation of the Indian Ocean Tsunami Warning System (IOTWS) (Table 1). All but 3 involved substantial financial

support from co-sponsoring agencies (the Intergovernmental Oceanographic Commission, IOC; the Asian Disaster Preparedness Center, ADPC; and USAID). Our ability to accomplish these installations at low costs to the co-sponsors 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. All 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.

Station	**Country**	**Date of Visit**	**Co-Sponsor**
Ko Taphao Noi	Thailand	2005/10	ADPC
Ko Meang	Thailand	2005/11	ADPC
Sibolga	Indonesia	2005/12	USAID
Padang	Indonesia	2006/02	IOC
Sabang	Indonesia	2006/02	IOC
Benoa	Indonesia	2006/02	IOC
Manila	Philippines	2006/03	
Legaspi	Philippines	2006/04	
Masirah	Oman	2006/03	IOC
Salalah	Oman	2006/03	IOC
Male	Maldives	2006/05	IOC
Gan	Maldives	2006/05	USAID
Hanimaadhoo	Maldives	2006/05	USAID
Colombo	Sri Lanka	2006/05	USAID
Lamu	Kenya	2006/07	IOC
Zanzibar	Tanzania	2006/07	IOC
Langkawi	Malaysia	2006/07	IOC
Mombasa	Kenya	2006/07	
Point Larue	Seychelles	2006/08	IOC
Qui Nhon	Viet Nam	2006/08	ADPC
Diego Garcia	United Kingdom	2006/09	IOC
Sittwe	Myanmar	2006/09	IOC
Moulmein	Myanmar	2006/09	IOC

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 10,651 station-years, including 6,054 station-years at 217 GLOSS sites. Of the 101 GLOSS stations that are presently operating on islands, 98 are available through the JASL. The 2006 submission of the JASL data to the World Data Center-A for Oceanography included 134 series that contained measurements through the year 2005.

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 181 stations, 142 of which are located at GLOSS sites, and 105 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 approximately 180 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.

GCOS Network Status

The UHSLC is working with GLOSS and international partners to bring the 180 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 some sort of 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 35 new GCOS stations into the near-real time data stream, so that 57% of the network is at that capability. An additional 11 stations report within a month as part of the Fast Delivery database. We expect many of these stations to transition to near-real time as upgrades continue, particularly in response to recent tsunami network improvements. 70 of the GCOS stations have nearby GPS or DORIS for datum control. Immediate implementation plans for the GCOS network are described in the FY2007 work plan.

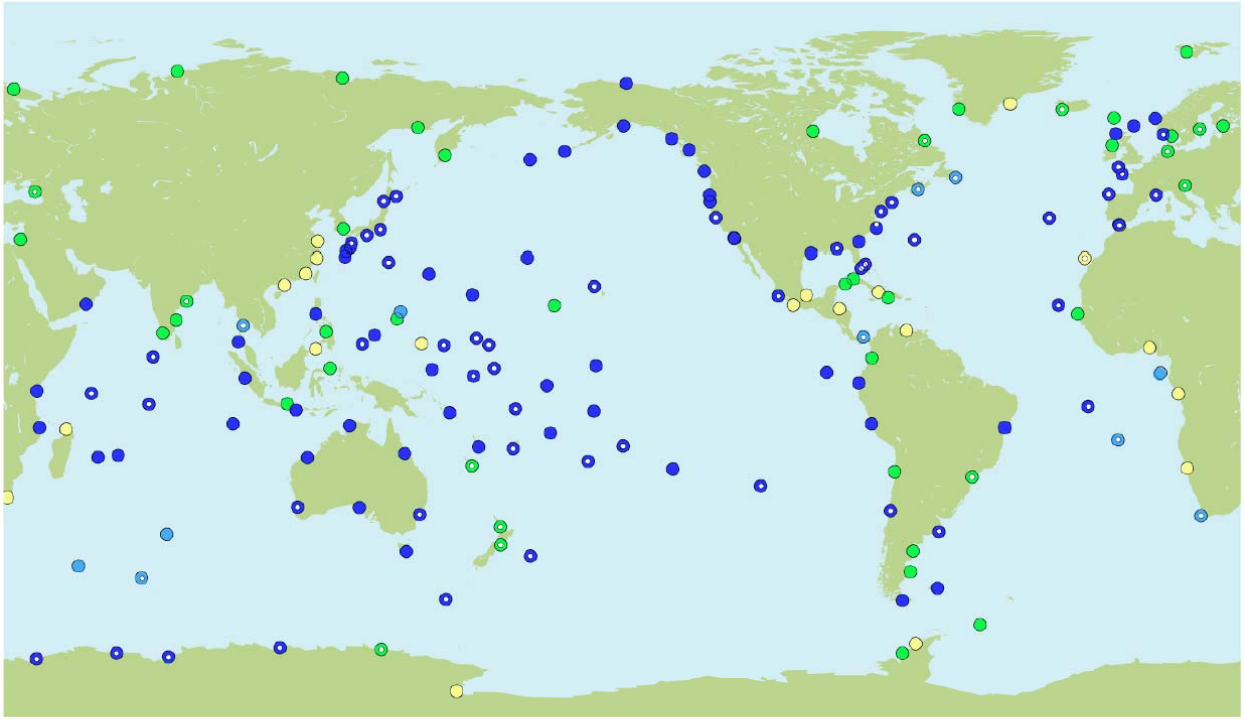

Figure 2. Summary of GCOS station data availability at UHSLC as of November 2006. "Data < 2000" indicates that hourly averaged data are not available after 2000. "Data > 2000" indicates that hourly averaged data are available after 2000, but not in Fast or Near Real-Time modes. Stations with nearby GPS/DORIS are indicated with a white dot.

Research Highlights

Research during FY06 focused on annual reporting of sea level, extreme events, and sea level rise estimates.

A method for estimating relative sea level rise using a combination of tide gauges, SAR, and GPS measurements was presented using the Southern California coastal region as a case study in a GRL manuscript (Brooks et al., 2006). SAR images are used to estimate vertical ground motion along the entire coastal strip. Tide gauge and GPS information are then incorporated to give a full description of relative sea level variability along the coastline. We are exploring the use of this method for the San Francisco Bay and Seattle/Tacoma metropolitan areas.

A climatology for extreme events is being developed for GLOSS tide gauges. The method produces annual exceedence estimates for extreme water levels, and determines the contribution

to these extremes caused by seasonal heating, tidal variations, and short-term meteorologically-forced events at each site. This work was presented at the WCRP Paris Sea Level Workshop and a manuscript is in preparation.

An estimate of land motion at all of our colocated GPS tide gauge stations was presented at the Jason Science Working Team meeting in Venice, Italy. We are evaluating how reference frame uncertainties affect these estimates. A paper is in preparation describing how land motion corrected trend estimates from these sites compare to recent altimeter estimates.

We took part in the second OCO contribution to the BAMS State of the Climate report, describing sea level patterns during 2005, and an update of global sea level rise estimates (Merrifield et al., 2006).

A summary of sea level rise estimates based on tide gauge and satellite altimeter datasets was presented at the WCRP Paris Sea Level workshop (Merrifield et al., 2006).

Conferences, Meetings, Expert Panels, and Working Groups

- December 2005 – Attended the Intersession Working Group for Sea level at the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWS), Second Session, Hyderabad, India.
- February 2006 – Presented "ICG/IOTWS-II: Working Group for Sea Level" at the NOAA International Tsunami Project Team Meeting in Seattle, WA.
- March 2006 – Presented "The Global Sea Level Observing System (GLOSS)" at the 6th Meeting of the North Indian Ocean Hydrographic Commission (NIOHC) in Colombia, Sri Lanka
- April 2006 – Attended the IOTWS Regional/National Tsunami Warning Center/Watch Provider CONOPS Workshop, Honolulu, Hawaii
- April 2006 - Met with ADPC in Bangkok concerning the Southeast Asia Tsunami Warning System.
- April 2006 – Attended and presented "The Global Sea Level Observing System (GLOSS)" at the International Round Table Dialogue on Earthquake and Tsunami Risk in Southeast Asia and the South China Sea Region.
- April 2006 – Attended the ICG/IOTWS-II Intersession Working Group for Sea level meeting in Melbourne, Australia.
- May 2006 – Attended the 21st Session of the ICG-PTWS-XXI, Melbourne, Australia.
- June 2006 - Co-chaired the working group on "20th Century Sea Level Change Estimates from Tide Gauges and Altimeters" at the WCRP Sea Level Workshop, Paris, France.
- August 2006 – Attended the ICG/IOTWS Intersession Working Group for Sea level at the ICG/IOTWS Third Session, Bali, Indonesia
- August 2006 - NOAA International Tsunami Project Team Meeting, Seattle

PUBLICATIONS AND REPORTS

Brooks, B. A., M. Merrifield, J. Foster, C. L. Werner, F. Gomez, M. Bevis, 2006: Space geodetic determination of spatial variability in relative sea level change, Los Angeles basin, accepted *Geophys. Res. Lett.*, 2006.

Caldwell, P. and M. Merrifield, 2006. Joint Archive for Sea Level Annual Data Report: March 2006. JIMAR Contribution No. 06-360, Data Report No. 19, SOEST, University of Hawaii, 41 pp.

Merrifield, M. A., S. Gill, and G. T. Mitchum, 2006: *Sea Level*. In chapter 3 of the "State of the Climate in 2005", K.A. Shein (ed.), *Bulletin of the American Meteorological Society*, **87** (6), S28-S29.

Mitchum, G. T., R. Steven Nerem, and M. A. Merrifield, 2006: 20th Century Sea Level Change Estimates from Tide Gauges and Altimeters, in Understanding Sea Level Rise and Variability, Ed. J. Church, P. Woodworth, T. Aarup, S. Wilson, in preparation.

NATIONAL WATER LEVEL PROGRAM SUPPORT TOWARDS BUILDING A SUSTAINED OCEAN OBSERVING SYSTEM FOR CLIMATE

Stephen K. Gill, Chris Zervas, and Lori Fenstermacher
NOAA/National Ocean Service
Silver Spring, Maryland 20910

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 the NOS Center for Operation 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 the NOAA National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) is providing support:

1) upgrade the operation of selected National Water Level Observation Network Stations to ensure continuous operation and connection to geodetic reference frames.

2) operate and maintain water level measurement systems on Platform Harvest in support of calibration of the TOPEX/Poseidon and Jason 1 satellite altimeter missions.

An ancillary task, to develop and implement a routine annual sea level analysis reporting capability that meets the requirements of the Climate Observation Program, is described elsewhere in this report.

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 a new 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 used by the Climate Program Office are very much the same as used for the NOAA National Water Level Program (NWLP) for which the National Water Level Observation Network (NWLON) is a long-term continuous operational oceanographic network that's strives to meet 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 also consists of technology development, continuous

quality control, data base management, and operational readiness and fully open web-site for data delivery. These data and related sea level products are made available over the web-site for use by PSMSL, UHSLC, and the WOCE communities.

1) Task One – Upgrade 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 stations of the National Water Level Observation Network (NWLON) has been increasingly more difficult over time due to the slow abandonment of the island facilities at which the stations reside. Finding routine flights and flights which are cost effective are 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. For example, the NWLON station at Johnson Island was recently de-commissioned because of the stoppage of routine access to the island.

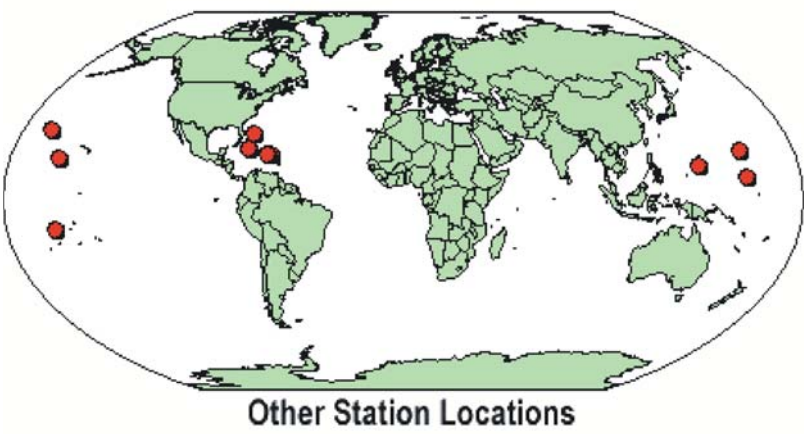

Figure 1. Ocean Island NWLON Station Map

Although operation of all of the long term NWLON and GLOSS stations is important, it is proposed that NOAA NWLON Ocean Island stations begin to be upgraded first with this funding to ensure their continuous operation (program funding and budget initiatives will be used for operation of the coastal stations). These targeted funds will be used for travel costs and for upgrade to backup systems. The upgrades will 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 will also be enhanced with GPS connections to geodetic systems followed by installation of 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.

Station:	CORS Operating
Guam	Yes
Kwajalein	Yes
Pago Pago	Yes

Wake	No
Midway	No
Adak	No
Bermuda	Yes
San Juan. PR	Yes
Magueyes Island, PR	No
Charlotte Amalie, VI	No
St Croix, VI	Yes

2) Task Two - 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 1983 (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. Hanes et al, Special Issue of Marine Geodesy, 2003 "The Harvest Experiment: Monitoring Jason-1 and TOPEX-Poseidon from a California Offshore Platform".

Figure 2. Platform Harvest Calibration Site at which NOAA tide gauges are located.

CO-OPS special support has included a vertical survey 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 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 and routine an 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.

FY2006 Progress

Task One:

Maintenance and upgrade of the ocean island NWLON stations continued. Redundant stations were installed at Wake and Pago Pago in FY 2006. The redundancy included the installation of additional DCP's and sensors at nearby, but independent, locations from the existing primary locations.

Figure 3. The NOAA tide station at Wake Island, which now includes redundant equipment

Task Two:

Operation and maintenance of the Platform Harvest station continued the past year. Coordination of activities continues with JPL. One of the pressure systems requires repair to bring it back online, however continuous data have been maintained. JPL is arranging for underwater maintenance of the bubbler pressure system orifices. JPL continues to provide reports on the status of the verification project at Platform Harvest.

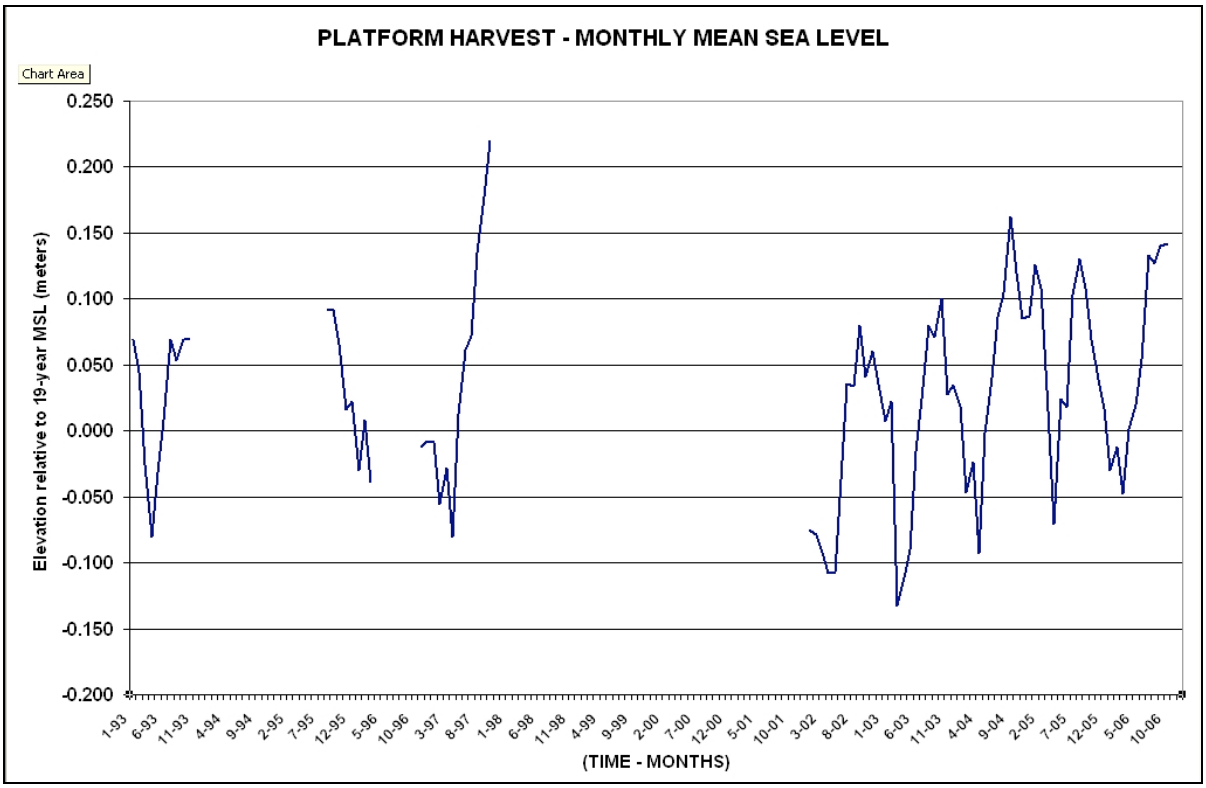

Figure 4. Platform Harvest Calibration Site – Observed Monthly MSL from the Tide Station

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

02. Drifting Buoys:

a. The Global Drifter Program
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. The principal climate index of oceans is sea surface temperature (SST) through which the atmosphere climate is forced to follow the oceans' change. A global array of drifters provide the operational instrumental data sets describing ocean surface circulation and SST 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) can now be added to drifters and these SSS data are critical to determining the oceans' fresh water cycle and onset of deep-water renewals. Atmospheric pressure measured on drifters is assimilated into weather prediction models and is used by operational meteorological agencies to discern severe weather conditions over the oceans. Wind sensor and subsurface temperature chain data are used to improve prediction of tropical storm and hurricanes. Drifters 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 JCOMM *"Global Surface Drifting Buoy Array"*. It is a "Scientific Project" of the DBCP of WMO/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 atmospheric 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, presently on a limited basis 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 an near-operational, near-real time data stream of SST, sea level pressure and surface velocity.

2) Observe the mixed layer velocity on a global basis with 0.5° resolution and, jointly with satellite altimeter data, produce charts on the seasonal and interannual changing circulation of the world ocean at 0.5° resolution.

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 (Figure 1).
• 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

GDP began in 1988 as a World Climate Research observational program in the tropical Pacific. Between 1992 and 2003, an array of approximately 600 SVP drifters was maintained in the global ocean with contributions of resources from a variety of operational and individual research programs. Since October 2003 the array has increased from 800 to of over 1300 drifters in 2006. Thus, full implementation of the required global array for SST observations was completed in September 2005 with the deployment of the 1250th element of the global array (Figure 3).

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 5° resolution, or the spatial scale of the error covariance function of operational NOAA satellite infrared SST sensors. Surface pressure sensors are supported by regional meteorological agencies based on regional needs. The actual number of drifters in the array has been larger than 1250 because the required uniform spatial distribution is difficult to maintain in the complex ocean surface circulation and many drifters go ashore in remote locations and continue to transmit.

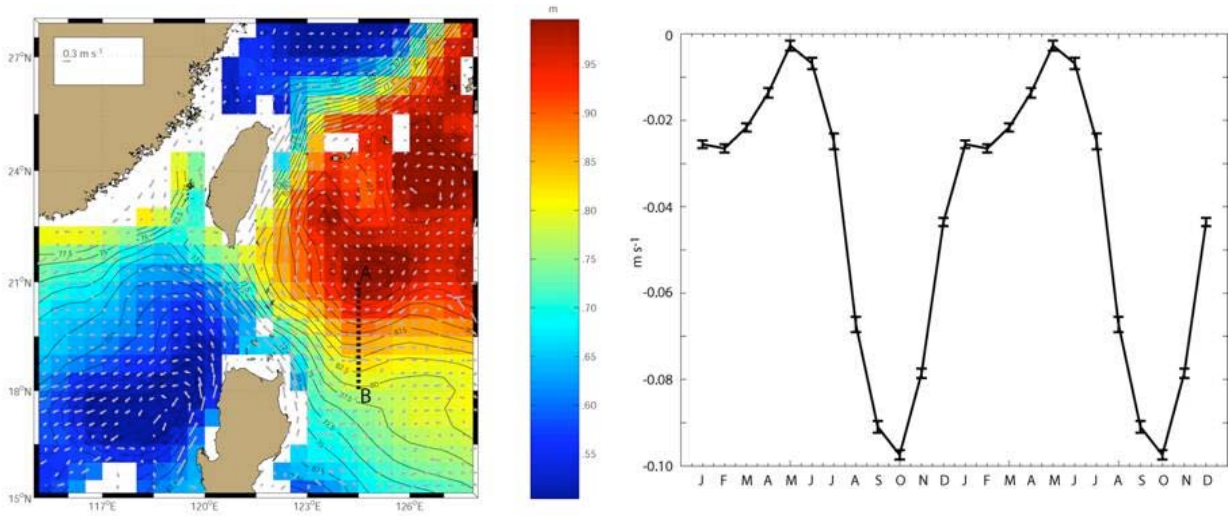

Figure 1. The mean geostrophic velocity of the Luzon Strait and Philippines Sea during northeast monsoon (Oct.-Jan.) overlain on the absolute dynamic topography (left panel). These data were produced with the combination of satellite altimeter, GRACE and drifter data and is available from GDP on a global basis. The A-B latitude average zonal velocity component from left panel. The strongest flow into the South China Sea across the Luzon Strait from the Philippines Sea occurs during the month of October.

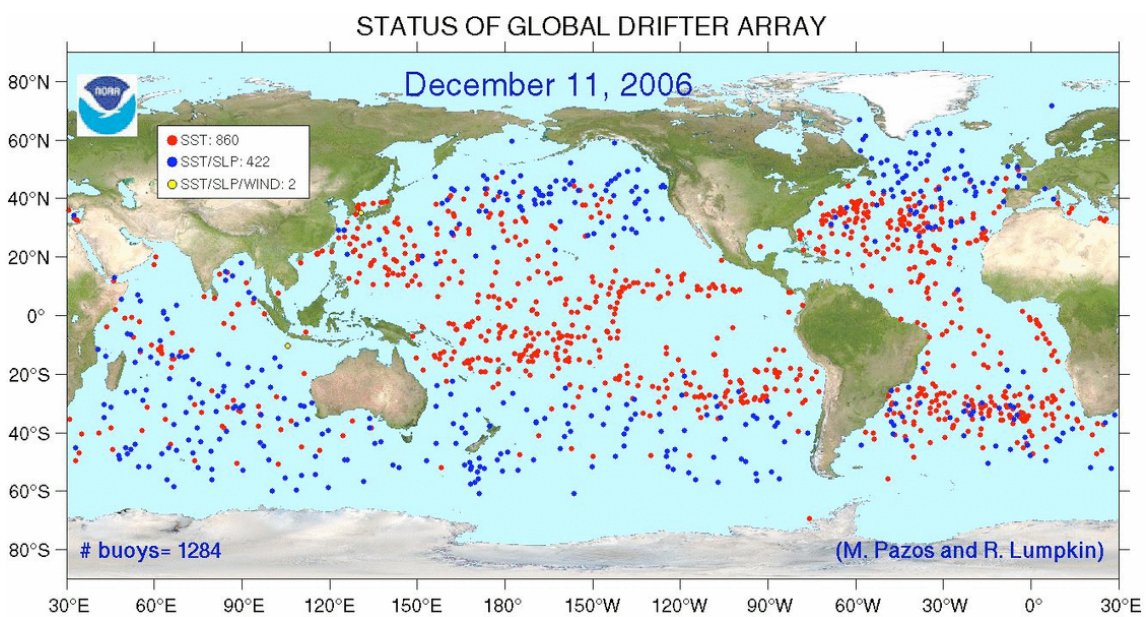

Figure 2. The *Global Drifting Buoy Array* on December 11, 2006.

Figure 3. Peter Niiler (left front) and Mike Johnson (right front) deploy SVP-B #1250 off the coast of Nova Scotia on September 18, 2005. The Global Drifter Array was the first international observing system of JCOMM to be completed and has been maintained at full 1250 drifter level since 9/18/05.

On December 11, 2006, 1296 of the 1250 'required' drifters are reporting to GTS and to the AOML *Drifter Data Center* (Figure 2). NOAA Climate Observations Program, funded to JIMO (920) and AOML (80) sufficient numbers of SVP drifters in FY'06, and with the contributions of drifters (200-300) from other national and international sources, the array was fully maintained from September 2005 to present date at the desired level. In 2007 the efforts will continue to adjust the array spatial density with the desired uniform coverage. Present distribution covers about 60%-70% of the surface of the ice-free ocean at 5º resolutions.

The international science bodies, such as JCOMM, require that the drifter array is to provide instrumental observations of SST and the operational met agencies desire to provide atmospheric pressure observations from as many drifters as possible. To this latter end, the DBCP ('06) requested these met agencies now begin to provide funds in earnest to attach a barometer to every SVP drifter. Even though no internationally mandated operational requirement for surface velocity exists, nearly all research program contributions to the drifter array have been justified on the basis of upper ocean velocity

observations. In the research community 99% of reviewed scientific research papers make principal use of drifter velocity observations: (viz. list of peer-reviewed research publications at: http://www.aoml.noaa.gov/phod/dac/drifter_bibliography.html). We anticipate that a surface velocity observation requirement will also be instituted in the next overview of climate observations requirements.

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 largely a NOAA funded program and is managed according to the *"Ten Climate Monitoring Principles"* established by JCOMM. In these management tasks, the principal investigator, 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 Carlsbad, CA*)* who build the SVP drifters according to closely monitored specifications. Internationally, a total of 6 private firms and 3 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).

• 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 upgrades 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.

This continuing proposal from JIMO addresses the progress of activities in FY'06 and proposes the activities for FY'07.

2. FY'06 Progress

In FY'06 NOAA Grants office funding of the *GDP* through JIMO occurred in the last week of September 2006. Additional funds were provided for a one-time acquisition 22 thermistor chain drifters for hurricane studies. This is a report of what was accomplished with both the FY'05 and FY'06 funding during the period of September 2005 - August 2006:

1. *Summary of Drifter Acquisitions and Technology: With the FY'05 funds 940 drifters with SST sensors were built and were delivered to AOML for deployment. With the FY'06 funds, 940 drifters were ordered in October 2006 and are now being*

delivered to AOML for deployment. In 2005, all 20 drifters deployed into Hurricane Rita worked well (12 were SVP-W wind drifters and 8 were SVP-T(z) thermistor chain drifters). Because of the operational success of the Rita deployments 22 SVP-T(z) thermistor chain drifters with air deployment capability, were built as an-add on project in with 2005 funds. All air deployable drifters were delivered to Keesler AFB for deployment for the 2006 hurricane season. Because no hurricane approached the US coast in 2006, there now are 30 SVP-T(z) and 12 Minimet drifters at Keesler AFB fully rigged for air-deployment in the 2007 hurricane season. With the FY'06 funds:

a) A total of 680 SVP-Mini 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 240 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 Minimet wind-drifters and 8 SVP-T(z) thermistor chain drifters, fully rigged for air deployment, were ordered from Pacific Gyre, Inc. This is the first time 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 June 1, 2007. Dr. Rick Lumpkin and Dr. Peter Black at AOML are jointly directing the deployment of what will now be 62 hurricane drifters in the 2007 hurricane season.
d) In April 2005 12 SVP drifters with salinity sensors were deployed in the Bay of Biscay by the French Met. Service. These were calibrated at various times against CTD measurements. Dr. Gilles Reverdin of the University of Paris directed this study and a multi-author paper was accepted in November 2006 for publication in the *Journal of Ocean and Atmospheric Technology* on the results (*Abstract* below).

In FY'06 JIMO has purchased 940 drifters and AOML purchased 60 drifters, for total NOAA contribution of 1000 drifters to the JCOMM *"Global Surface Drifting Buoy Array".*

2. Enhanced Data Sets and Publications: Between Octobe 2005 and December 2006, there were 18 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).

3. Meetings and Lectures: The following JIMO personnel participated in the GDP presented lectures or attended the following organization meetings:

• DBCP-XXII, October 15-20, La Jolla, CA: "Permanent Meanders in the California Current System and Comparison of Near-Surface Observations with OGCM Solutions" (Luca Centurioni, Peter Niiler and Carter Ohlmann)

• DBCP-XXI, October 16-19, Buenos Aires, Argentina: " Hurricane Drifter Thermistor Chain Deployment Results" (Bill Scuba, Jan Mozel and Peter Niiler). Bill Scuba is the co-organizer of the DBCP Technical Session in 2005 and 2006.
• DBCP-XXII, October 15-20, La Jolla, CA: "Global Drifter Program" (Rick Lumpkin of AOML for Peter Niiler)
• Invited Lecture at the SIO Director's Council, SIO, March 3, 2006: "The Global Ocean Surface Circulation" (Peter Niiler)
• Ocean Climate Observations Workshop, May 10-12, 2006, Silver Spring, MD (Peter Niiler)
• Invited Lecture at the workshop on *Climate Effects on California Current Ecosystems,* November 15, 2006: "Unresolved Physics in the Circulation Models of the Coast" (Peter Niiler"

Appendix

"Surface salinity measurements – COSMOS 2005 experiment in the Bay of Biscay"

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Abstract

Sea surface salinity (SSS) data were collected in the Bay of Biscay between April and November in the Bay of Biscay. The major source of data is from 15 surface drifters deployed during the COSMOS experiment in early April and early May 2005 (12 from SIO, and 3 from METOCEAN). This is complemented by thermosalinographe (TSG) data from four French research vessels, four merchant vessels, from salinity profiles collected by ARGO profiling floats and CTD casts, and from surface samples during two cruises. Time during two cruises was dedicated to provide direct inspection of the drifters, recover some, and provide validation data. This data set provides a unique opportunity to estimate the accuracy of the SSS data, and to evaluate the long term performance of the drifter salinities. Some of the TSG SSS data presented a large noise, presumably from bubbles. The TSG data from the research vessels needed to be corrected from biases, very commonly larger than 0.1 pss-78 (practical salinity scale), and which in some instances evolved quickly from day to day. These corrections are only available when samples were collected or ancillary data are available (for example from CTD profiles). The resulting accuracy of the corrected TSG data set is discussed, and varies strongly in time. The surface drifter SSS data presented anomalous day-time values during days with strong surface warming. These data had to be excluded from the data set. The drifter SSS presented initial biases in the range 0.009 to -0.026 pss-78. The (usually) negative bias increased by an average of -0.007 pss-78 during the average 65 days period before the COSMOS-2 cruise on June 22-27. High chlorophyll derived from satellite ocean colour and therefore high density of phyto-planktonic cells is observed in MERIS/MODIS composites during part of the period in particular in late April or early May. No correlation was found between the change in bias and the estimated surface chlorophyll. Evolution during the following summer months is harder to ascertain. For

three buoys, there is little change in bias, but for two others, there could have been an increase in bias by up to 0.03 or 0.04 pss-78 during July- August. Seven drifters were recovered in the autumn, which provide recovery or post-recovery estimates of the biases, suggesting in three cases (out of seven) a large (0.02 to 0.03 pss-78) increase in bias during the autumn months, but no significant increase for the other four drifters.

Surface Drifter Program

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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 (IOOS) and a scientific project of the Data Buoy Cooperation Panel (DBCP). The primary goals of this project are to maintain a global 5°x5° array of ARGOS-tracked Lagrangian surface drifting buoys to meet the need for an accurate and globally dense set of in-situ observations, 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 and monitoring. AOML's GDP responsibilities are to: (1) 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 and archive the data at AOML and at MEDS (Canada); (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), near surface (mixed layer) currents, air pressure and wind observations needed to (a) calibrate SST observations from satellite; (b) initialize SI forecast models; and (c) provide nowcasts of the structure of global surface currents. Global drifter coverage is required as present forecast models simulate not only Pacific conditions but also global conditions to improve prediction skill. 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.

Of particular interest is the data collected in the Tropical and subtropical South Atlantic. Large-scale SST distributions drive the response of the climate in the tropical Atlantic sector, and over land areas as distant as the southern and eastern Unites States. In spite of its importance, no dynamical model has successfully predicted tropical Atlantic SST one-to-several seasons in advance. The current generation of coupled ocean-atmospheric models cannot reproduce, much less predict, the SST in the tropics. A recent comparison of 23 GCM results (Davey et al., 2002) concentrated on simulated fields from the tropical oceans (i.e. SST, zonal wind stress and upper layer depth averaged temperature). In the Atlantic Ocean, discrepancies between the model and observed mean states were dramatic. Specifically, in the equatorial Atlantic, the simulated meridional temperature gradient was wrong, with cold temperatures in the west and warm temperature in the east (Figure 4, Davey et al., 2002[1]). While some very recent experimental coupled models demonstrate improvements in simulating these SST distributions, their parameterization of the underlying physical processes must be carefully evaluated against in-situ observations before operational coupled models can be reliably improved. Beyond these issues, the variability of the subtropical Atlantic and its interaction with the tropics is far from understood, primarily due to the paucity of data that for years have been mainly collected in the major commercial lanes. The variability of the inter-tropical convergence zone (ITCZ) is highly sensitive to changes in SST gradients within the broader tropical Atlantic region, particularly in the meridional direction south of the tropics and during boreal spring (Kushnir et al., 2003). To better understand this variability, improved SST products must be developed and calibrated/validated with in-situ observations. Starting in 1998, a new component was added to this sustained program to fill existing gaps in the observational network, by deploying additional surface drifters in the tropic and subtropical South Atlantic (30°N to 40°S). The main objective was to accurately describe the basin-scale Atlantic currents system and SST seasonal to interannual variations, and the effects of the variability in the climate of the surrounding areas. During FY06, this grant received additional support to deploy surface drifters in support of the CLIVAR Mode Water Dynamics Experiment (CLIMODE). The goal of this effort is to resolve eddy fluxes across the Gulf Stream front, where strong interannual variability is poorly simulated in present ocean models. Drifters in support of CLIMODE were deployed primarily from WHOI CLIMODE cruises in November 2005 and January 2006.

Accomplishments

The global drifter array became the first component of the IOOS that reached completion, with 1250 active in September 2005. This number has since been maintained. During FY06, the GDP coordinated worldwide deployments of 999 drifters, 851 funded by NOAA/OCO; 158 were deployed in the Atlantic between 30ºN and 40ºS. AOML managed observations from 2079 unique drifters during FY06 (this is greater than 1250, as some died while new ones were deployed to maintain ~1250).

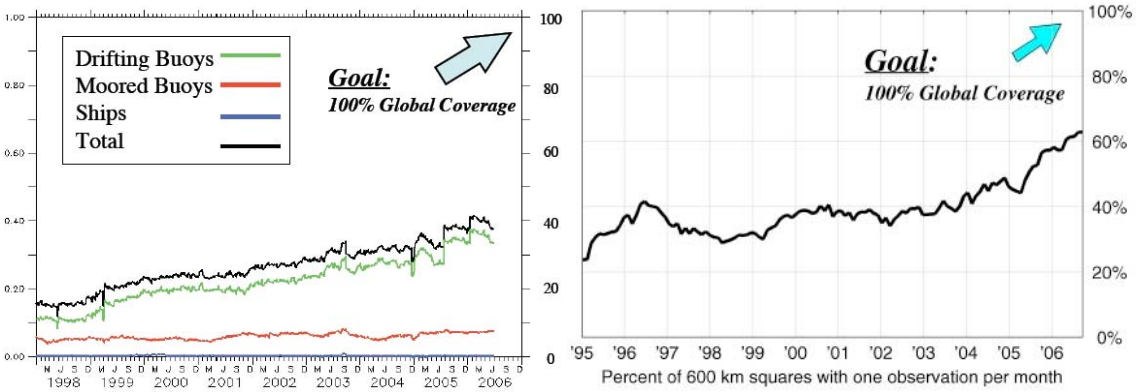

Fig. 1: FY06 Q4 reports evaluating the spatial coverage of the Integrated Ocean Observing System (IOOS) for SST (left) and near surface current (right) measurements. On the left, the black curve is for the entire IOOS; green curve is for surface drifters. Drifters dominate the overall IOOS' spatial coverage of near-surface current measurements.

The main challenge is now to increase the spatial coverage of the array while maintaining its size. We are addressing these challenges with a two-pronged strategy. First, we are actively seeking new ships to participate in the VOS program. For example, this year AOML has initiated drifter deployments from a Ghana-to-Cape Town vessel to help fill the gap in the Gulf of Guinea. We are also seeking deployments with a broader group of Global Drifter Program collaborators such as Kenya's Division of Oceanography and Marine Meteorology Services (20 drifters deployed in FY06 in a data-sparse region of the Indian Ocean). Second, we have developed a tool to predict the array coverage, in order to anticipate and plan for gaps before they develop (Fig. 2). These forecasts are publicly available at http://www.aoml.noaa.gov/phod/graphics/dacdata/forecast90d.gif.

In FY06 AOML completed a study of drifter performance from four manufactures. This evaluation was particularly valuable in reassessing drogue (sea anchor) presence on the drifters. Results led to a major effort to reevaluate drogue presence for all drifters deployed since 1998, initiated in FY05 and completed in May 2006. During the FY05 performance study, the GDP identified some systematic problems for individual manufacturers' drifters. Numerous interactions during FY06 were used to communicate these problems to the manufacturers and the broader DBCP community; the results of the FY06 comparison study demonstrated that the manufacturers have solved all of these problems.

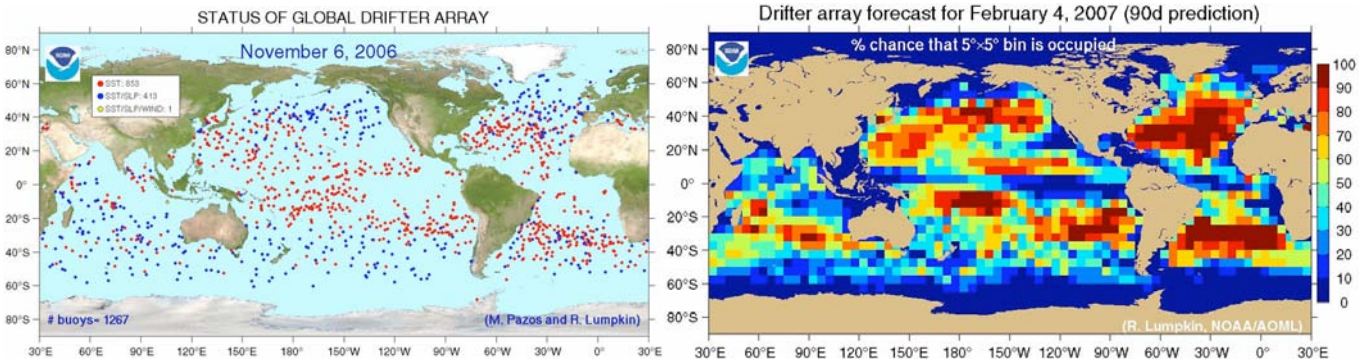

Fig. 2: Global population of drifters as of November 6, 2006 (array size 1267 drifters), and 90 day prediction of coverage (% chance that a 5°x5° bin will have a drifter if no additional drifters are deployed in the interim).

During FY06, the GDP conducted a major revision of the web pages used to distribute drifter data, information and products (http://www.aoml.noaa.gov/phod/dac/gdp.html). We have received uniformly positive feedback on these changes.

Publications and Reports:

- Lumpkin, R. and M. Pazos, 2006: "Measuring surface currents with Surface Velocity Program drifters: the instrument, its data, and some recent results." Chapter two of *Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics* (LAPCOD), ed. A. Griffa, A. D. Kirwan, A. J. Mariano, T. Ozgokmen, and T. Rossby.

- Garzoli S. L., B. Molinari and R. Lumpkin, 2006: Surface drifter program. In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* ed. J.M. Levy, D.M. Stanitski, and P. Arkin. NOAA Office of Climate Observation, Silver Spring, MD, 124-127.

- Lumpkin, R. and G. J. Goni, 2006: Global oceans: Surface currents. In *State of the Climate*

in 2005, K.A. Shein, A.M. Waple, H.J. Diamond, and J.M. Levy (eds.). Bulletin of the American Meteorological Society, **87**(6), S25-S26.

- Lumpkin, R. and G. J. Goni, 2006: Surface currents. In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 61-67.

03. Tropical Moored Buoys:

a. Tropical Moored Buoy Array Program
b. Tropical Atmosphere Ocean (TAO) Array
c. Tropical Atmosphere Ocean (TAO) Refresh

Tropical Moored Buoy Array Program

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1. Project Summary:

This report describes FY 2006 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 web site containing comprehensive information on the program can be found at http://www.pmel.noaa.gov/

Five major elements to the Tropical Moored Buoy Array program are described below. These are the Pilot Research Moored Array in the Tropical Atlantic (PIRATA), the Indian Ocean array, Flux Reference Stations, Tropical Salinity, and Engineering Development. Discussion of these elements is followed by comments about fishing vandalism, a summary of community service, and a list of FY 2006 publications.

2. Accomplishments

2.1 PIRATA

PIRATA is a joint effort between the U.S. (NOAA/PMEL and NOAA/AOML), France (Institut de Recherche Scientifique pour le Développement en Coopération [IRD] and Meteo-France), and Brazil (Instituto Nacional de Pesquisas Espaciais [INPE] which is the Brazilian space agency and Diretoria de Hidrografia e Navegacao [DHN] which is the naval hydrographic service). The program targets Atlantic climate variability and tropical storm formation in the maximum development region for hurricanes. PMEL is

charged with providing equipment, technical support for moorings and instrumentation, and support for data processing, dissemination, and display. AOML provides for collection of some key ship-based measurements in support of the mooring program. France and Brazil provide ship time and support for equipment shipments as part of a trilateral agreement to maintain the array. France and Brazil also provide technician support at sea. NOAA provided PIRATA ship time for the first time in FY 2006.

The 10-mooring PIRATA core array configuration (as agreed upon for the 2001-2006 consolidation phase of the program, plus three 'Southwest (SW) Extension" moorings sponsored by INPE in Brazil (first deployed in August 2005), were continued in FY 2006. A "Southeast (SE) Extension" mooring sponsored by the University of Capetown, South Africa, was deployed in June 2006, and two "Northeast (NE) Extension" moorings, sponsored by NOAA were deployed in June 2006. Thus for FY 2006 the total number of mooring sites occupied was 16.

For PIRATA, 8 new ATLAS moorings were deployed on 2 cruises in FY 2006. A total of 64 sea days were required to service these moorings. A 41-day cruise on the French R/V L'Atalante in May-June 2006 maintained 4 core moorings and deployed the SE Extension mooring. As has been the norm for the past several years the L'Atalante cruise was staffed entirely by technicians from IRD. A 51-day cruise on the NOAA Ship Ronald H. Brown in May-July 2006 maintained 1 core moorings and deployed the 2 NE Extension moorings. PMEL personnel spent 46 person-days and AOML personnel spent 144 person-days at sea on the Brown cruise. In addition to these scheduled cruises, the Brazilian DHN provided ship time to recover a SW Extension mooring which had gone adrift. Brazil did not provide ship time for scheduled maintenance in FY 2006. A cruise aboard the Brazilian R/V Antares is scheduled for October-December 2006 to provide maintenance for 5 core and 3 SW Extension moorings.

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 proposed as flux reference sites (see 2.3 below), two of which were enhanced for flux measurements in FY 2006.

PIRATA moored time series 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 are also mirror sites in France and Brazil. Collection, processing, and dissemination of shipboard CTD and ADCP data are the responsibility of France and Brazil.

Real-time data return was 75% overall for FY 2006, 3% higher than for FY 2005. Sites with the lowest data return were 0, 35W (28%), 6S, 10W (30%), 8N 38W (38%), and 0, 10W (66%). The mooring at 0, 10W was vandalized, went adrift in February 2006,

and went aground on the Coast if Ghana in March. Through the collaboration of IRD, the University of Ghana and PMEL, some of the surface instrumentation was recovered and returned to PMEL, along with the delayed-mode data contained in its memory. A new mooring was deployed at this site in June 2006. The mooring at 6S, 10W stopped transmitting in September 2005. When recovered in June 2006 it was found to have been vandalized. Delayed-mode data obtained from memory increased the data return from this site to 93%. Much of the real-time data loss at 8N, 38W and 0, 35W is due to loss of subsurface measurements. These sites have not yet been recovered, but all or some of these data may be available after the moorings are recovered in November 2006. PIRATA data return remains lower than data return for TAO/TRITON of 82%. The difference between the two arrays relates to the greater susceptibility of the smaller PIRATA array to fishing vandalism and to a less frequent servicing schedule (one per year or less vs. twice per year for much of the Pacific).

Real-time PIRATA data return by variable for FY 2006 (and for comparison, FY 2005) is shown below.

	AIRT	SST	T(Z)	WIND SAL	RH	Rain	SWR		ALL
FY 2006	72	78	73	91	67	74	87	72	75
FY 2005	78	69	74	70	78	72	76	66	72

During the May 27—July 16 2006 PIRATA Northeast Extension (PNE)/AMMA cruise of the R/V Ronald H. Brown, NOAA/AOML personnel and AMMA collaborators collected a suite of observations in support of PIRATA and AMMA. A total of 105 CTD and LADCP casts were conducted to 1500 m depth, including casts at the PIRATA sites 15ºN, 38ºW; 11.5ºN, 23ºW; 4ºN, 23ºW; 0º, 23ºW, and the future PNE site 20.5ºN, 23ºW. Seabeam bathymetric surveys were conducted at these PIRATA sites while occupying the stations. Continuous shipboard ADCP measurements were made along the track by the 75 kHz Ocean Surveyor system, including the meridional 23ºW section from 20.5ºN to 5ºS. The cruise was also used to opportunistically deploy 15 Argo floats, 21 surface drifting buoys, and 105 expendable bathythermographs in the northeast Tropical Atlantic region. All XBT temperature profiles and CTD temperature/salinity profiles were transmitted in near-real time on the Global Telecommunication System (GTS) for model calibration and validation. While XBT data is commonly transmitted on the GTS from Voluntary Observation Ships, this is the first time to our knowledge that CTD profiles have been transmitted in near-real time on the GTS for weather and climate prediction. Meteorological observations collected by AMMA collaborators on the cruise include skin SST, radiation, direct turbulent flux measurements, and atmospheric sonde and ozone sonde profiles.

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 2006, a total of 12943 separate user requests delivered 47,354 PIRATA data files. These numbers are up 234% and 79%, respectively from the year before.

PIRATA data are distributed via the GTS to centers such as NCEP, ECMWF, and Meteo-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 Monterrey, California.

2.2 Indian Ocean

The Indian Ocean influences the dynamics of the Indian and Asian monsoons. It also remotely affects the climate over the US and North America via monsoon-ENSO interactions and via atmospheric intraseasonal oscillations which are spawned over the Indian Ocean. The Indian Ocean is much less well sampled than either of the other two tropical basins however, resulting in serious limitations in the ability to predict seasonal-to-interannual climate variability. Thus, international planning efforts assign a high priority to establishing a comprehensive *in situ* observing system in the Indian Ocean. As in the two other tropical basins, a broad scale Indian Ocean moored buoy array will form the cornerstone of systematic *in situ* ocean measurement efforts designed to improve description, understanding, and prediction of large ocean-atmosphere interactions and their influence on regional and global climate. The CLIVAR/GOOS Indian Ocean Panel has developed a design for this array available at http://www.clivar.org/organization/indian/.

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. Four ATLAS moorings (at 1.5N, 0, 1.5S and 80.5E; and0, 90E) and one subsurface ADCP mooring (at 0, 80.5E) were deployed by PMEL and India's National Institute of Oceanography from the Indian R/V Sagar Kanya in October-November 2004. The 0, 80.5E ATLAS mooring was enchanced for flux refererence measurements (see 2.3 below)

All four of the surface moorings were vandalized to some degree with transmissions stopping at 1.5N, 80.5E in January 2005, at 1.5S, 80.5 E in May 2005, and at 0, 80.5E in August 2005. While transmissions did not stop at the 0, 90E mooring, no good data were

received after May 2006. The ATLAS mooring design lifetime is 1-year, but ship time for maintenance of these moorings was not available until August 2006. None of the moorings along 80.5E were recovered. The 0, 90E mooring had been stripped of most sensors and was fouled with fishing line. As might be expected, the combination of vandalism, plus the lack of annual maintenance, FY 2006 real-time data return from Indian Ocean ATLAS mooring sites was low, 12%. The subsurface ADCP mooring was recovered and returned 100% data for its 22 month long deployment. New moorings were deployed at all sites, plus an additional ATLAS mooring at 1.5N, 90E, by the ORV Sagar Kanya in August-September 2006.

PMEL is working with international partners to develop new resources for expansion of the Indian Ocean moored buoy array. With invaluable assistance from Sid Thurston of NOAA's Office of Climate Observation, we have been granted 15 sea days on RV Baruna Jaya I from Indonesia's BPPT for deployment of 2 additional ATLAS moorings in November 2006. .

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. PMEL is a major contributor to OceanSITES in the context of the Tropical Ocean Atmosphere (TAO) mooring array in the tropical Pacific, the Pilot Research Moored Array in the Tropical Atlantic (PIRATA), and the Indian Ocean moored buoy array under development. Four equatorial Pacific moorings within the TAO Array, three PIRATA moorings, and eight moorings in the Indian Ocean have, or are scheduled to have, full air-sea heat, moisture and momentum flux measurement capability. Enhancements to the primary measurements of 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 multiple depths. All 4 TAO moorings (along the equator at 110W, 140W, 170W, 165E), 2 of 3 PIRATA moorings (10S, 10W and 0, 23W), and 1 Indian Ocean ATLAS mooring (0, 80.5E) were enhanced for flux measurements in FY 2006.

2.4 Tropical Sea Surface Salinity

The goal of this program element is to ensure that all tropical moorings measure sea surface salinity (SSS) for improved documentation of SSS variability, ENSO forecasting, and validation of satellite salinity missions scheduled for launch in 2007 (SMOS by the Eurpoean Space Agency) and in 2009 (Aquarius by NASA). Funding in FY 2006 provided support to instrument moorings of TAO array, which is that last of the arrays in the three ocean basins needing SSS sensors. At the end of FY 2006 all PIRATA and

Indian Ocean moorings, and 33 of 55 TAO moorings were equipped to measure surface salinity. Additional instruments were procured in FY 2006 and will be used to increase the number of moorings making surface salinity measurements in FY 2007.

2.5 Engineering Development

The goal of this program element is to design and develop a next generation mooring system for use in NOAA's tropical moored buoy arrays. This effort builds on the 30 years of expertise at PMEL in moored buoy programs and takes into account requirements for improved measurement and data transmission capabilities in the future.

Funding was received in April '06 and we accomplished several steps in advancing the state of NOAA's in-situ open ocean observation systems. We are developing PICO (Platform and instrumentation for Continuous ocean Observations) mooring system which makes 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. This effort is motivated by the need to develop a mooring 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. Specifically we are developing a self deployed surface mooring technology designed with the following characteristics:

- Low cost
- Significantly safer operations
- Ship of opportunity deployable
- Rugged & self-deploy
- Pre-packaged and palletized
- Vandal resistant

A machine was built to simulate high cycles of ocean deployments for tension and bending of mooring lines and termination. The DLT (Dynamic Line Testing) machine consists of variable speed rotating spindle, that simulates bending and a ball-screw linear actuator that simulates tension. From this machine, we are starting to learn important interactions and failure mechanisms of mooring line construction and necessary bending strain relief in the upper 1-2m of the mooring.

New Seabird OEM inductive modems have been procured and tested on the bench and on PICO mooring lines. Findings of the tests include the need for a small and easy to manufacture electrode at the bottom of the inductive section of the mooring line. Planned deployment is for early 2007.

We determined the physical properties of PICO lines and built a base PICO mooring model. Mass, wet weight and diameters were obtained from manufactures specifications, backed up with actual measurements of test segments. Preliminary efforts

concentrated on 3 potential problem areas in the baseline mooring design, 1) Termination, 2) Jacketed rope and 3) Weighted section. Results of this effort were captured as part of an internal 22 page engineering report.

This recent design effort on the PICO Profiler follows on the success of previous steps which validated the basic concepts: The integrated mooring and profiler self deployment scheme; subsurface telemetry from a profiler on the mooring line; wave driven mechanism to move the profiler along the mooring line. The profilers developed and used for those tests were limited in scope but clearly showed the actual profiler must be very robust and have a small virtual mass. Consequently, we focused on power requirements (to minimize batteries or power generation requirements) and on materials that would provide high strength and low weight with limited corrosion potential.

A cast titanium 'drive pawl' was refined and fabricated to grip the mooring line when engaged. A small neoprene rubber link was designed to attach the pawl to a unique magnetic actuator. The failure mode and lifespan of elastomer materials are being evaluated with a custom made fixture that cycles the parts in cold sea water. A link will see approximately 6 million cycles so this small element deserves a significant effort.

The magnetic actuator is imbedded in a carbon filled PEEK tube which has been machined and tested for structural properties in the PMEL pressure vessel. Mandrel wound carbon fiber tubes have been fabricated and tested for housing all electronics and sensors. A cast titanium end cap with imbedded jam cleats for holding line ties has been designed and fabricated. The body of the profiler has been made from vacuum formed UHMW Polyethylene which gives a strong shape and some buoyancy. We have purchased PVC foam for the PROFILER but it will receive significant testing to assure it will perform as specified. A draft paper on the topic of profiling float CTD sensors was carefully studied with the plan to integrate an SBE sensor into the PROFILER. The PICO concept and profiler results were presented at the technical workshop of the DBCP on October 16, 2006 in San Diego, CA.

The PICO mooring concept calls for an instrument that moves up and down the mooring line measuring and transmitting subsea data, including CTD data. For this effort two small prototype CTD sensors manufactured by Sea Bird Electronics have been purchased and integrated into an instrument. One instrument was modified to reduce the power requirements and the other was maintained as a control. The vehicle to carry the two instruments was designed and fabricated and tested at PMEL. The vehicle falls down a wire suspended from the ship, drops weights at the bottom of the wire, and then floats back smoothly to the surface where the system is recovered and the data is extracted. A total of 5 drops were made to depths up to 225m using a variety of travel velocities and intake ports. The data collected from this cruise is very encouraging and we are optimistic further processing will yield the information needed.

FLEX (Flexible and Low-powered Electronics for ocean eXperiments) electronics and software including CPU, serial and analog interface and power switching and Iridium and short-haul RF modems were designed, built and are currently being evaluated in the Laboratory. Instruments that were procured and are currently under testing include: 1) Vaisala WXT 510 which combines air temperature, relative humidity, wind, rain and barometric sensor in a single package; 2) Seabird Electronics prototype temperature, salinity, now called SBE-51 and; 3) joint PMEL-RDI current meter development and testing now called the Doppler Volume Sampler (DVS) with spec sheet available: http://www.rdinstruments.com/dvs.html. An expected field test for the FLEX electronics is scheduled for early 2007.

3. Vandalism

Vandalism continues to present a problem in all three tropical ocean basins. Data and equipment return are generally lower in regions of high tuna catch, namely the far western and eastern portions of the tropical Pacific, in the Gulf of Guinea in the Atlantic, and near 80E in the Indian Ocean. Efforts to combat vandalism continue, though it is not clear they are making much impact. These efforts include distribution of information brochures to national fishing agencies, fishing boats in ports of call, and industry representatives, and have contributed to international efforts to decrease vandalism through the DBCP. The attractive RM Young wind sensor may be replaced with a less conspicuous sonic anemometer if tests of the latter prove encouraging and funding for system upgrades become available. Evaluation of field-tested sonic anemometers is presently underway. Development of a more compact mooring (see 2.5 above) is also underway at PMEL. This mooring may possibly be less easily found by fishermen and more difficult to attach to.

4. 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 an editor for the *Bulletin of the American Meteorological Society* and serves on the Executive Committee of the AGU Ocean Sciences Section. In 2006 he attended several CLIVAR panel meetings, two PIRATA SSC meetings (in Toulouse France and in Brazil), and an OceanSITES planning meeting (Honoulu).

Paul Freitag, The PMEL TAO Project Manager, represents the Tropical Moored Buoy Implementation Panel at the JCOMM Data Buoy Cooperation Panel (DBCP), and serves on the OceanSITES Data Team. He attended the DBCP meeting in October 2005

(Buenos Aires), a JCOMM Workshop on Real Time Metadata in February 2006 (Reading, UK), the first OceanSITES Data Team meeting in March 2006 (Honolulu), a NOAA/BKRT Workshop in June 2006 (Bali, Indonesia), and Oceans2006 in September 2006 (Boston).

Rick Lumpkin serves on the PIRATA Scientific Steering Committee (SSC), the CLIVAR Tropical Atlantic Climate Experiment (TACE) working group on observations, and represents the Global Drifter Program at the JCOMM Data Buoy Cooperation Panel. In 2006 he attended the PIRATA SSC meeting in Toulouse France and served as chief scientist of leg one of the Northeast Extension cruise aboard the R/V Ronald H. Brown.

Christian Meinig, the PMEL Engineering Director, made several presentations on OCO sponsored ocean observing technology including: 1) ONR/MTS Buoy Workshop in College Station, Texas March 2006, 2) Dr. Kusmayanto Kadiman. State Minister for Research and Technology of the Republic of Indonesia in July 2006 (Seattle), 3) Joint Australian Bureau of Meterology (BOM) and Indonsesia BPPT meeting September 2006; 4) Attended Ocean 2006 (Boston) and 5) Invited DBCP presentation in October 2006 (San Diego).

5. Publications and Reports

5.1 Refereed Publications

Behrenfeld, M.J., K. Worthington, R.M. Sherrell, F.P. Chavez, P. Strutton, M.J. McPhaden, and D.M. Shea, 2006: Controls on tropical Pacific ocean productivity revealed through nutrient stress diagnostics. *Nature, 442,* 1025-1028.

Bennett, A.F., B.S. Chua, H.-E. Ngodock, D.E. Harrison, and M.J. McPhaden, 2006: Generalized inversion of the Gent-Cane model of the Tropical Pacific with Tropical Atmosphere-Ocean (TAO) data. *J. Mar. Res., 64*, 1-42.

Cheng, W., M.J. McPhaden, D. Zhang, and E.J. Metzger, 2006: Recent changes in the Pacific subtropical cells inferred from an eddy resolving ocean circulation model. *J. Phys. Oceanogr.,* in press.

Cronin, M.F., C. Fairall, and M.J. McPhaden, 2006: An assessment of buoy derived and numerical weather prediction surface heat fluxes in the tropical Pacific. *J. Geophys. Res., 111,* C06038, doi:10.1029/2005JC003324.

Delcroix. T., S. Cravatte, and M.J. McPhaden, 2006: Decadal variations and trends in tropical Pacific sea surface salinity since 1970. *J. Geophys. Res.,* submitted.

Feely, R.A., T. Takahashi, R. Wanninkhof, M.J. McPhaden, C.E. Cosca, S.C. Sutherland

and M.-E. Carr, 2006: Decadal Variability of the Air-Sea CO_2 Fluxes in the Equatorial Pacific Ocean. *J. Geophys. Res., 111.*, C08S90, doi:101029/2005JC003129.

Foltz, G.R. and M.J. McPhaden, 2006: Unusually warm sea surface temperatures in the tropical North Atlantic during 2005. *Geophys. Res. Lett.,* 33, L19703, doi:10.1029/2006GL027394.

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McPhaden, M.J., X. Zhang, H.H. Hendon, and M.C. Wheeler, 2006: Large Scale Dynamics and MJO Forcing of ENSO Variability. *Geophys. Res. Lett., 33*(16), L16702, doi:10.1029/2006GL026786.

McPhaden, M. J., S. E. Zebiak, and M. H. Glantz, 2006: ENSO as an integrating concept in Earth Science. *Science*, in press.

Morris, V., P. Clemente-Colon, N. R. Nalli, E. Joseph, R. A. Armstrong, Y. Detres, M. D. Goldberg, P. J. Minnett and R. Lumpkin, 2006: AEROSE Science Team Conducts Ongoing Investigations of Downwind Transport from Saharan and Sub-Saharan Africa in the Tropical Atlantic. *EOS*, in press.

Schein, K.A. et al, 2006: The state of the climate 2005. *Bull. Am. Meteorol. Soc., 87,* S1-S102.

Zhang, D., and M.J. McPhaden, 2006: Decadal variability of the shallow Pacific meridional overturning circulation: relation to tropical sea surface temperatures in observations and climate change models. *Ocean Modelling*, in press.

Zhang, X. and M.J. McPhaden, 2006: Wind stress variations and interannual sea surface temperature anomalies in the eastern equatorial Pacific. *J. Climate, 19,* 226-241.

5.2 Other Reports and Publications:

Freitag, H. P., M. J. McPhaden, M. F. Cronin,C. L. Sabine, D. C. McClurg, and P. D. McLain, 2006: PMEL contributions to the OceanSITES program. Proc. Oceans2006 MTS/IEEE Conference, 18-21 September 2006, Boston, MA.

McPhaden, M.J., 2006: El Niño and Ocean Observations: A Personal History. In: *Physical Oceanography*, Developments Since 1950. M. Jochum and R. Murtugudde (Eds.), Springer, New York, p. 79-99.

Tropical Atmosphere Ocean (TAO) Array

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1. PROJECT SUMMARY

FY 2006 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 Nino/Southern Oscillation (ENSO). Management of the array 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). Web sites containing comprehensive information on both programs can be found at http://www.tao.noaa.gov/ or http://www.pmel.noaa.gov/tao/. This report summarizes the progress and accomplishments of the TAO project in FY2006. In FY 2006, there were a lot of progress and achievements for the TAO transition from PMEL to NDBC, which are also summarized in this report.

2. FY 2006 PROGRESS

2.1 TAO/Triton Array

2.1.1 Background

FY 2006 was the sixth 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 to 138°W. 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/ or http://www.pmel.noaa.gov/tao/).

2.1.2 TAO Project Highlights

At present, TAO/TRITON data indicate weak El Niño or neutral conditions in the tropical Pacific. Forecast models, many of which depend heavily on TAO/TRITON data for initialization, suggest that near neutral conditions will continue into early 2006.

2.1.3 Field work

PMEL 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 ADCP mooring is deployed. An ADCP mooring is maintained by JAMSTEC at 0°, 147°E. During the past year, the TAO Project deployed 65 ATLAS moorings and 5 subsurface ADCP current meter moorings in the tropical Pacific. The number of ATLAS deployments exceeds the number of ATLAS sites

in the array because of mooring system failures or losses during the year, because one site (the equatorial current meter mooring 140°W) was turned around on a 6-month rather than 12-month schedule for research and development purposes and because cruise schedules are such that some moorings are deployed for slightly shorter than their 12-month design lifetime.

2.1.4 Ship Time and Sea Time

In FY 2006, 256 days at sea were required (222 days on the Ka'imimoana and 34 on the Ron Brown) to support the TAO portion of the TAO/TRITON array. PMEL participated in 446 person-days at sea (number of people times days at sea). For comparison, during FY 2005, 255 days at sea (220 days on the Ka'imimoana and 35 on the Ron Brown) were required and PMEL participated in a total of 620 person-days at sea.

As part of the TAO Transition, NDBC participated in 386 person-days at sea (number of people times days at sea) for getting familiar with TAO operations and in support of TAO field work. The 386 days were both government and contractor personnel as well as engineers and technicians.

2.1.5 Data Return

Percentage real time data return for primary TAO variables integrated over all 55 sites for FY 2005 was as follows:

	AIRT	SST	T(Z)	WIND	RH	ALL
FY 2006	91	86	83	82	87	84
FY 2005	89	91	92	86	87	91

The main reason for the lower overall percentage in FY2006 is because of the vandalism (as discussed in Section 2.4). For examples, the percentages of the two most vulnerable lines on vandalism 95W and 110W line were 76% and 74%, respectively. In FY 2006, 14 sites (out of 55 sites) had the percentages lower than 80%, and seven of them were from 95W and 110W lines (7 out of 14 sites in the two lines).

In addition, FY2006 was the first year that data from the point-source current meters were reported in real time on the four ADCP sites (i.e., TAO moorings next to the ADCP moorings). Totally, there were 18 point-source current meters at various depths (i.e., 5 at 0-110W, 5 at 0-140W, 4 at 0-170W, and 4 at 0-165E), based on the TAO funded requirements. The data return percentage for the current meter in FY2006 was 57.7%. We will continue to monitor and report this new measurement in the future.

2.1.6 Shipboard Measurements

CTD casts, and underway ADCP and thermosalinograph measurements, are conducted from mooring servicing cruises on the Ka'imimoana and Ron Brown. These data are an integral part of the TAO Project, 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.

A total of 299 CTD casts were made on TAO cruises in FY 2006, which was a decrease over FY 2005 (407). The decrease in number of CTDs was caused primarily by the ship being diverted from its normal track on several cruises due to breakdown of ships

equipment, medical emergencies, and recovery of moorings which had drifted from their original location. The shipboard ADCP data are forwarded to, processed, archived, and distributed by Eric Firing and colleagues at the University of Hawaii. Underway sea surface salinity measurements are processed at PMEL, and then forwarded regularly to the IRD laboratory in Noumea for distribution (by CD-ROM) with other sea surface salinity data (http://www.ird.nc/ECOP/siteecopuk/cadres.htm).

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 the NOAA Ship Ka'imimoana is to service buoys of the TAO/TRITON array. However, the TAO Project Office actively promotes use of the Ka'imimoana and, when it is used for TAO cruises, the Ron 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 2006 (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/ETL (BROWN)
Carbon cycle, Michael Bender, Princeton University (BROWN)
Dissolved Inorganic Carbon (DIC) Analysis, Andrew Dickson, Scripps Institution of Oceanography (KA)
Argo float deployments, Greg Johnson, PMEL (KA)
Global Drifter Program, Robert Molinari, NOAA/AOML (KA and BROWN)
Iron limitation, Mike Behrenfeld, NASA/Goddard (BROWN)
CO2 moorings, Chris Sabine, NOAA/PMEL (KA)
Bio-optical measurement and nutrient analysis, Francisco Chavez, MBARI (KA)
Haruphone mooring recoveries/deployments, Robert Dziak, NOAA/PMEL (BROWN)
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)
Nitrate and O_2 isotope analysis, Patrick Rafter, Scripts Institution of Oceanography (KA)
Equatorial Box Project, Michael Behrenfeld, Oregon State University (KA)
Microstructure Chipod development, James Moum, Oregon State University (KA)
Nutrient Samples, Cathy Cosca, PMEL (KA)
CTD program, Greg Johnson, PMEL (KA and BROWN)

b. One-time or limited-term ancillary projects on TAO cruises for FY 2006 (Project, Principal Investigator, Institution (Ship):

Lagrangian Float, Ren-Chieh Lien, Eric D'Asaro, University of Washington,(KA)
PICO Buoy test deployments, Chris Meinig, PMEL (BROWN)
Moored Fluorometer deployments, Pete Strutton, Oregon State University (KA)

Seawater fluorometery, Maria Baca, Universidad Agraria, La Molina

2.2 TAO Project Web Pages

In FY06, the TAO Project continues to maintain the content and functionality of two web sites: one at NDBC (http://tao.noaa.gov/) and one at PMEL (http://www.pmel.noaa.gov/tao/). These sites provide easy access to TAO/TRITON data sets, as well as updated technical information on buoy systems, sensor accuracies, sampling characteristics, and graphical displays.

For FY 2006, NDBC TAO web site received 2,441,778 hits and PMEL TAO site received 22,699,591 hits. So, the total hits from both web sites are 25,141,369. Also during FY 2006, a total of 301,002 TAO data files were delivered to end users: 28,673 files from NDBC web site and 272,329 from PMEL web site.

As of FY2006, NDBC became the official TAO data center and NDBC's TAO web site is the official TAO website after one year of end-to-end parallel testing. The parallel testing has demonstrated the successful transition of the TAO IT and Quality Control functions with the agreement rates for all categories met or exceeded the agreement criteria (i.e., 95% or 99%) of the test plan. Please refer to the "TAO End-to-End Test Plan" and "TAO Transition Information Technology and Quality Control Parallel Test Final Report" for more details.

2.3 Operational Use of TAO/TRITON Data

TAO/TRITON data are distributed via GTS to national and international operational 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 routinely in climate forecasting and analyses. The data are also used for operational weather and Pacific tropical cyclone forecasting. Weekly ftp transfers to NCEP, ceased in April 2006 at NCEP's request. TAO data placed on the GTS include spot hourly values of wind speed and direction, air temperature, relative humidity, [barometric pressure], and sea surface temperature. 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 processing algorithms for MCSST. TAO/TRITON and PIRATA are the only moored buoys used for MCSST validation. Daily averaged subsurface temperature and salinity data are also transmitted on the GTS. The Global Temperature-Salinity Profile Program (GT/SPP) collects the GTS provided subsurface temperatures and salinities and makes them available in real-time via NOAA's National Oceanographic Data Center web site.

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, 7 complete moorings systems were confirmed lost in the Pacific in FY 2006 due to the effects of vandalism.

Efforts to combat vandalism continue, though it is not clear they are making much impact. These efforts include distribution of information brochures to national fishing agencies,

fishing boats in ports of call, and industry representatives, and have contributed to international efforts to decrease vandalism through the DBCP.

2.5 Public Service

PMEL TAO Project Director serves on the International CLIVAR Pacific Panel and Global Synthesis and Observations (GSOP) Panel and the International CLIVAR/GOOS Indian Ocean Panel (IOP). He is a member of the PIRATA SSG. He is a member of the JCOMM Observations Coordination Group, chairs the Tropical Moored Buoy Implementation Panel (TIP) which is an action group of the Data Buoy Cooperation Panel (DBCP), and is a member of the OOPC/CLIVAR OceanSITES Working Group. McPhaden serves as past president of the Ocean Sciences Section of the American Geophysical Union and is a member of the Bulletin of the American Meteorological Society editorial board.

NDBC continues to represent the North Pacific Data Buoy Advisory Panel (DPDBAP). This panel is interested in data buoys located in the North Pacific – and the membership includes Canada, China, Japan, Korea, Mexico and the United States. NDBC served as a co-host, with the NOAA Office of Global Programs (OGP), to the 22nd Session of the Data Buoy Cooperation Panel (DBCP) and the 26th meeting of the Joint Tariff Agreement (JTA) that was held in La Jolla, California. NDBC currently chairs the DBCP Drifter Evaluation Subgroup and is developing the DBCP's "Best Practices and Standards" booklet for quality control and assurance of moored buoy data.

NDBC Chief Scientist serves as one of the U.S. representatives to the Ocean SITES program of which selected TAO and PIRATA stations are critical components. He also serves as a U.S. representative to the PIRATA Resources Board, and is actively involved in the PIRATA effort including a working group to identify national contributions to PIRATA. Participated in PIRATA 11 and 12 meetings.

The PMEL TAO Project Manager represents the Tropical Moored Buoy Implementation Panel at the JCOMM Data Buoy Cooperation Panel (DBCP), and serves on the OceanSITES Data Team. He attended the DBCP meeting in October 2005 (Buenos Aires), a JCOMM Workshop on Real Time Metadata in February 2006 (Reading, UK), the first OceanSITES Data Team meeting in March 2006 (Honolulu), a NOAA/ SEACORM Workshop on *"Use of Ocean Observations to Enhance Sustainable Development - Training and Capacity Building Workshop for the Eastern Indian Ocean"* in June 2006 (Bali, Indonesia), and Oceans 2006 in September 2006 (Boston).

NDBC TAO Project Manager visited Japanese Agency for Marine-Earth Science and Technology (JAMSTEC) and briefed JAMSTEC's TRITON team about TAO transition and technology refresh. During his visit, JAMSTEC briefed him and provided information to him about the newly-developed mini-TRITON buoy. He also attended Oceans 2006 Conference in September 2006 (Boston) and briefed the status of TAO transition and technology refresh during his presentation of "Technology Refresh of NOAA's Tropical Atmosphere Ocean (TAO) Buoy System".

Given the proximity of NDBC's new hurricane buoys to the PIRATA array, NDBC, in consultation with the PIRATA Science Steering Committee, has begun to upgrade stations 41040 and 41041 with additional observations to enhance their usage as a climate resource in conjunction with PIRATA. In the second year of this effort, the NDBC Observations Supporting PIRATA (NOSP) project added temperature and salinity profiles and 10m current measurement with a companion mooring near 41041. This adds to the rain and solar radiation efforts of the prior year.

2.6 TAO Transition FY 2006 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 2006 TAO Transition efforts focused on four areas: (1) completion of TAO data and IT transition and NDBC's TAO site became the official TAO web site, (2) NDBC's familiarization of TAO operations and readiness of FY07's cruises, (3) development and testing of the TAO refreshed buoy system which to replace obsolescent components and sensors, and (4) development of new 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 2006:

- Completed the TAO End-to-End Test with satisfied testing reports.
- Completed the one year Parallel Testing for both real-time data and delayed mode data.
- Added Assorted Plots per community user requests.
- Published the TAO Daily Status web pages to the public.
- Completed the version control of all TAO software and enable the Configuration Management (CM) for TAO data systems.
- Completed DAC QA/QC Procedures and SOPs for TAO data monitoring.
- Trained the DAC personnel and integrated the TAO data monitoring and quality control into the NDBC DAC operational workflow.
- Started visual data analysis of real-time current meter and conductivity data.
- Developed or enhanced the capabilities of processing delayed mode rainfall data, Sontek current meter data, and ADCP profile data.
- Integrated the delayed mode data processing into the NDBC DMAC operational workflow.
- NDBC TAO web pages were updated with QA/QC technical information from the NDBC Data Assembly Center.

In order to smoothly take over all TAO field operations in FY07, NDBC sent technical people (two people most of the time) to each of the FY06 cruises (both the Ka'imimoana and the Ron Brown). PMEL and NDBC met a few times and communicated via e-mails

and phone calls to discuss various inventory and logistical support during TAO transition. In FY 2006, NDBC started to purchase and to prepare many items for FY07's cruises.

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

- A new data logger AMPS was fully developed and tested for TAO.
- A new layout of electronics and batteries was designed with the same form factors of the external tube.
- The Commercial-Off-The-Shelf (COTS) underwater sensors (i.e., temperature, conductivity, and pressure sensors) were adopted and tested.
- A new design of the inductive modem (IM) coupler was adopted and integrated.
- Preliminary Design Review (PDR) and Critical Design Review (CDR) on the design of the refreshed buoy were conducted.
- Two prototype TAO refreshed buoys were integrated and tested in the lab.
- A prototype refreshed buoy was deployed in the Gulf of Mexico for field testing. Minor problems on the AMPS and IM connection were found and corrected. More testing on the prototype refreshed will be conducted in FY07.

During FY 2006, NDBC accomplished the following goals for data/IT part of theTAO refresh:

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

In addition to the technical management aspects of TAO, NDBC provided Project Management of the TAO transition to include numerous schedule details and updates, status briefs and reports, contract management, and coordination between PMEL and NDBC.

Tropical Atmosphere Ocean (TAO) Refresh

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1. PROJECT SUMMARY

FY2006 funding was expended to refresh the Tropical Atmosphere Ocean (TAO) array as part of the National Oceanic and Atmospheric Administration's (NOAA) effort to "refresh" the TAO system by replacing the obsolete and unsupportable components during the TAO transition from NOAA's Pacific Marine Environmental Laboratory (PMEL) to NOAA's National Data Buoy Center (NDBC). The refreshed TAO system is intended to ensure continuous operation and ongoing integrity of the TAO array. There were two major efforts under this project in FY2006: (1) integration and deployment of two refreshed TAO buoys and (2) Development of refresh TAO data system.

2. FY2006 PROGRESS

2.1 Two Refresh TAO Prototype Buoys

Two refresh TAO prototype buoys were integrated with the refreshed components, some modified designs, and many unchanged legacy TAO design and components (as described in the following).

(1) Refreshed components.

- Use newly-developed data logger AMPS.
- Use Commercial-Off-The-Shelf (COTS) subsurface temperature (T) sensors, conductivity/temperature (CT) sensors, and temperature/depth (TP) sensors, inductive modems (IM), and inductive coupler from Sea-Bird.
- Use the Iridium communication system (Short burst data mode) which can provide hourly high-resolution data.
- Use new Sparton SP3000 internal compass (inside AMPS).

(2) Modified designs

- Surface CT sensor is mounted on bridle using direct connection to the data logger
- Internal battery/electronics design of the electronic tube is modified for the new data logger.
- Explosion mitigation for the electronic tube is provided.

(3) Unchanged legacy designs and components

- ATLAS buoy hull, bridle, and mast design
- Dimensions, location, and mounting of the electronic tube
- Rotronics MP101A air temp/ humidity sensor
- RM Young 5103 anemometer

Note that, D-cell batteries are currently used in the electronic tube. A new power system using lithium batteries was designed and is being tested in the lab. The lithium

battery design will make the electronic tube smaller and lighter, which will make field maintenance much easier and faster. NDBC plans to use this lithium battery design as the refresh TAO configuration after it is fully tested.

The buoy electronic systems were successfully tested in the lab. An intranet webpage was set up to monitor data from all the refreshed systems (including the two refresh prototype buoys, the bench testing system, and spare systems) in the lab and in the field.

The two prototype TAO refresh buoys were deployed at the Gulf of Mexico for field testing. Both buoys are located at 28° 54' 53" N 088° 15' 59" W (Station ID 42A70 and 42B70) with a water depth of 1189m (3900ft), which is 16 nm South of Station 42040.

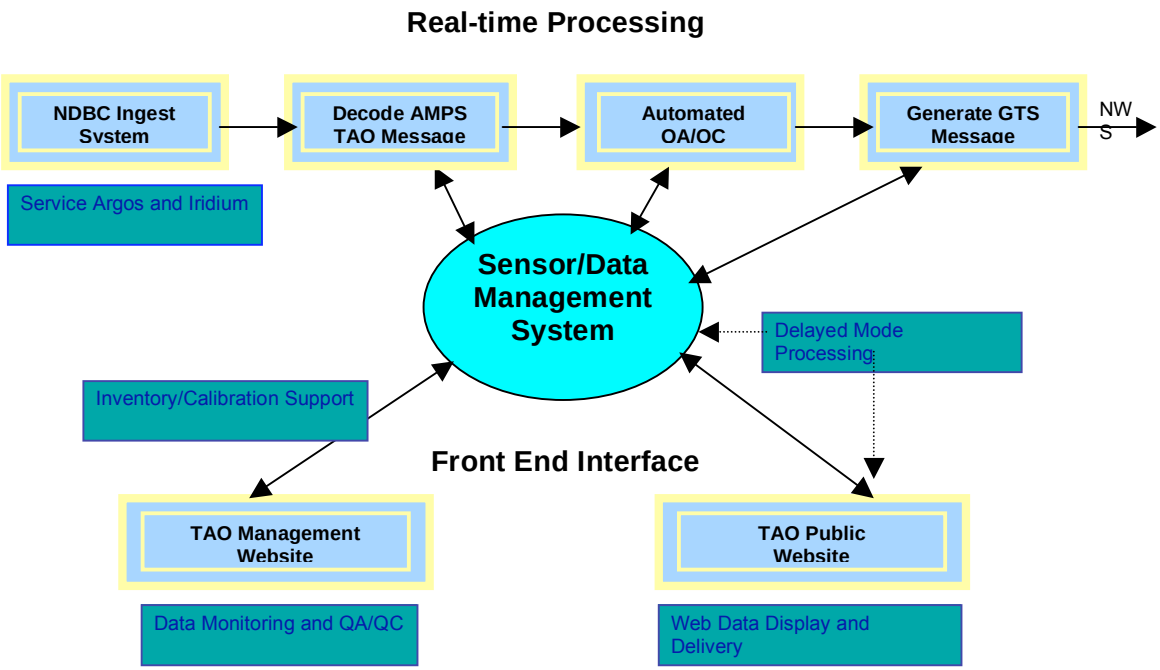
The moorings for the TAO refreshed buoys are the same as the taut mooring design for the legacy TAO system, which uses 3/8" jacketed galvanized steel wire on the top part as the inductive modem line and 3/4" Nylon rope for the remaining of the mooring. An acoustic release (ORE Offshore 8242XS) is used for easy retrieval of the mooring and attached underwater sensors. Due to the depth and budget limitations, only one conductivity/temperature (CT) sensor (at a water depth of 10m), two temperature (T) sensors (at water depths of 20 and 30m), and one temperature and pressure (TP) sensor (at a water depth of 100m) mounted along the mooring line using inductive modems (IM) for data transmission. In addition, a CT sensor is mounted on the bridle (at a water depth of 1m) and is connected directly to the data logger via a serial connection.

These two buoys were first deployed on August 29, 2006 by R/V Pelican. The following photo shows one of the two TAO refreshed buoys deployed at the Gulf of Mexico. The buoy at Station 42B70 was adrift shortly after deployment and was retrieved at a very shallow location. After examining the battered mooring line, it is clear the line was cut possibly by a fishing or survey vessel. The buoy at 42A70 was successfully deployed and is still on station. Although the met and surface CT data were correctly measured and transmitted, data from underwater T and TP sensors (via IM transmission) were intermittent. NDBC is working with the IM manufacturer Sea-Bird to design a more robust inductive connection. It is planned to redeploy a refreshed TAO buoy at 42B70 and to service the refresh buoy at 42A70 in December 2006.

2.2 Development of Refresh TAO Data System

Compared to limited data transmitted daily from the current ARGOS system, the detailed data collected by AMPS is transmitted hourly via the Iridium SBD system used for the refreshed TAO buoy system. Thus, the shore side data system has to be modified for the much larger data volume in near real time and more frequent data transmission of the refreshed TAO system and to compute the hourly and daily average products now provided from the TAO array. In addition, during the TAO transition and technology refresh, data from the legacy TAO buoys are still transmitted via ARGOS system. So, the new data system for the refresh TAO system also needs to be able to handle the data from the legacy TAO buoys.

This data system for the refreshed TAO buoys includes four components: (1) Ingest system, (2) Real-time processing, (3) Sensor management, and (4) Web display. These components all connect to a centralized sensor/data management database (as shown in the following figure).



Currently, most of the tasks for developing the data system of the refreshed TAO system are complete. The progress and status of the tasks are summarized in the following.

(1) Migrate fifty-five (55) legacy buoy data to refreshed databases.

- Import current PMEL calibration files to refreshed databases (done)
- Covert daily Argos message to refreshed databases (done)
- Import historical PMEL calibration files to refreshed databases (done)
- Convert historical daily data to refreshed databases (ongoing)
- Convert historical high resolution data to refreshed databases (ongoing)
- Compare converted data with original data (to do)

(2) Data Assembly Center Management Console Development

- Engineering support (done)
- Site/Range limit management (done)
- Sensor management (done)
- Deployment/Recovery management (done)
- QA/QC management (ongoing)
- Data availability report (to do)
- Infrastructure and security (to do)
- QC plotting support (to do)
- On-board management (to do)
- Service Argos account (to do)

(3) Web data display and delivery

- Convert legacy data to new NetCDF format (ongoing).
- Extract and build new NetCDF dataset (ongoing)
- Web data display with new presentation (ongoing)
- Web data delivery via OPenDAP (to do)

(4) Refreshed QA/QC methodologies

- Research static range limits (done)
- Implementation and evaluation (to do)
- Research dynamic range limits (ongoing)
- Research sort term and long term QA/QC methods (to do)
- Load delayed mode data into databases (to do)

04. Ocean Reference Stations:

a. Ocean Reference Stations

b. Western Boundary Time Series in the Atlantic Ocean

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

d. Progress Report: Southern Ocean Modern Observations/Weddell Sea Moorings November 2006

e. Monitoring the Indonesian Throughflow in Makassar Strait

f. Meridional Overturning Variability Experiment

g. Integrated Boundary Current Observations In The Global Climate System

h. High Resolution Climate Data From Research and Volunteer Observing Ships

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

Ocean Reference Stations

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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 these Ocean Reference Stations at three key locations: the 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 ASIMET (Air-Sea Interaction Meteorological 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.

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 (Fig. I-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. Testing of Iridium data telemetry hardware was begun on WHOTS and worked successfully.

Figure I-1: The old rigid hull (left) and the new modular buoy (right). Photo taken during the December 2004 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 8-27, 2006 cruise of the NOAA Ship *Ronald H. Brown*. 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.

Data recovery this year was good, post-calibrations are being done, and data files have been shared with colleagues. 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, 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 grid point nearest the model. 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. We are providing the data to Ocean SITES (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 II-1, for example) 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.

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

Table II-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.

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 FY2007 have come from many institutions: NOAA Environmental Technology Laboratory, Servicio Hydrografico y Oceanografico de la Armada (SHOA, Chile), University of Concepcion (Chile), University of Hawaii, University of Buenos Aires, and University of Miami. The 2006 stratus cruise also hosted a teacher from NOAA's Teachers-at-Sea program (Brett Hoyt). The work this year included servicing the Chilean Navy tsunami warning installation; this tsunami warning installation was recovered and a new one deployed for the Chilean Navy. The deployment marked the beginning of a growing partnership between the ORS project and SHOA. We installed self-recording ASIMET modules on the tsunami buoy and temperature and temperature/salinity recorders on the buoy's mooring line (Fig. II-1). This also marks the beginning of the use of a tsunami mooring for climate observations.

We supported the participation of a student from the University of Buenos Aires, Argentina as a further effort at outreach and capacity building; this student works for Dr. Alberto Piola who is at both the University of Buenos Aires and at the Argentine Navy equivalent of SHOA. We have invited the student and Dr. Piola to visit our group at

WHOI to explore further collaboration with Argentina in developing the global array of ORS.

Figure II-1: Chilean Navy (SHOA) DART buoy equipped with WHOI meteorological sensors.

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° N, 51° 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 conducted on the NOAA ship *Ronald H. Brown* February 2006 in order to retrieve the existing mooring (NTAS-5, deployed 11 March 2005) and replace it with a new mooring (NTAS-6). In preparation for this cruise,

three Air-Sea Interaction Meteorology (ASIMET) systems were calibrated and tested, and two systems, comprised of the best performing sensors, were prepared for deployment. The NTAS-6 mooring was deployed on 25 February 2006 and the NTAS-5 mooring was recovered on 28 February. 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 was good, with all sensors showing 90-100% data return except for wind, which had just under 50% return on one system. Since the second system had 100% return for wind, no data will be missing in the combined record.

The 2006 NTAS cruise represented the start of a collaboration with the National Data Buoy Center (NDBC) wherein the newly established NDBC west and middle Atlantic sites (41040 and 41041) were serviced. The 2006 cruise also included the deployment of 7 ARGO floats at the request of NOAA AOML, and a bathymetric survey offshore of Barbados at the request of the US Embassy in Barbados and in support of work being done by the Barbados Coastal Zone Management Unit.

Evaluation of NTAS surface meteorology in conjunction with our volunteer observing ship (VOS) data from the Atlantic and nearby NDBC buoys has been initiated. The goal is to determine the appropriate spatial "footprint" for the buoy meteorology on various time scales. Auto-correlation times for both buoy and VOS meteorological variables are from 3-6 h. Barometric pressure, dominated by the semidiurnal atmospheric tide, and shortwave radiation, dominated by the diurnal cycle, show the most consistent results. The VOS variables show variability on time scales of hours that is not seen in the buoy records, and is attributed to spatial variability. Cross-spectra of NTAS vs. an NDBC buoy 200 km to the west show that coherence begins to increase on 3-5 day synoptic weather scales, and is significant for all variables at 10 days and longer (Fig. III-1, left). Significant coherence is also seen near 12 and 24 h periods relating to the diurnal cycle and the atmospheric tide. The short duration (1 day) of the VOS records near the buoy do not allow coherence on synoptic weather scales to be evaluated. Cross-spectra of NTAS vs. the VOS passing 300-500 km to the west show significant correlation for barometric pressure and shortwave radiation, significant, but weak correlation for SST and wind at the longest resolved periods (near 24 h), and no significant correlation for other variables (Fig. III-1, right).

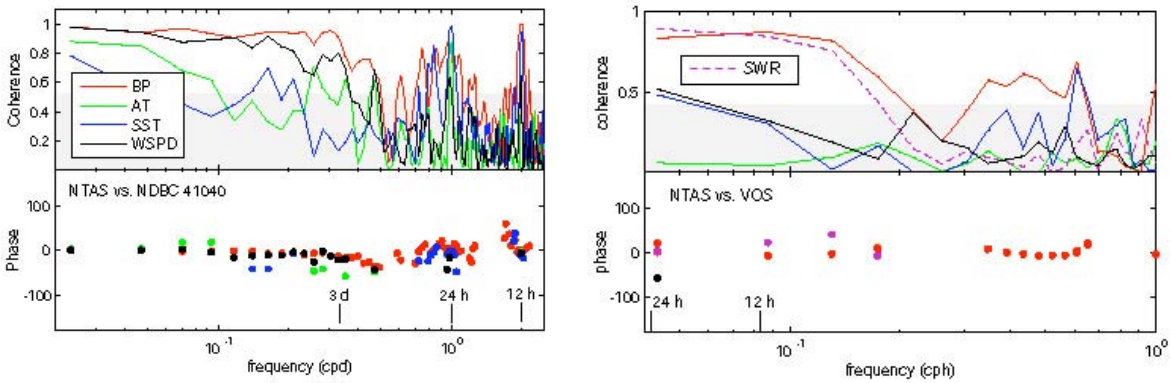

Figure III-1: Coherence and phase from cross-spectra of NTAS meteorological variables vs. the same variables on NDBC 41040 (200 km to the west) and the VOS Merkur (six passes 300-500 km to the west).

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 in June 2006 on the Scripps ship *Revelle*. In preparation for this cruise, three Air-Sea Interaction Meteorology (ASIMET) systems were assembled and tested. The WHOTS-2 mooring was recovered on 24 June 2006 and the WHOTS-3 mooring was deployed on 26 June. Periods of about 24 hours prior to the WHOTS-2 recovery and after the WHOTS-3 deployment were dedicated to an intercomparison of the buoy and shipboard meteorological systems. The intercomparison last year showed evidence of diurnal heating effects suggesting that some sensor positions on the 2.7 m buoy tower were suboptimal. For the WHOTS-3 buoy, mounts for air temperature/relative humidity sensors were extended, and no evidence of this heating was seen. Commercial bird-prevention spikes were installed on the WHOTS-3 buoy to reduce contamination and shadowing due to birds. A cruise report is in preparation.

The WHOTS-2 mooring was used as a test-bed for implementation of an Iridium data telemetry system, developed under the ORS Engineering, Oversight and Data project. Initial results indicate that the system worked well, and the WHOTS-3 buoy was deployed with two such Iridium systems as a further test. Additional systems based on the WHOTS design are now being developed for the telemetry of subsurface data on NTAS and Stratus.

Preliminary processing of the WHOTS-1 meteorological data has been completed and that of WHOTS-2 has begun. Data return was good. The hourly Argos and Irdium data are available on-line from the Upper Ocean Processes (UOP) group web site (http://uop.whoi.edu/projects/WHOTS/whots.htm). Daily surface temperatures and fluxes (Fig. IV-1) show relatively strong, episodic cooling in the winter of 2004/2005 due to strong wind events and large air-sea temperature differences. Warming the following spring and summer was more steady, leading to maximum surface temperatures in late August 2005. The contribution of the surface fluxes to the local heat and momentum balance will be assessed in cooperation with Lukas, who is analyzing the first two years of subsurface data from the WHOTS moorings (Fig. IV-2).

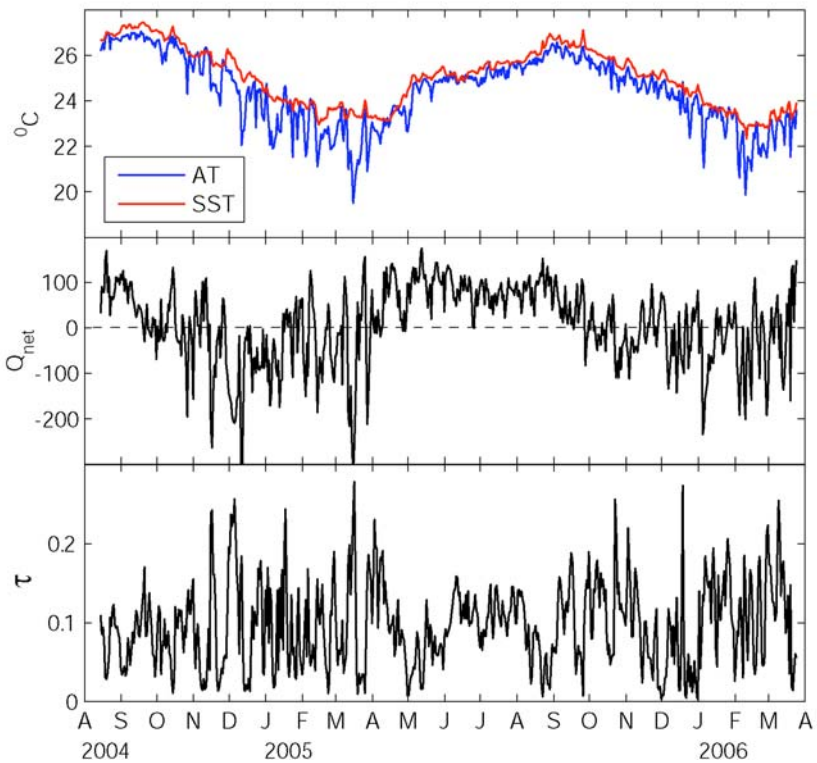

Figure IV-1: Surface conditions and fluxes from WHOTS-1 and 2. Daily values of air temperature and sea surface temperature (upper), net heat flux (middle) and wind stress (lower) are shown from preliminary processing of meteorological data from the WHOTS buoys.

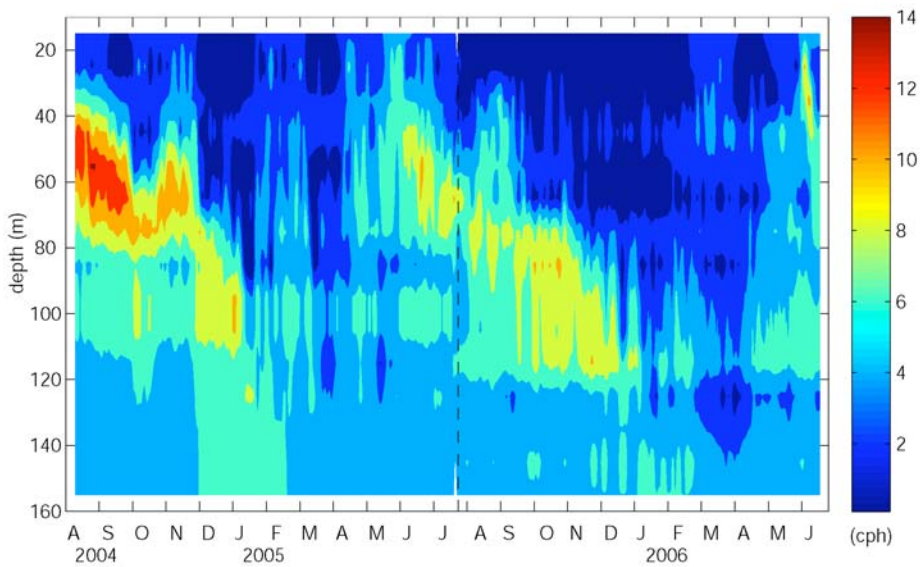

Figure IV-1: Contours of buoyancy frequency vs. depth and time from the WHOTS 1 and 2 moorings. Data from temperature/conductivity sensors, vector measuring current meters, and an acoustic Doppler current profiler are combined to compute the buoyancy frequency (figure courtesy of Roger Lukas, U. Hawaii).

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Western Boundary Time Series in the Atlantic Ocean.

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PROJECT SUMMARY

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 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 it becomes 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 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: *Task 1:* Real-time Florida Current transport measurements using a submarine telephone cable and calibration cruises, *Task 2:* Deep Western Boundary Current water property measurements using dedicated research ship time and quasi-real-time transport monitoring using moored instruments.

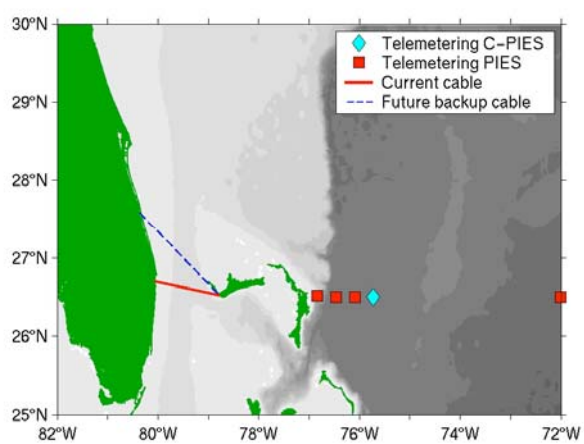

Figure 1: Observational components

of the Western Boundary Time
Series project in the North Atlantic.

Task 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 22 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 the decadal changes track the North Atlantic Oscillation Index. The strong correlation of Florida Current transport variability with the North Atlantic Oscillation, 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 one-day charters onboard small fishing vessels.

Task 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, chloroflourocarbon, 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 26ºN. 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 task includes annual cruises across the DWBC to measure the water mass properties and transports and, in September 2004, a new low-cost monitoring system was put in place to provide continuous long-term monitoring of this flow in quasi-real-time. 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 (C-PIES). The line of IES 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 26ºN in the Atlantic.

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/wbcts/

FY 2006 PROGRESS

Task 1: Continuous transport of the Florida Current

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 without significant incident excepting the period from May 7, 2006 through July 13, 2006 when a failure in a subterranean wire between the recording system and the anode (Earth ground) began to fail. While this event resulted in the delayed release of about two months of data, it is expected that all of this data will be recoverable and should appear online early in FY07. 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.

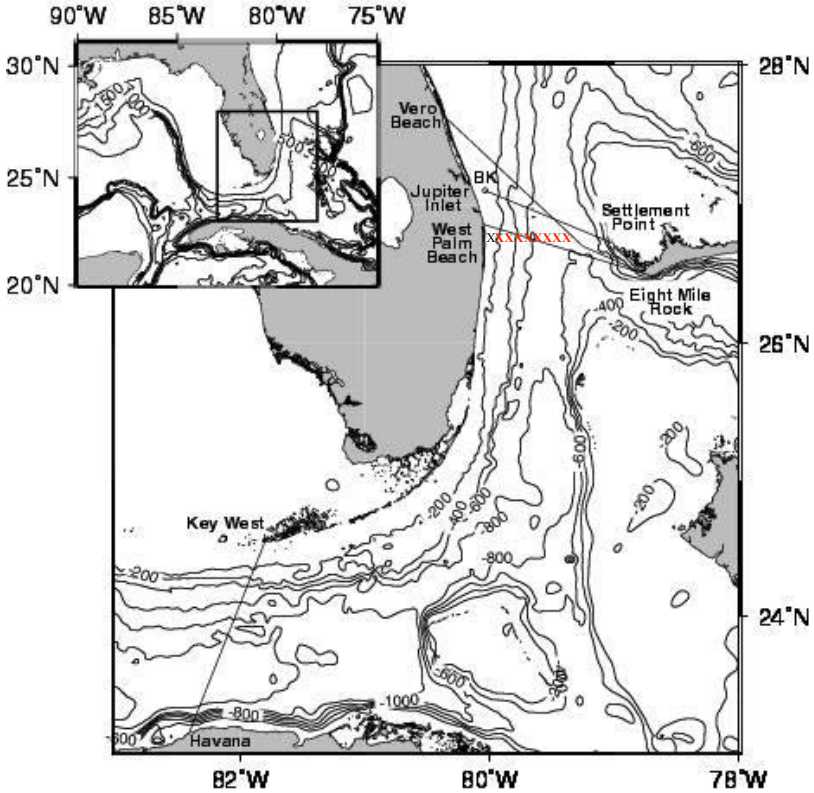

Figure 2: Location of submarine telephone cables (solid black) and nine stations (red) occupied during calibration cruises.

FY 2006	FY 2005	FY 2004	FY 2003	FY 2002
98% Return[1]	88% Return[2]	87% Return[1]	89% Return	72% Return[3]

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).

[1] Presuming May 7 – July 13 time period is successfully recovered, which is likely.
[2] Note a pair of hurricanes destroyed the recording equipment and damaged the infrastructure in Sept. 2004.
[3] Note old recording system failed in FY 2002.

Planned Cruise	FY 2006	FY 2005	FY 2004	FY 2003	FY 2002
1	11-Nov-2005	19-Nov-2004 dropsonde lost	9-Dec-2003	clearance problems	weather problems
2	17-Nov-2005	29-Nov-2004	16-Dec-2003	clearance problems	Dec 14, 2001
3	2-Feb-2006	17-Feb-2005	9-Jan-2004	equipment problems	Mar 12, 2002
4	14-Mar-2006	24-Feb-2005 section incomplete due to weather	13-Jan-2004 – GPS failure on two stations	18-Mar-03	Mar 18, 2002
5	27-Mar-2006	18-May-2005	7-May-2004	June 7, 2003 – dropsonde failure	June 3, 2002
6	22-Jun-2006	21-Jun-2005 dropsonde lost	24-May-2004	no dropsonde	June 6, 2002
7	30-Jun-2006	31-Aug-2005	Jun 7, 2004	no dropsonde	Aug 23, 2002 – dropsonde lost
8	20-Jul-2006		Jun 11, 2004	no dropsonde	
9	15-Sep-2006		Aug 24, 2004		
10			1-Sep-2004 - GPS antenna failure		
	100% successful	50% successful[4]	80% successful[5]	13% successful[6]	63% successful

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

Small charter boat calibration trips

A total of nine 1-day surveys were conducted using a dropsonde profiler (the first cruise had been postponed from the last FY due to weather). Measurements are taken at nine stations along 27ºN and include vertically averaged horizontal velocity, surface velocity and expendable temperature probes (XBTs). The cruise dates are shown in Table 2.

[4] 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.

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

[6] Sections missing due to: dropsonde failure (4) and clearance problems (2).

Full Water Column calibration cruises:
Two-day cruises on RV Walton Smith are generally scheduled four times per year (the final cruise of FY05 was postponed into early FY06). All cruises include nine stations with full water column CTD, lowered ADCP, and continuous shipboard ADCP. The station locations are shown in Figure 2. Table 3 below includes the cruise dates and number of water samples taken for oxygen concentration (O2) and salinity (S).

FY2006		FY 2005		FY 2004		FY 2003	
Date	Water Samples	Date	Water Samples	Date	Water Samples	Date	Water Samples
Nov 20-23, 2005	60 O2, 48 S	Dec 3-4, 2004	58 O2, 44 S	Jan 8-9, 2003	55 O2, 46 S	Nov 20, 2002	43 O2, 44 S
Dec 14-16, 2005	60 O2, 48 S	Jun 3-4, 2005	58 O2, 45 S	May 6-7, 2004	47 O2, 43 S	Mar 22, 2003	59 O2, 49 S
Jan 29-31, 2006	60 O2, 48 S	Jul 11-12, 2005	58 O2, 45 S	Jul 4-5, 2004	56 O2, 46 S	Jul 16, 2003	56 O2, 46 S
Jun 25-27, 2006	60 O2, 48 S			Aug 27-28, 2004	55 O2, 42 S	Oct 2-3, 2003	57 O2, 43 S
Sep 18-19, 2006	68 O2, 48 S						
125% of Planned Cruises[7]		67% of Planned Cruises[8]		100% of Planned Cruises		100% of Planned Cruises	

Table 3: Cruise dates for 2-day calibration cruises on the R/V Walton Smith.

Task 2: Deep Western Boundary Current time series
Two full water column cruises of CTD, lowered ADCP, and shipboard ADCP were conducted during FY06 within the Florida Straits and east of Abaco Island, Bahamas, one on the NOAA Ship Ronald H. Brown and the other on the R/V Seward Johnson. 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 lowered to the bottom. This provided 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 NOAA Ship Ronald H. Brown during Mar 9-28, while the second took place on the R/V Seward Johnson during Sept 25-Oct 12. The stations were occupied at the locations shown in Figure 3. Table 4 lists the cruise dates and bottle samples taken compared to previous years. Five inverted echo sounders (IES) sites were maintained as shown in Figure 3 including: four IES with pressure sensors (PIES) and one IES with pressure sensor and bottom current meter (C-PIES). Four additional temporary IES/PIES sites were deployed during the September 2006 cruise between the permanent sites to test array resolution.

[7] First cruise had been postponed from the previous FY.
[8] The last cruise was postponed to next FY due to weather/equipment/scheduling problems.

FY	Date	Stations	Bottle Samples	Comments
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

Table 4: Cruise dates and water samples taken for Large Vessel full water column surveys of the Deep Western Boundary Current. September 2006 cruise aboard the R/V Seward Johnson and May 2005 cruise aboard the R/V Knorr with ship time funded by NSF. April 2001 cruise on the R/V Oceanus. All other cruises were conducted on the R/V 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.

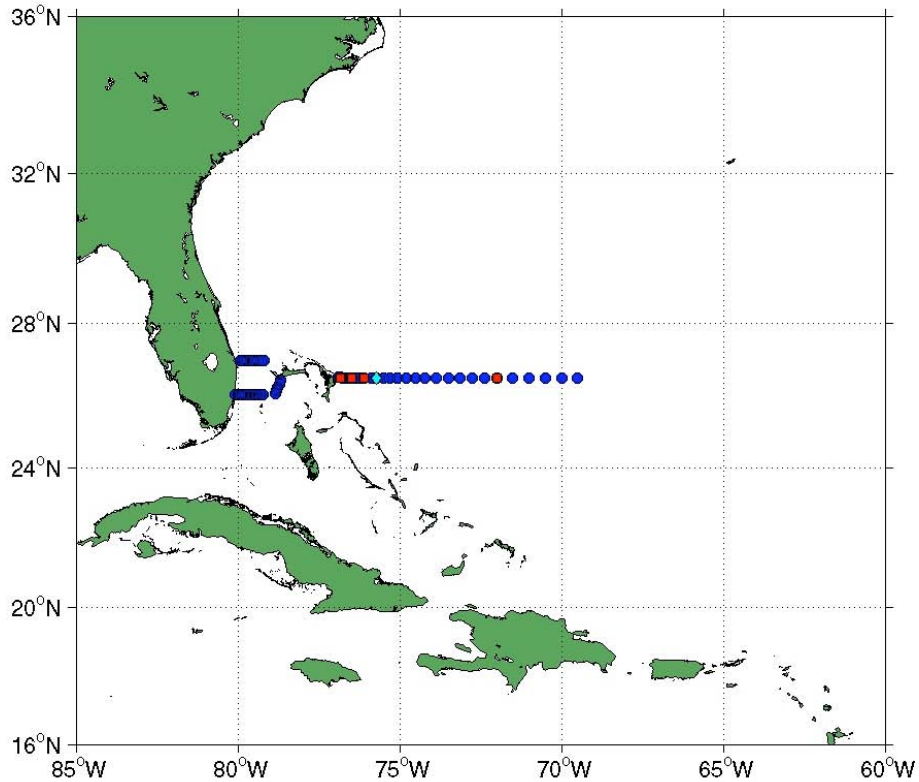

Figure 3: Approximate locations of full water column hydrographic stations sampled on the two cruises in FY 2005. Blue circles denote CTD sites. Red squares denote PIES moorings and the cyan diamond denotes a C-PIES mooring. Note Northwest Providence Channel stations and 26ºN Florida Straits sections were not completed during September 2006 cruise due to time constraints.

Research highlights

1. Numerous climate models have shown that variations in the Meridional Overturning Cell could have significant climate impacts over a wide range of locations around the globe. We compared the use of bottom pressure gauges and inverted echo sounders to a more traditional picket fence of current meters and showed that the far less expensive option of using bottom pressure and inverted echo sounders was able to reproduce the transport fluctuations observed by the current meter arrays well. This has led to a more efficient, lower cost monitoring system (now funded through the NOAA Office of Climate Observations) for the lower limb of the meridional overturning circulation.

2. A recent publication utilizing the PIES/C-PIES mooring data has shown that there is no sign of a significant trend in the components of the meridional overturning cell near the western boundary over the past twenty years. Furthermore these results demonstrate that the baroclinic and barotropic components of the transport variability are partially compensating one another, indicating that monitoring of

MOC transport variations via hydrographic sections is more inherently problematic than had previously been known.

Peer Reviewed Publications:

1. Meinen, C. S., M. O. Baringer, and S. L. Garzoli. "Variability in Deep Western Boundary Current transports: Preliminary results from 26.5ºN in the Atlantic". Geophysical Research Letters, 33, L17610, doi:10.1029/2006GL026965, 2006.
2. Baringer, M. O. and C. S. Meinen, "Thermohaline Circulation", in "State of the Climate in 2005", K. A. Shein, ed., Bulletin of the American Meteorological Society, 87(6), s1-s102, doi: 10.1175/BAMS-87-6-shein, 2006.
3. Shoosmith, D. R., M. O. Baringer and W. E. Johns, 2005. A continuous record of Florida Current heat transport at 27°N, *Geophys. Res. Letters*., 32, L23603, doi:10.1029/2005GL024075.

Abstracts/Meeting Proceedings:

1. Baringer, M. O., Heat transport variations in the subtropical North Atlantic. Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.
2. Meinen, C. S., M. O. Baringer, and S. L. Garzoli, Variability of the Western Boundary Currents in the subtropical North Atlantic. Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.
3. Longworth H. R., H. L. Bryden, M. O. Baringer: Variability in the Atlantic Meridional Overturning Circulation at 25ºN from 1980 to 2005. Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.
4. Cunningham, H. Bryden, J. Hirschi, D. Rayner, J. Marotzke, W. Johns, M. Baringer, C. Meinen: Vertical compensation of mass transports associated with the meridional overturning circulation in the Subtropical North Atlantic.
5. Bryden Harry L., Torsten O. Kanzow, Hannah R. Longworth, Stuart A. Cunningham, Molly O. Baringer, Lisa M. Beal, Joel J.- M Hirschi, William E. Johns, Christopher S. Meinen, Jochem Marotzke, Darren Rayner: Variability in the Atlantic meridional overturning circulation at 25°N.
6. Rayner D., S. Cunningham, H Bryden, T. Kanzow, J. Hirschi, J. Marotzke, W. Johns, M. Baringer, C. Meinen, L. Beal : Evolution and maintenance of the transatlantic mooring array at 26.5°N.
7. Meinen, C. S., M. O. Baringer, and S. L. Garzoli, Variability in transports along the subtropical Atlantic western boundary: Implications for monitoring the MOC, EGU General Assembly, April 2-7, 2006, Vienna, Austria.
8. Meinen, C. S., M. O. Baringer, and S. L. Garzoli, Transport variability along the subtropical Atlantic western boundary: Implications for monitoring the Meridional Overturning Circulation, Office of Climate Observations Review Workshop, May 10-12, 2006, Silver Spring, Maryland.

Technical/Progress Reports:

1. Baringer, M. O., C. S. Meinen and S. Garzoli, 2006. The Meridional Overturning Circulation and Oceanic Heat Transport, In *Annual Report on the State of the*

Ocean and the Ocean Observing System for Climate (FY-2005), J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 68-73.

2. Baringer, M. O., C. S. Meinen and S. Garzoli, 2006. Western Boundary Time Series in the Atlantic Ocean, In *Annual Report: The State of the Ocean and the Ocean Observing System for Climate*, J.M. Levy, D.M. Stanitski, and P. Arkin (eds.), Office of Climate Observation, Climate Program Office, National Oceanic and Atmospheric Administration, 150-158.

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

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PROJECT SUMMARY

Overview

As a NOAA contribution to the global network of Ocean Sustained Interdisciplinary Timeseries Environmental Observatory (OceanSITES) timeseries reference stations, an air-sea flux buoy, referred to as the Kuroshio Extension Observatory (KEO), was deployed in the Kuroshio recirculation gyre at 144.5°E, 32.3°N in June 2004. In June 2005, KEO was enhanced with a pCO_2 system to monitor carbon flux and additional subsurface instrumentation. The site is within the study domain of the 2-year (June 2004 - June 2006) NSF-funded Kuroshio Extension System Study (KESS) and KEO data are being combined with KESS measurements to evaluate processes affecting the heat content, Subtropical Mode Water formation, and recirculation gyre strength. For KEO's first three deployments, KESS provided shiptime, equipment and personnel for mooring operations. Collaborations with Japanese colleagues have begun and a formal partnership between JAMSTEC and PMEL is being developed. In February 2007, JAMSTEC IORGC in partnership with NOAA PMEL will deploy a KEO mooring (J-KEO) north of the Kuroshio Extension jet. For FY07, we plan to do KEO repairs and the mooring turnaround on Japanese research vessels. With the success of the KEO time series reference site, PMEL has been approached by several other potential partners. In particular, as part of a NSF-funded Carbon and Water Cycle project led by biogeochemical scientists from the University of Washington, in June 2007 PMEL will deploy a KEO-type air-sea flux mooring at the Ocean Weather Station PAPA in the Northeast Pacific. The PAPA and J-KEO offshoots of KEO represent a major expansion of the OceanSITES array. However, longterm funding for the PAPA air-sea flux mooring still needs to be secured to continue the PAPA mooring past the planned final recovery in August 2009. For more details on the KEO project and to access the realtime and delay mode data, see the KEO project website: http://www.pmel.noaa.gov/keo/

Scientific Rationale

The Kuroshio, the North Pacific's poleward flowing western boundary current, separates from the coast near 35°N and becomes an eastward flowing jet, the Kuroshio Extension (KE). The KE represents the entrance region of the Pacific storm track and is characterized by some of the largest air-sea fluxes found in the entire North Pacific. It is one of the largest sinks of carbon in the North Pacific and has the characteristic maxima lobes of latent, sensible, and net surface heat loss. The net surface heat loss is particularly large during winter when the zenith angle of solar radiation is low and cold, dry continental air blows across the warm KE waters. Wintertime net surface heat losses average 330 W/m^2, and instantaneous fluxes can be much higher (Fig. 1).

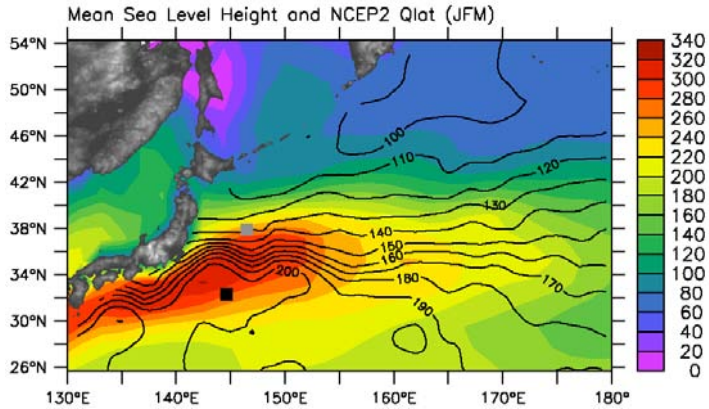

Fig 1. Climatolocial wintertime (January-March) latent heat flux and sea level height in the Kuroshio Extension region. The KEO site is indicated by a black square. The J-KEO site is indicated by a grey square.

The KE atmosphere-ocean system represents a major branch of the global heat cycle, whereby the input of excess heat 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. At the KE, heat is transferred from the ocean to the atmosphere. North of the KE, more heat is carried poleward by the atmosphere (in large part through transient eddies, i.e., storms) than by the ocean. Since the partitioning of the meridional heat flux between the atmosphere and ocean is closely related to KE air-sea interactions, fluctuations in the latter are surmised to impact the climate variability of the North Pacific basin.

As with the Gulf Stream in the North Atlantic, the KE is highly variable, featuring large-amplitude meanders that can pinch off to form anti-cyclonic warm-core eddies north of the jet and cyclonic cold-core eddies south of the jet. It carries 140 million cubic meters (140 Sv) of warm water eastward into the North Pacific. Wind driven Sverdrup transport accounts for about a third of this transport; the other 90 Sv is due to a tight anticyclonic recirculation gyre south of the jet whose size varies on seasonal-decadal time scales. At the center of the recirculation gyre, the thermocline is deep. During spring and summertime, a seasonal mixed layer can form. Wintertime convection erodes this stratification producing a thick (up to 400 m thick) isothermal ~17°C surface layer, termed *Subtropical Mode Water* (STMW). The STMW acts as a reservoir of heat. After it is isolated beneath the seasonal thermocline, it retains its water mass characteristics, reemerging the following winter to once again interact with the atmosphere. Through this "re-emergence mechanism", mode water formed in a given winter is expected to affect SST in the subsequent fall and winter. Mode water formation is also associated with the sequestering of carbon. Large dust clouds blowing eastward off Asia are visible in satellite images and can be traced all the way across the Pacific basin. Asian dust is rich in iron and other nutrients. With the KEO carbon flux system, we hope to monitor whether the carbon cycle's biological pump is affected by the passage of these clouds.

With surface currents of 3 knots (~150 cm/s) or more, a typically rough sea state, and lying in the Jet Stream's storm track, the KE is an extremely difficult region to observe. Ships have been the traditional platform for observing air-sea interaction in western boundary currents. However, research cruises typically last no more than a month or two, and measurements from research ships

and vessels of opportunity are biased towards good weather. With the successful first year deployment, the instrumentation of the KEO mooring was expanded to include a carbon flux system and additional subsurface sensors as described below in Section 2. The KEO mooring is serving a wide community of climate sciences both in the US and in Japan. It is being used as a reference time series for comparison with numerical weather prediction products as well as satellite products (Kubota et al. 2006). It is also expected to provide new insights into the air-sea interactions within this climatically important region.

The KEO buoy is a contribution to the network of Ocean Reference Stations in a key region for air-sea interaction and therefore directly addresses the sixth element of the Program Plan for *Building a Sustained Ocean Observing System for Climate* (Ocean Reference Stations). This mooring also carries a Carbon Flux sensor to directly address the seventh element "Ocean Carbon Networks". The KEO site has been endorsed by the International Time Series Science Team (co-chaired by R. Weller), which reports to the Ocean Observations Panel for Climate (OOPC). The two primary international ocean carbon research programs are the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and the Surface Ocean Lower Atmosphere (SOLAS) programs. Both groups strongly recommend carbon time-series measurements and are very supportive of NOAA's efforts to develop a global pCO_2 mooring network. The KEO mooring is an important part of that effort. Time-series carbon measurements are also a key element of the United States research programs like the Ocean Carbon and Climate Change Program (OCCC).

The KEO mooring is operated by the NOAA Pacific Marine Environmental Laboratory and has several strong partners. The KEO buoy is an element of the OceanSITES network of reference sites and therefore is partners with other buoy programs in the network (e.g. STRATUS, NTAS, HOT, TAO/TRITON). Because KEO carries a carbon flux system, the KEO project also is a partner to the Global Carbon Cycle Program. This partnership is represented by co-PI Sabine. TAO and the NSF-funded Kuroshio Extension System Study (KESS) are particularly close working partners. The buoy was originally purchased under the now-complete NOAA OGP funded TAO-Eastern Pacific Investigation of Climate (EPIC) project. Professional staff supported by the KEO project are drawn from the pool of professional staff that participate in the TAO program. Located within the KESS array and within 10 km of N. Hogg and S. Jayne's subsurface profiler mooring, the KEO buoy is contributing scientifically to the KESS experiment. KESS in turn has provided ship time, technicians and equipment for mooring operations. After the final KESS recovery cruise in June 2006, ship time will be provided through JAMSTEC. Drs. Ichikawa, Konda, and Tanimoto have developed a plan to deploy a surface buoy, much like KEO, north of the jet. This buoy (J-KEO) will be deployed in February 2007 through partnership with PMEL. Because KEO carries a carbon flux system, the KEO project also is a partner to NOAA's Global Carbon Cycle Program. This partnership is represented by co-PI Sabine.

FY2006 ACCOMPLISHMENTS

The KEO project has 3 broad deliverables, each described below.

Deliverable 1: Calibrated surface meteorological and subsurface temperature, salinity and currents at the KEO site in the Kuroshio Extension recirculation gyre at 32.3N, 144.5E.

The KEO mooring diagram is shown in Fig 2. 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.

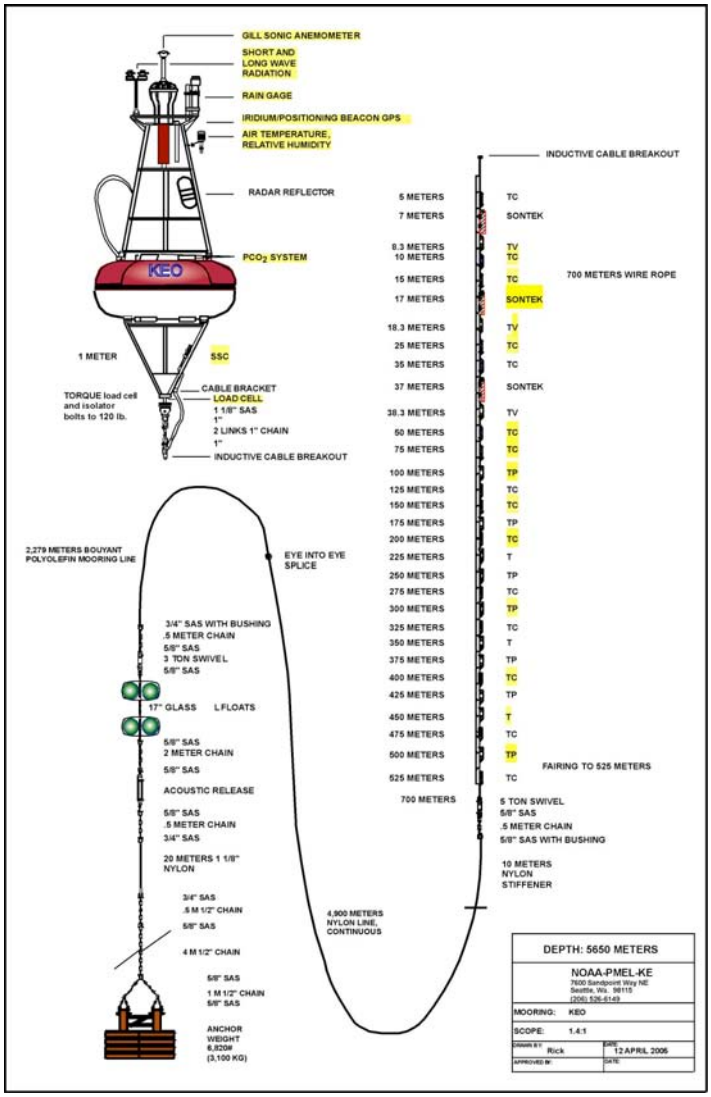

Fig. 2. KEO diagram. Telemetered measurements are highlighted in yellow.

On November 6, 2005, the buoy and the line with all of the subsurface sensors broke away from its anchor and began drifting southeastward. Since the buoy position is monitored on a daily basis, we were able to make immediate arrangements for a rescue. As luck would have it, Dr. Ichikawa had just left port on the R/V Kaiyo. Within 3 days, he had recovered the KEO buoy and all of the subsurface sensors. The equipment recovered was valued at more than $150,000. However, perhaps more important, since the high resolution data are stored in the subsurface modules and the surface electronics "tube", the recovery included not only valuable equipment, but also valuable data. The quick response from JAMSTEC is recognized as a testament to the long collaboration between PMEL and JAMSTEC.

The break occurred under relatively benign conditions in the middle of a continuous section of ¾" nylon, 300 m below the lower terminus of the jacketed wire rope, ~1000 m below the surface. Because of the quick and careful recovery, a thorough engineering analysis of the break could be performed (Lawrence-Slavas et al. 2006). The break did not occur at a splice. The cause of the break is not certain, although, it appears to be most likely due to a manufacture defect in the nylon.

In May 2006, KEO was redeployed as a piggy-back project on the final KESS mooring cruise aboard the R/V Melville with S. Jayne (WHOI) as chief scientist. KESS also supported KEO by providing additional mooring technicians and shipboard equipment. The KEO project is very grateful for the support provided by KESS. The PMEL scientific party included 1 mooring technician (P. A'Hearn) and a TAO programmer (S. Moon). The KEO PI (M. Cronin) traveled to Yokohama Japan to help stage the buoy prior to deployment and to meet with JAMSTEC scientists to discuss the PMEL-JAMSTEC partnership.

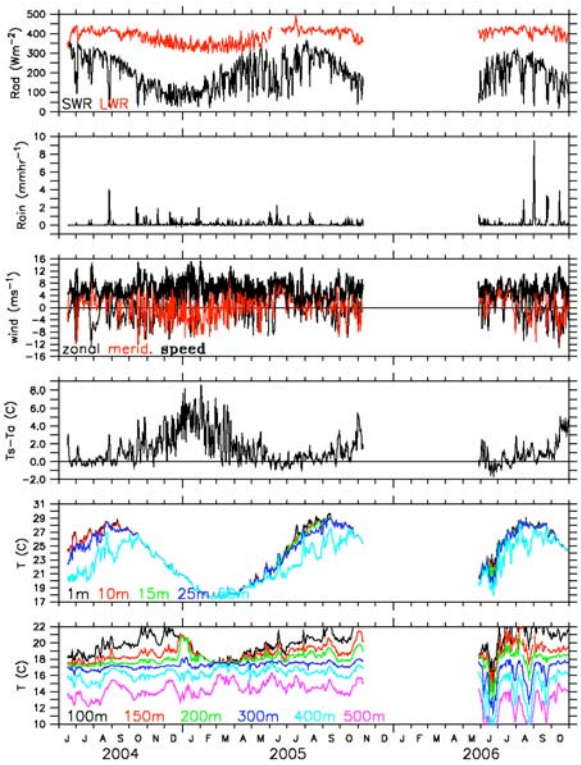

Fig. 3. Select KEO daily-averaged data through October 2006.

Select time series are shown in Fig. 3. The full suite of KEO meteorological measurements include: wind speed and direction from a sonic anemometer, air temperature, relative humidity, rainfall, and solar and longwave radiation. Daily-averages of all met data are telemetered in near-realtime. Surface and subsurface measurements include sea surface temperature and salinity at 1 m (both of which are telemetered), subsurface temperature at 28 depths down to 525m (12 of which are telemetered), subsurface salinity at 15 depths down to 525m (5 of which are telemetered), and pressure at 7 depths (3 of which are telemetered). Thus 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.

	FY06 Data Returns	
	full year	**while in water**
Meteorological variables	45%	100%
Upper ocean temperature	33%	99%
Upper ocean salinity	30%	91%
Near surface currents	19%	42%

Table 1. KEO data return for FY06 based upon daily-averaged delay-mode data and telemetered daily-averaged data after May 28 2006.

Data returns are reported in Table 1 for the full 365 days of FY06 as well as for the 162 days that the mooring was in the water. Current meters have had a troubling data return, with complete failure of one of the three sensors during each deployment and many data drop outs. The other sensors however had in general excellent data return (when the mooring was in the water). In particular, as with FY04 and FY05, in FY06 the meteorological sensors had 100% data return when the mooring was in the water. This period included the passages of two typhoons: IOKE in August 2005 and YAGI in September 2005. The center of YAGI in particular came within 30 nm of KEO and will be analyzed in great detail. Unfortunately, the third typhoon to pass over KEO (SOULIK on October 17 2006) damaged the relative humidity sensor. We are very grateful to JAMSTEC for helping us make arrangements for this sensor to be repaired in January 2007.

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

KEO data are the first PMEL data to be 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:

http://www.pmel.noaa.gov/keo/data.html

Because the KEO array has been an array of one buoy, the data have been withheld from the Global Telecommunications System (GTS) so that they can be used as an independent validation in comparisons with satellite and numerical weather prediction (NWP) fields. With the deployment of the second buoy in the region, this decision will be reviewed. High-resolution surface and subsurface data will be made publicly available through the KEO website within 6-months of recovery. At this point there is no user registry and so we have no way of monitoring the number of data downloads. This will likely be reviewed in FY07.

Deliverable 3: Scientific analyses utilizing KEO data.

KEO data is a critical component of various scientific studies in progress. In particular, the KEO PI (Cronin) and Dr. N. Bond at PMEL/UW JISAO were recently funded to do a set of KEO analyses under a NOAA CLIVAR project titled "Role of Air-Sea Interaction in the Kuroshio Extension Recirculation Gyre". At the 2006 Ocean Sciences conference, both Cronin and Bond presented results on the upper ocean heat budget for the Kuroshio Extension Recirculation gyre (Cronin et al. 2006) and regional air-sea interactions during KESS (Bond and Cronin 2006a). The analysis of regional weather patterns during periods of anomalous air-sea interaction has subsequently been submitted to the Journal of Climate (Bond and Cronin 2006b).

Large air-sea temperature differences can be seen in the KEO time series (Fig. 3) from October through March. Heat fluxes associated with cold-air outbreaks can contribute to explosive cyclogenesis, yet are often poorly modeled and can contribute to systematic biases in seasonal and climatological NWP flux estimates. However, the summertime radiative heat fluxes appear to also have large biases. Radiative and turbulent air-sea heat fluxes computed from the KEO data are being used for comparisons with the J-OFURO satellite derived flux products (Kubota et al., 2006).

As can be seen in Fig. 4, the Kuroshio Extension appears to have switched from a quasi-stable path-state, to an unstable path state. Periods with quasi-stable path, tend to have larger eastward surface transport, more northern zonal-mean path, and an elongated recirculation gyre; while periods with the unstable path tend to have a weaker eastward surface transport, more southern mean path, a contracted recirculation gyre. The KEO site is well-placed for investigating the processes affecting the recirculation gyre's heat content and their relationship to the state of the system.

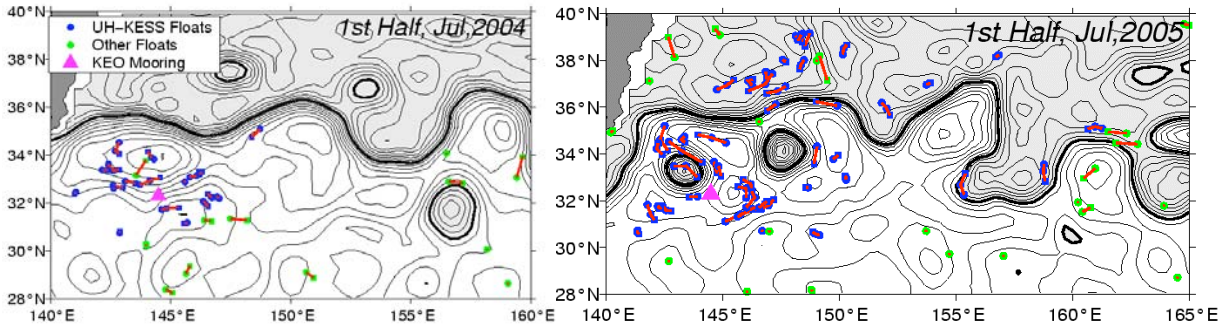

Fig. 4. Sea level height and ARGO float tracks in the Kuroshio Extension region during the first half of July 2004 when the KE was in a quasi-stable state (left) and during the first half of July 2005 after it had become unstable. The KEO site is indicated by a magenta triangle. Sea level height contours can be interpreted as surface geostrophic streamlines of flow.

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Progress Report: Southern Ocean Modern Observations/Weddell Sea Moorings
November 2006

Arnold L. Gordon and Bruce Huber
Lamont-Doherty Earth Observatory of Columbia University; Palisades, NY

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 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 Consortium on Oceans Role in Climate: AbRupt climate CHangE Studies (CORC-ARCHES) Southern Ocean Modern Observations program.

First installed in April 1999, the moorings are 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, CTD/tracer stations are occupied at the mooring sites and at stations distributed along a line between the mooring locations (Figure 1).

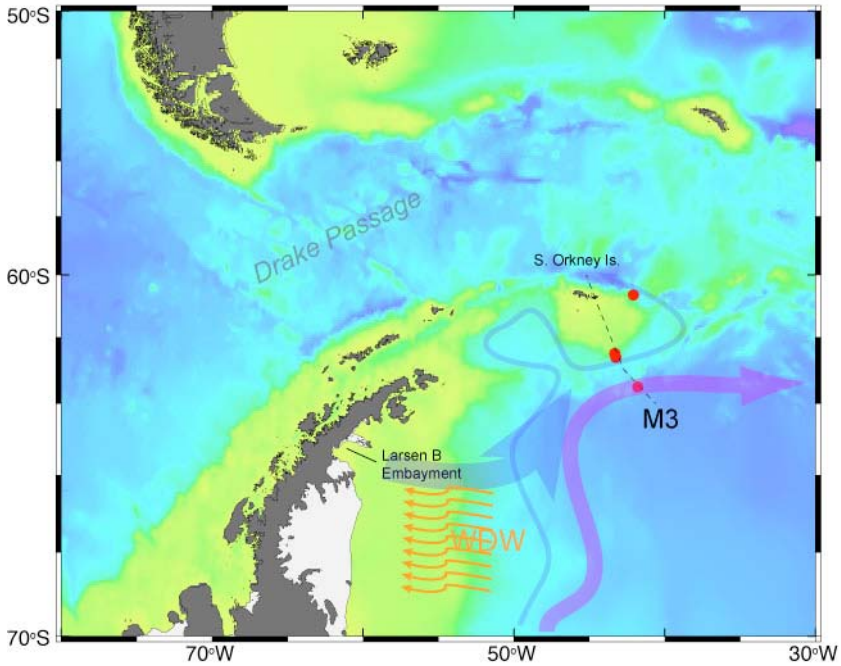

Figure 1. Location of the Weddell Sea moorings (red dots) and repeat CTD/Tracer line (dashed line). Shown schematically are the pathways of deep and bottom waters formed by interaction of WDW with continental and ice shelf waters.

Continuing a collaboration that began in 2004, we were invited to join Eugene Domack and his co-investigators on cruise NBP0603 (N B Palmer) to the western Weddell in April-May 2006. Time was set aside at the end of the cruise to service the ARCHES moorings near the South Orkney plateau. Funding for the ARCHES-related ship time was provided by OCO.

As part of the ongoing collaboration with Domack et al., we had deployed instrumented sediment trap moorings in the Larsen B embayment in 2005 (during cruise LMG0502) which we attempted to recover in 2006. Two of the moorings could not be recovered, presumably because they were carried away by large ice shelf calving events which had occurred just prior to the cruise. Ice, weather, and time limitations prevented attempts to recover the other 3 moorings. While in the Larsen B embayment, CTD stations were occupied. Preliminary analysis of the data from these stations, in combination with data collected in 2005, resulted in two poster presentations at the Geological Society of American meeting in October 2006 (Philadelphia).[1]

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[1] "Deep Access to the Larsen Ice Shelf-B Embayment: an International Geologic and Geophysical Expedition (E. Domack, A. Leventer, B. Huber, G. Halverson, R. Gilbert, S. Brachfeld, V. Wilmott, A. Rathburn, M. Rebesco, S. Ishman) and

"Transport of supended particulate material by Ice Shelf Water cold tongues: a new observation from Spillane Fjord (Crane Glacier), Antarctica (A. Mention, E. Domack, B. Huber, A. Leventer, S. Brachfeld, L. Padman

At the conclusion of the Larsen B science program the vessel transited to the ARCHES work site, where we attempted to deploy a mooring at site M2. Severe weather and ice conditions during the transit reduced the working time available to only 8 hours on site. The mooring was successfully deployed, but a catastrophic flotation failure at depth caused the release to trigger, returning the mooring to the surface. All instruments were recovered, but we were unable to redeploy the mooring as there was insufficient time remaining.

We have established a cooperative arrangement with colleagues at the British Antarctic Survey (BAS) to continue servicing the ARCHES moorings, and to expand the array in conjunction with the BAS program in the region. We are sending one member of our group to join a BAS cruise on board RRS Ernest Shackleton in February-March 2007, during which the BAS and LDEO ARCHES moorings will be serviced.

Monitoring the Indonesian Throughflow in Makassar Strait

Arnold L. Gordon
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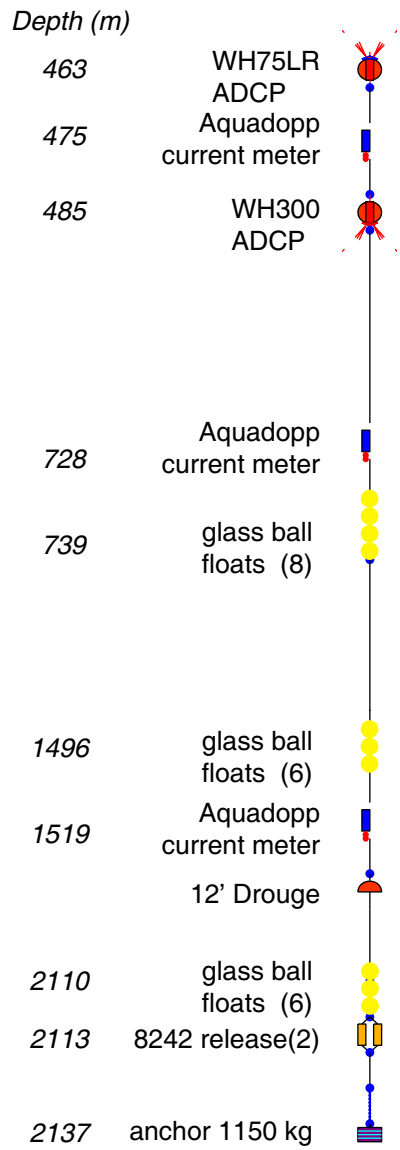
Project Summary

The Indonesian Throughflow (ITF) of Pacific water in to the Indian Ocean represents an important part of the ocean system of interocean fluxes. The ITF is believed to govern aspects of ENSO and the Asian monsoon. The ITF amounts to ~12 Sv, 80% of which is channeled through Makassar Strait. Within then Labani constriction of Makassar Strait near 3°S, the throughflow was measured during Arlindo program from December 1996 to July 1998, and during the INSTANT program from January 2004 to July 2005, and with the presently deployed INSTANT moorings, with planned recovery in November 2006. NSF funded both Arlindo and INSTANT. With NOAA OCO support a single mooring within Makassar Strait will be maintained after completion of the INSTANT array. The NOAA monitoring mooring will be deployed in November 2006. The NOAA mooring will be placed in the same location as the INSTANT MAK-WEST. A transfer function based on the Arlindo and INSTANT time series will allow the MAK-WEST data to be converted to a full Makassar ITF. The MAK-EAST is very close to a constant 80% of MAK-WEST along channel speeds.

The NOAA Mak Mooring: Building on experience gained from the Arlindo and INSTANT programs, we will install a simplified mooring with instruments placed well below the high-velocity core of the throughflow. The mooring will be instrumented as shown schematically in Figure 1. An upward-looking RDI Longranger ADCP will provide velocity profiles from approximately 500 m to near the surface, resolving the bulk of the throughflow velocity field without being subjected to the blowover associated with the large velocities in the thermocline. Additional current meters, including an RDI 300 kHz Workhorse ADCP, will provide velocity measurements throughout the remainder of the water column. Dual acoustic releases will be used to give an added measure of reliability. The ADCPs are mounted in syntactic foam buoys with in-line mooring cages. Backup flotation is provided by distributed glass ball floats in plastic hard hats.

All of the instruments will be equipped with battery and memory capacity for a 2 year deployment.



For the ADCPs, this entails using a sampling rate of one ensemble per hour. The Aquadopps will also be set for hourly sampling, but they can also record bursts of higher frequency samples for diagnostic purposes. The releases will be prepared for 4 year endurance.

The ADCPs, syntactic foam buoys, and Aquadopp current meters will be provided by LDEO after recovery of the INSTANT moorings. We are requesting funds to purchase 2 ORE 8242 acoustic releases, 20 17" Benthos glass ball floats, mooring line, shackles, batteries, anchor, and related hardware which will not be available from recovery of the INSTANT moorings.

Cost of shipping the new materials to Indonesia will be absorbed by the INSTANT program, since we must send a container for that program anyway, and adding the materials to that shipment will have no impact on the total cost of the shipment. We do anticipate, however, that due to the tight schedule, there will be some items requiring airfreight, for which we have budgeted.

Deployment will be carried out from the Indonesian research vessel Baruna Jaya I, during the INSTANT recovery cruise on approximately 25 November 2006, directly after the final recovery of the two INSTANT Mak moorings.

MERIDIONAL OVERTURNING VARIABILITY EXPERIMENT

Uwe Send, Scripps Institution of Oceanography, La Jolla, CA

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 new 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 6-year deployment period from German funding. 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.

FY 2006 Activities

A German cruise on RV 'Merian' was used in December 2006 to re-deploy the MOVE moorings. An arrangement had been reached with IfM-Geomar (Kiel) and the German funding agency whereby two days of ship time could be saved on the December cruise by doing acoustic data readout from two inverted echosounders/pressure sensors (PIES) on the later spring'07

NOAA NTAS cruise. These two days of ship time were then available for the mooring deployments for the current MOVE project.

November 2006

Due to the limited funding in year 1, not all the required mooring hardware and sensors could be purchased from MOVE. Therefore, the two new microcat moorings that were deployed in December on the German cruise still use some German equipment and wire purchased with leftover German funds, and the current meter mooring on the continental slope carries entirely German equipment (current meter, flotation, acoustic release). Also the PIES which were to remain in the water were mainly German ones. Additional flotation and microcats were borrowed from other SIO projects of the P.I..

On the other hand, we used the MOVE startup funding to purchase 20 microcats, to pay salaries for the mooring and cruise preparations, to pay container shipment and travel of three SIO participants in the German cruise. We also constructed new top float assemblies for the moorings, which carry new ARGOS beacons purchased (these activate after surfacing) plus recovery aids (FM radio and flasher).

The joint SIO/IfM-Geomar cruise in December 2006 successfully recovered the previous MOVE moorings (plus a tomography system) and redeployed 2 microcat transport moorings, and 1 current meter mooring on the continental slope. However, not all equipment is MOVE or even SIO owned.

Problems were found with the existing PIES in the array, four of which were meant to be only visited and have data read out acoustically. All of them were found inoperational, i.e. they did not transmit data and were not acquiring data anymore. Since the release mechanism is powered separately, they could be recovered and diagnosed. A faulty battery configuration by the manufacturer had caused failure of the units one year prior to this cruise.

Because of this problem with the PIES, the April 07 NTAS cruise was used to redeploy PIES systems with corrected battery assemblies. Two new PIES purchased with NOAA funds were

prepared and shipped to the “Ron Brown” NOAA cruise, and another three PIES were sent from Germany to complement the MOVE bottom pressure array for GRACE validation measurements. At the time of writing, the cruise is proceeding, and has already successfully deployed the two NOAA owned PIES next to the microcat moorings (deployed in December), and two additional German PIES. The PIES are expected to operate for 4years, and data will be retrieved each year on the NTAS cruises, when the moorings are serviced.

As such, we now have a rudimentary MOVE array operating again, with the two basic geostrophic endpoint moorings covering the North Atlantic Deep Water using microcats, plus PIES bottom pressure measurements, and a slope mooring. Next year, all the loaned equipment has to be returned and both sensors and mooring hardware have to be from NOAA project funding. In the long run, the mooring coverage should be extended to the surface again, and dual PIES should be deployed at each mooring, to allow rotating the 4-year deployments with 2-year overlap – this would significantly reduce the long-term sensor drift in the bottom pressures and allow recognition of interannual variability.

INTEGRATED BOUNDARY CURRENT OBSERVATIONS IN THE GLOBAL CLIMATE SYSTEM

U.Send, R.Davis, D.Rudnick, P.Niiler, B.Cornuelle, D.Roemmich
Scripps Institution of Oceanography, La Jolla, CA

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.

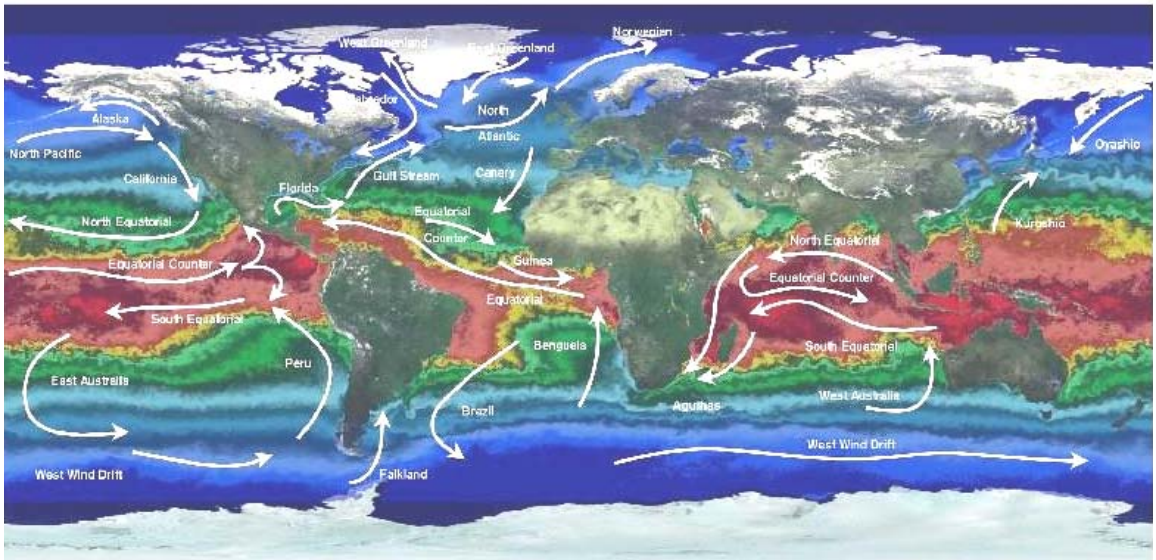
We propose to develop, demonstrate, and implement a system that can fully monitor the intensity (mass and heat transports) of most boundary currents in a sustained and routine mode, delivering indicators about the state of those regimes in near-realtime. To this end we will merge several technologies 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 will be 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 will contribute 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, implementation 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).

FY 2006 Activities



November 2006

A: Glider Operations in Integrated Boundary Current Observations Pilot
(Russ E. Davis and Daniel L. Rudnick)

There are two components to our project on using underwater gliders to monitor climatically significant variability of boundary currents to augment the global Argo array. In the longer running component, we are using Spray gliders to observe, first, the structure and magnitude of the flows from the tropical South Pacific to the equatorial zone and, eventually, temporal variability of this transport. A component that began this grant year is expanding the capability of the Spray glider so that, in strong boundary currents where surface piercing moorings are not feasible, the glider can acoustically gather data from submerged instrumentation and carry it to the surface for satellite communication.

In the current reporting period, we have (1) completed another crossing of the South Pacific's Equatorial Current (SEC) between Guadalcanal and New Caledonia, (2) prepared and shipped a second Spray for exploration of the SEC as it enters to Solomon Sea on its way to the equator, and (3) made substantial progress modifying Spray for its acoustic transponder capability.

Our second sampling of the SEC between Guadalcanal and New Caledonia, completed in collaboration with William Kessler (PMEL) and Lionel Gourdeau (IRD, Noumea), was less successful than the first crossing, which was reported in "Zonal jets entering the Coral Sea" by Gourdeau, L., W.S. Kessler, R.E. Davis, J. Sherman, C. Maes and E. Kestenare, submitted to *Journal of Physical Oceanography.* About halfway across the transit, while operating well below the surface, Spray 01 was hit/bitten hard enough by something that its attitude was upset and it could not subsequently maintain its cruising speed; on recovery, part of the tail was

missing. Further into the mission, the CTD salinity underwent a sudden step change of O(0.1) the cause of which we cannot diagnose until the vehicle returns to SIO. Attack by predators and measurement errors caused by bio-fouling are intrinsic problems with autonomous sampling and, although rare, this cruise shows they are a real operational factor.

A second Spray is in transit to Noumea for deployment this September near the south-east corner of the New Guinea land mass where it will begin to transit east to Guadalcanal and then possibly to New Caledonia. This will first of all give direct observations of the SEC as it turns north, both in the New Guinea Coastal Undercurrent, where strong currents have been documented, and in other interior-ocean pathways to the equator. The strength of these flows is a concern for future operations as is the remoteness of the sites for shore support.

CORC contributions to monitoring climate variability in the California Current were development of a 750 kHz acoustic Doppler current profiler (ADCP) for the Spray glider and the implementation of continuous sampling along CalCOFI Line 90 since 19 October 2006. This is the section where the pilot boundary current array will be deployed. The objectives of this effort are (1) to begin monitoring conditions on the line that our prototype boundary current monitoring system will be tested on in order to extend the temporal context, (2) to gather scales (energy, temporal and spatial) of variability on this line to use in optimizing control of gliders when they are interrogating bottom instruments, and (3) to gain operational experience steering Spray to a fixed point as will be necessary to get within acoustic range of transponding instruments. These gliders support a CTD for temperature and salinity observations, a chlorophyll-a fluorometer as a qualitative measure of phytoplankton abundance, and a 750 kHz acoustic Doppler current profiler to measure velocity shear and acoustic backscatter, which serves as rough index of zooplankton abundance and the presence of schools of small fish. This instrument suite was developed under previous CORC funding and seems well suited for characterizing the coupled physical and biological responses to climate variability.

For the new integrated system using gliders together with PIES and moorings, we have purchased one acoustic modem and transducer that will be used on Spray to interrogate submerged instruments. A way has been devised to install a transponder in Spray by lengthening it by only about 5 cm, and construction of the larger hull has begun. A way to physically incorporate the electronics for the modem into Spray has also been designed. Work has further begun for structuring the software expansion that will be needed. We look to having a prototype ready for testing this summer.

B: Moorings and PIES in the Integrated Boundary Current Observations Pilot
(U.Send)

An acoustic modem system has been selected for use on the moorings, on the inverted echosounders/pressure sensors (PIES) and in Spray gliders in their role of interrogating subsurface instruments in the pilot boundary current array. Two such modem systems have been purchased for this task (plus one in the glider task). Engineering bench tests with the modems have been completed to check their functionality, power consumption, and performance.

Designs for the modem integration (hardware and software) with the PIES and the moorings are completed. Modifications for the PIES have been agreed on and implemented with the manufacturer, and two such PIES ready for external modem interfacing have been purchased and received. The mechanical design for adding the modem to the PIES on their bottom tripod is completed and will be tested soon.

For the mooring work, a new controller is nearing completion which will allow collection of data from moored instruments (inductively from microcats, and via serial line from ADCPs), and which will pre-process the data, and pass them to the acoustic modem. Some mooring sensors have been acquired already, and more mooring hardware is now being purchased to prepare the first test moorings off San Diego. We plan a trial deployment of a PIES with the acoustic modem on the seafloor soon, which can be used to test the telemetry from small boats and later with a prototype glider.

C: XBT data in support of the California Current observing system
(D.Roemmich)

We are organizing CalCOFI and XBT datasets to address questions about interannual variability in the transport of the California Current. First, we have updated, to the present, estimates of geostrophic velocity and transport for CalCOFI lines 80 and 90. Similarly, we have calculated geostrophic velocity for the XBT lines out of Los Angeles and San Francisco. Scientific questions are: (i) do we see the same interannual variability in CalCOFI Line 90 and the Fiji-Los Angeles XBT line, (ii) where is the offshore edge of the California Current in the Fiji-Los Angeles XBT line, (iii) is the interannual transport variability in the California Current at the two XBT lines correlated?

For the research-quality deep XBT probes (LMP-5 T1) development work at Sippican is proceeding slowly. Sippican carried out an unsuccessful test at Bermuda a few months ago. We're hoping for a new batch of probes for evaluation in the next few months.

D: Synthesis of transports through the southern CCS
(Peter Niiler, Yoo Yin Kim, Luca Centurioni)

The combined data sets on circulation of the CCS are being analyzed for the purpose of computing both the time mean and the deviations from that mean. In the period of February-April, 2007 we have organized the historical drifter and altimeter data sets from 1985-2006 and computed from these the 15m geostrophic velocity distribution in the 1982-2007 CALCOFI survey area (Figure 1). In the present funding period, we will combine these observations with the ADCP data sets acquired from the CALCOFI surveys since 1993 by Dr. T. Chereskin at SIO, as well as the CALCOFI hydrographic data to compute the mass transports of the upper layers through the CORC observation regions. Of interest is both the time mean and time variability of the geostrophic (that contains no divergence) and the ageostrophic (that contains the divergence and upwelling) horizontal circulation patterns.

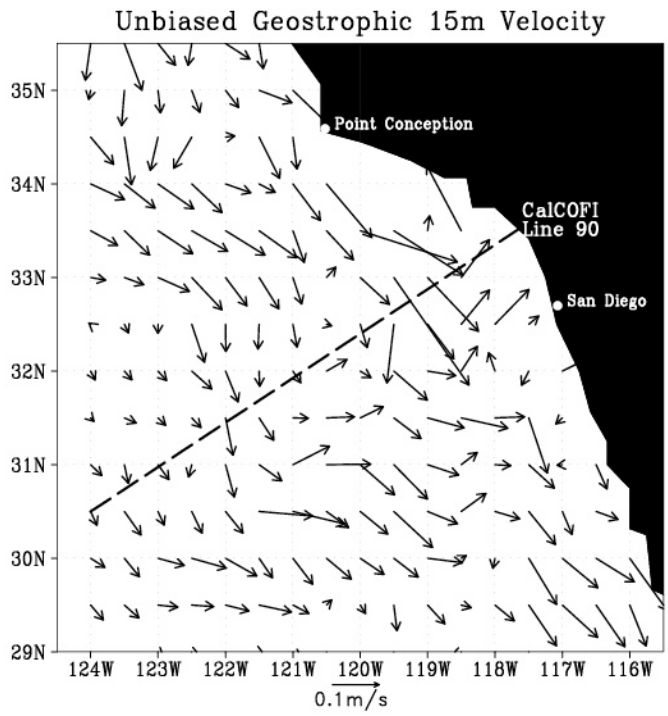


Fig.1: *Unbiased 1992-2002 geostrophic 15m velocity in the CCS off southern California (from Centurioni, L. , J.C. Ohlmann and P.P. Niiler: Permanent meanders in the California Current System, submitted to J. Phys. Oceanogr., February, 2007). Along CalCOFI line 90, the section to be sampled by CORC, the CCS is concentrated in two branches.*

E: Modelling and assimilation of future CORC data in the California Current
(B. Cornuelle)

A second paper on the modeling and assimilation in the tropical pacific from the previous CORC project has been accepted (J. Atm. Ocean. Tech.), and we are working on two others, one on TIWs and one on the completed assimilation for the year 2000.

For the modeling work, an MITgcm model grid has been made for the CCS region from north of San Francisco to south of San Diego, at 1/6 degree resolution. A few months of test assimilation runs have been performed using altimeter SSH and satellite SST only. The assimilation seems to work as expected so far, but a lot of work is needed to evaluate the choices of parameters (viscosity, diffusivity, Kpp, etc.) and to assemble the datasets.

We are continuing to work on the California Current assimilation, although we have not yet incorporated the in situ observations. We are presently updgrading to the newer version of the ECCO code (which is the assimilation package including the MITgcm), so we are in a debugging process, since many features have changed. We are planning to do hindcast experiments from CalCOFI observations to evaluate the model skill. To that end, we have begun to look at assembling forcing fields and observations.

Summary
At present, the project is proceeding as planned. For the coming months first in-water tests are expected with the acoustic hardware near San Diego. First trials with a glider are anticipated for the summer. If everything is successful, we will be ready for first combined mooring, PIES, and glider deployments after the summer.

High Resolution Climate Data From Research and Volunteer Observing Ships

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

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 new 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.

FY2006 ACCOMPLISHMENTS

For the *Ronald Brown* C-band and wind profiler radar project, routine maintenance was performed on the wind profiler at Charleston, SC, prior to the NOAA 2006 AMMA in June and July 2006.

ESRL completed two research cruises as planned: the Bob Molinari buoy deployment cruise in the Atlantic in the summer of 2006 (this is the *AMMA/Saharan Dust* cruise) on board the R/V *Ronald H. Brown* and the joint ESRL/WHOI cruise to the climate reference buoy (25 S 80 W), also on board the *Brown* in October 2006. The preliminary processed data can be found at ftp://ftp.etl.noaa.gov/et6/archive/

A synthesis of the main results of the previous five years of strategic observations were produced in the form of three scientific publications (two have appeared in print and one is submitted). The first two (Cronin et al., 2006a and 2006b) dealt with the quality of TAO buoy observations (through intercomparison with ESRL ship data) and analysis of the annual cycle of turbulent and radiative fluxes. Deficiencies in satellite and operational numerical weather prediction (NWP) surface fluxes in the Eastern Equatorial Pacific were identified. The third paper (Fairall et al., 2006) dealt with the analysis of radiative cloud forcing based on the four years of ESRL ship-based observations. Here the emphasis was on the linkage cloud forcing to cloud properties such as fractional coverage and liquid water path. This paper showed that the three observational data sets (ESRL ship data, TAO buoy data, and ISCCP satellite estimates) agreed much more closely than NWP estimates, which have considerable problems with the representation of clouds.

Considerable progress was also made on developing the portable flux standard and implementing ship and buoy intercomparisons for quality assurance. Dr. Frank Bradley of CSIRO Canberra Australia visited ESRL for a month in the spring of 2006 to work on the flux

measurement handbook. Considerable progress was made and a draft was circulated among coauthors. The handbook has now been published as a NOAA Technical Memorandum (ftp://ftp.etl.noaa.gov/user/cfairall/wcrp_wgsf/flux_handbook/). Production of the roving flux standard is nearly complete. We have upgraded one of the existing ESRL flux systems to create the portable standard (i.e., rather than build an entire new system from scratch). The upgrade features two parts: 1) convert from a network cabled sensors to wireless transmission and 2) improve the radiative flux and navigational measurements. The first step is to simplify the shipping, installation, and tear down process so that it is cheaper and more practical to operate on a series of ships. The second step is necessary to close some accuracy shortcomings, balance the sources of error between radiative and turbulent fluxes, and take advantage of recent developments in GPS technology.

*Wireless hardware was acquired in FY2005. A field test was conducted in Boulder in June and a prototype system was installed on the *Brown* at WHOI. The fall Stratus 2005cruise was done with the prototype system. Some technical problems were encountered (including loss of data) and we are working on fixing that.

*A market survey of pitch/roll compensation systems for the radiative flux measurements was conducted and a suitable system could not be located for a reasonable cost. A system was designed in-house at ESRL and components were ordered in FY2005. The system was built in 2006 and laboratory motion tests were conducted. The system will be field tested in FY2007.

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.

PUBLICATIONS (FY 2006)

Wick, Gary A., J. Carter Ohlmann, Christopher W. Fairall, and Andrew T. Jessup, 2005: Improved oceanic cool-skin corrections using a refined solar penetration model. *J. Phys. Oceanogr.*, **35**, 1986-1996.

Zhou, Mingyyu, Xubin Zeng, Michael Brunke, Zhanhai Zhang, and C. W. Fairall, 2005: Study on macro- and microphysical properties of stratus and stratocumulus over the Eastern Pacific. *Geophys. Res. Lettl.,* **33(2)**, Art. No. L02807.

Cronin, M. F., N. Bond, C. W. Fairall, and R. A. Weller, 2006: Surface cloud forcing in the Eastern Tropical Pacific. *J. Clim.*, **19**, 392-409.

Cronin, M., C. W. Fairall, and M. J. McPhaden, 2006: An assessment of buoy-derived and NWP surface heat fluxes in the Tropical Pacific. *J. Geophys. Res.*, **111**, C06038, doi:10.1029/2005JC003324.

Grachev, A. A., E. L Andreas, C. W. Fairall, P. S. Guest, and P. O. G. Persson, 2006: SHEBA flux-profile relationships in the stable atmospheric surface layer, *Boundary-layer*

Meteorol., accepted.

Fairall, C. W., J. E. Hare, Ludovic Bariteau, A. Grachev, and R. J. Hill, 2006: Coastal effects on turbulent bulk transfer coefficients and ozone deposition velocity in ICARTT. *J. Geophys. Res.*, accepted.

Fairall, C. W., J. E. Hare, T. Uttal, D. Hazen, Meghan Cronin, Nicholas A. Bond, and Dana Veron, 2005: A seven-cruise sample of clouds, radiation, and surface forcing in the Equatorial Eastern Pacific. *J. Clim.*, submitted.

CONFERENCES (FY 2006)

27h Session of the Joint Scientific Committee for the WCP, World Climate Research Program, Pune, India, 3-22 March, 2006 Presentation: The WCRP Working Group on Surface Fluxes.

First Joint SAMOS/GOSUD Workshop, Boulder, CO, 2-4 May, 2006. Paper presented: High-Resolution Climate Data from Research and Volunteer Observing Ships: A Strategic Intercalibration and Quality Assurance Program.

Office of Climate Observation 3rd Annual System Review, NOAA, Silver Spring MD, 10-12 May 2006. Poster presented: The NOAA Portable Seagoing Air-Sea Flux Standard.

Focus 2 Working Group for the International SOLAS Implementation Plan, Surface Ocean-Lower Atmosphere Study, IGBP, Heidelberg, Germany, 4-8 September, 2006. Paper presented: Updates on the WCRP WGSF.

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

Mark L. Morrissey, Susan Postawko and J. Scott Greene
University of Oklahoma, Norman, OK

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' (OCO) program.

This project supports 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/).

2. Base Project

Scientists need only to access the EVAC/SRDC web site http://www.evac.ou.edu/pacrain to obtain the most comprehensive Pacific rainfall data set anywhere in the world and http://www.evac.ou.edu/srdc to obtain critical world-wide regional rain gauge data sets. 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 OCO'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, error-checked and then made available to the general research community.

To create the most comprehensive Pacific base possible it is necessary to continue work with the Pacific meteorological services individually and collectively to help them sustain high quality gauge networks. One of our most successful efforts during 2006 was (and is) the implementation of a large network of hundreds of new manual-read rain gauges and automatic data-logger equipped tipping bucket raingauges located on various atolls and islands managed by the local Pacific meteorological services. 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 raingauge measurements while learning about the importance of weather and claimte. In total we now have approximately 55 high quality, tipping bucket gauges and hundreds of manual read gauges operated by most of the Pacific Island Meteorological Services (PIMS) and local education organizations. Underlying this project is the long-term effort to help build the capacity of the all the PIMS to better serve their constituents. This will ultimately result in the PIMS 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 RANET project) until the PIMS become completely self-sustainable. 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.

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 enhancement. In turn, the local meteorological services also benefit directly through enhanced forecast products developed by the scientific community using these critical data sets.

3. Deliverables

A. Deliver 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 algorithm, 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 raingauges 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 for distribution to the various PIMS. We are currently receiving tip data back from many PIMS 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 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 Secretariat for the Pacific Regional Environmental Programme (SPREP), the New Zealand Meteorological Service, the New Zealand Institute for Research in Water and Atmosphere, the Australian Bureau of Meteorology, Meteo-France and the US National Weather Service.

Project Web site and related web sites:

. http://www.evac.ou.edu/pacrain (PACRAIN site)

http://www.evac.ou.edu/srdc (SRDC site)

http://sparce.evac.ou.edu (Schools of the Pacific Rainfall Climate Experiment, SPARCE)

http://www.pi-gcos.org/ (the P.M. 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 METONE Tipping Bucket Gauge at the Samoa Meteorological Service

B. Provide high spatial density world regional raingauge 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. Part 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 raingauge data.

C. 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 begin in 1874
- daily begin in 1942

Over the past few years the PACRAIN database has undergone a number of upgrades, and this trend continued in FY 2005. Previous upgrades focused on infrastructure, but the most recants 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 SPaRCE project, NCDC, NIWA, and the island of Niue. For the period October 2004 – September 2005, approximately 85000 new records were added to the database. Also, work has begun to expand both of these presentations into journal articles.

D. Enhance Educational Outreach Component of the SPaRCE Program

For the past 14 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 a hurricane, by the general public. The SPaRCE program is uniquely situated to be able to both continue collaborations 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 would 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.

Papers, Conferences

"Upgrades to and expansion of the Comprehensive Pacific Rainfall Database (PACRAIN)" ,Jnuary 2005, presented at the 85th AMS Annual Meeting in San Diego, CA.

"Temporal comparison of the Comprehensive Pacific Rainfall Database (PACRAIN) with satellite rainfall estimates", September 2005, accepted for presentation at the 86th AMS Annual Meeting in Atlanta, GA.

Automated Weather/Climate stations in the Pacific, May 2006: Conference organized by the Mark Morrissey held in concert with the 11th RMSD in New Caledonia.

JS Greene, M Klatt M Morrissey, and S Postawko, The Comprehensive Pacific Rainfall Database: An enhanced tool for research and education, submitted to Journal of Atmospheric and Oceanic Technology.

JS Greene, B Paris, M Morrissey, Analysis of Historical Changes in Extreme Precipitation Events in the Tropical Pacific, Climate Research, in press.

Morrisssey, M. and J. S. Greene, 2006: Measuring Precipitation from Space, EURAINSAT and the Future, *Title of the contribution: Ground validation for the Global Precipitation Climatology Project*, V. Levizzani, P. Bauer, T. J. Turk Editors.

05. Ships of Opportunity:

a. High Resolution XBT Transects: Progress Report

b. Ship of Opportunity Program (SOOP): Volunteer Observing Ships: Expendable Bathythermograph and Enviromental Data Acquisition Program

c. Ships of Opportunity

High Resolution XBT Transects: Progress Report

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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 (IMET), Argo float deployments

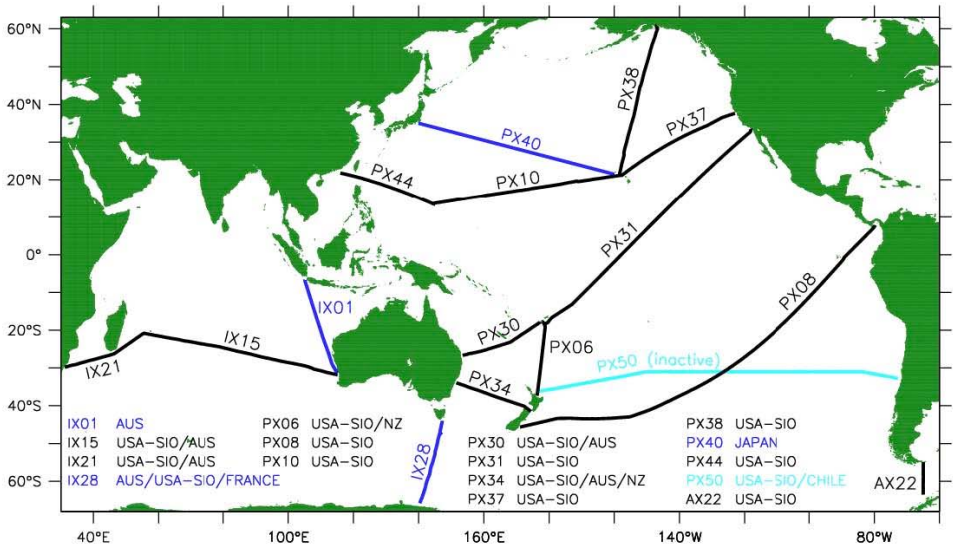

Fig 1: The HRX Network in the Pacific and Indian Ocean. International partnerships are indicated in the notes on the bottom of the figure.

and surface drifter deployments. Fig 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 Fig 2.

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.*

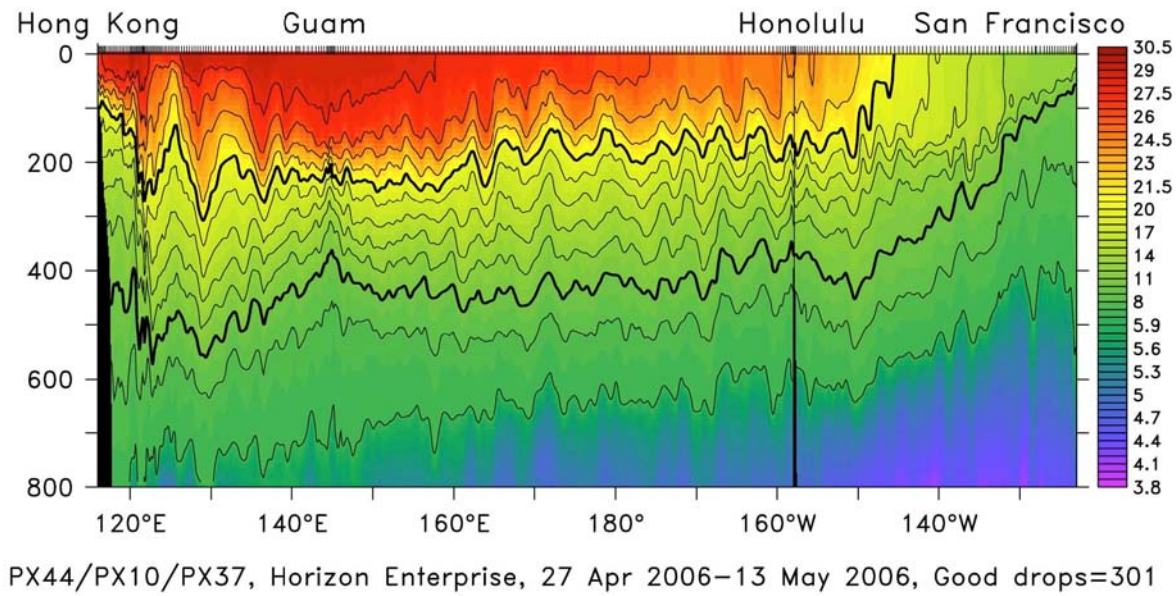

Fig 2. Example of a single temperature transect using 301 XBT profiles along PX37/10/44.

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.

FY2006 Accomplishments: October 2005 – September 2006.

Observations

HRX transects were collected by ship riders along the routes illustrated in Fig 1, and as described in the previous section, in the following months:

PX37/10/44 (North Pacific -San Francisco to Hawaii to Guam to Hong Kong) 4 transects: November 2005, February 2006, April 2006, August 6

PX38 (North Pacific – Hawaii to Alaska) 2 transects: January 2006, August 2006

PX08 (South Pacific – New Zealand to Panama) 4 transects: December 2005, February 2006, April 2006, July 2006 +2 transects along PX50 New Zealand to Chile: October 2005, August 2006

PX06/31 (Central Pacific – New Zealand to Fiji to Los Angeles) 5 transects – October 2005, January 2006, April 2006, July 2006, September 2006

PX30 (South Pacific – Brisbane to Fiji, collaborative with Australia) 4 transects – November 2005, March 2006, June 2006, September 2006

IX21 (South Indian – Durban to Mauritius) 3 transects – March 2006, July 2006, September 2006

IX15 (South Indian – Mauritius to Bass Strait) 4 transects – October 2005, January 2006, April 2006, July 2006

Data return rate is close to the planned four occupations per year for all lines, except for the short PX38 line due to lack of shipping. The number of transects in any 12-month period may vary from 3 to 5 depending on ship schedules. Sampling issues and our strategy for dealing with them are explained in the logistics section below.

In addition, logistical assistance and/or some XBT probes are provided collaboratively for:

PX34 (South Pacific – Wellington to Sydney)
IX28 (Southern Ocean – Hobart to Antarctica)
AX22 (Southern Ocean -Drake Passage, including 2 ship rider cruises)

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, including in early 2005. We have re-initiated sampling in September 2005 using two vessels (including a feeder vessel on IX21), and have enlisted collaborative support from the University of Capetown. This line appears stable for the time, but is logistically 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.

Development –

Two substantial development tasks took place in the present year.

First, the conversion of the SIO Automatic XBT Launcher System from Sippican MK12 data acquisition card to the new Windows-based MK21 was successfully completed. New software was developed and tested, and is fully compatible with NOAA/SEAS XBT data acquisition. This work was done collaboratively with NOAA/AOML. Replacement of shipboard computers and acquisition of MK21 is ongoing. The new systems are being used along all routes.

A new electronic temperature profiler from Sippican (LMP5-T1), providing research quality data to 2000 m from a 20 knot ship, is being tested and evaluated. Such a profiler is badly needed, especially for profiling in the western boundary currents. Test drops with LMP5-T1 probes have been carried out and are being evaluated.

Analysis and research highlights -

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

- Interannual circulation variability in the Northeast Pacific was described by Douglass *et al* (2006a) using XBT data from PX37 and PX38 together with a data assimilation model. Principal variability during the decade of observations was an increase in the eastward transport of the North Pacific Current in 1998, with a resultant increase in the subtropical gyre recirculation in the eastern Pacific.
- The time mean and interannual variability in heat and freshwater transport is investigated in Douglass *et al.* (2006b). The heat and freshwater budgets for the North Pacific north of PX37/10/44 are closed using HRX data and results from the ECCO data assimilation model.

- At the WCRP Workshop on Understanding Sea Level Rise and Variability, Roemmich *et al* (2006) reviewed the present state of knowledge on ocean heat content and steric sea level rise. This review focused on the past 50 years, the past 13 years, and the improved capabilities of the present ocean observing system.

Refereed publications –

Bowen M. M., P. J. H. Sutton, D. Roemmich, 2006. Wind-driven and steric fluctuations of sea surface height in the southwest Pacific, *Geophys. Res. Lett., 33*, L14617, doi:10.1029/2006GL026160.

Ueno, H., E. Oka, T. Suga, H. Onishi and D. Roemmich, 2006. Formation and variation of temperature inversions in the eastern subarctic North Pacific. Submitted to *Geophys. Res Lett.*

Douglass, E., D. Roemmich, and D. Stammer, 2006. Interannual variability in northeast Pacific circulation, J. Geophys. Res., 111, C04001, doi:10.1029/2005JC003015.

Douglass, E., D. Roemmich, and D. Stammer, 2006. The mean and Interannual variability of heat and freshwater transport in the North Pacific Ocean. In preparation.

Roemmich, D. and 15 co-authors. Global warming and sea level rise. WCRP Workshop on Understanding Sea Level Rise and Variability, Paris, June 6-9, 2006.

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 and Enviromental Data Acquisition Program.

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PROJECT SUMMARY

This project includes data acquisition 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 input ocean and meterological information to be supplied in real-time to users world-wide called SEAS (Shipboard Enviromental Acquisition System).
- Upper ocean temperature observations using expendable bathythermographs (XBTs) deployed broadly across large ocean regions: the low-density/frequently repeated XBT program.
- Upper ocean temperature observations using XBTs deployed closely spaced in order to measure the meso-scale field: the high-density XBT program

A brief description of each of the three components is included below.

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 and transmits the data in real-time to the GTS and to operational databases to be used by scientists. Additionally, the 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. SEAS 2K is employed on ships of the Volunteer Observing System (VOS), Ship of Opportunity Program (SOOP) and on NOAA, UNOLS, Coast Guard vessels.

SEAS 2K is 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 350 ships of the Voluntary Observing System (VOS) and SOOP. Over 200,000 SEAS meteorological messages are transmitted per year. Approximately thirty ships of the SOOP are deploying XBTs using SEAS 2K software. This includes low, frequently repeated and high-density deployment modes. NOAA/AOML and Scripps are the principal users of the software. National Marine Fisheries Service is running an Antarctic line (AX22) using this software.

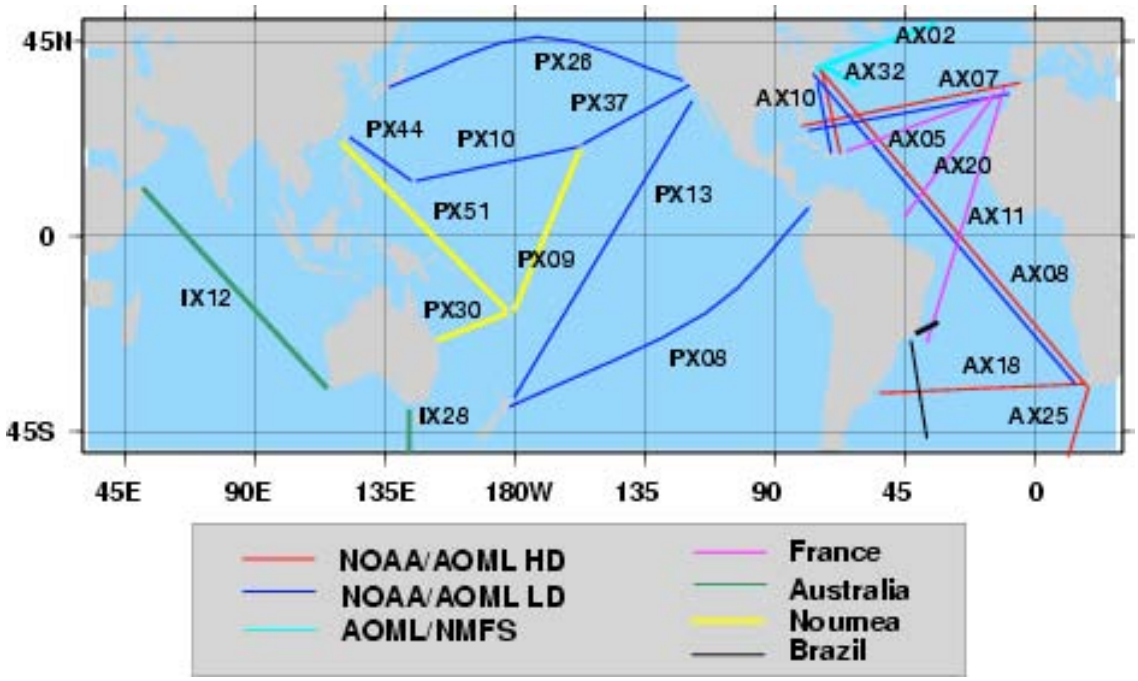

Figure 1. Map showing the network of XBT transects maintained by NOAA/AOML and by NOAA/AOML in collaboration with international partners.

Low-Density/Frequently Repeated XBT Observations

Low-density (broadly spaced) XBT observations are 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 high-density (HD) mode. Sampling in low density (LD) mode has been the dominant mode in the early days of the Ship of Opportunity Program (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 (Figure 1). Occasionally these lines are also sampled through basic research and operational experiments in which XBTs are deployed to observe various oceanographic processes. Some lines are maintained in cooperation with international partners (France, Australia, Noumea, and Brazil). All XBT lines are maintained through an international consortium with oversight by the SOOP Implementation Panel (SOOPIP). Some lines include time series measurements providing more than 30 years of data.

Frequently repeated XBT lines (FRX) are mostly located in tropical regions to monitor strong seasonal to inter-annual (SI) variability in the presence of intra-seasonal oscillations and other small-scale geophysical noise. These lines typically run north/south, and cross the equator or intersect the low latitude eastern boundary. 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 ideally covered 18 times per year with an XBT drop every 100 to 150 km (or approximately 6 drops per day). This mode of sampling tries to

draw a balance between the spatial undersampling, with good temporal sampling inherent in low-density deployments and the good spatial sampling, marginal temporal sampling in the high-density (HD) deployments. Increasing both the temporal and spatial sampling in frequently repeated lines relative to low-density sampling greatly decreases the risk of aliasing in equatorial regions.

High-density XBT Observations

This program is designed to measure the upper ocean thermal structure in key regions of the Atlantic Ocean (Figure 2). Along five sections in the Atlantic Ocean expendable bathythermograph (XBT) observations are deployed approximately quarterly in time and measure the temperature as a function of depth from the surface to about 850 meters. The XBTs are deployed between 5-50 km apart in order to measure the meso-scale structure of the ocean. This close spacing is important to measure the meso-scale structure in order to diagnose the ocean circulation responsible for redistributing heat and other water properties globally.

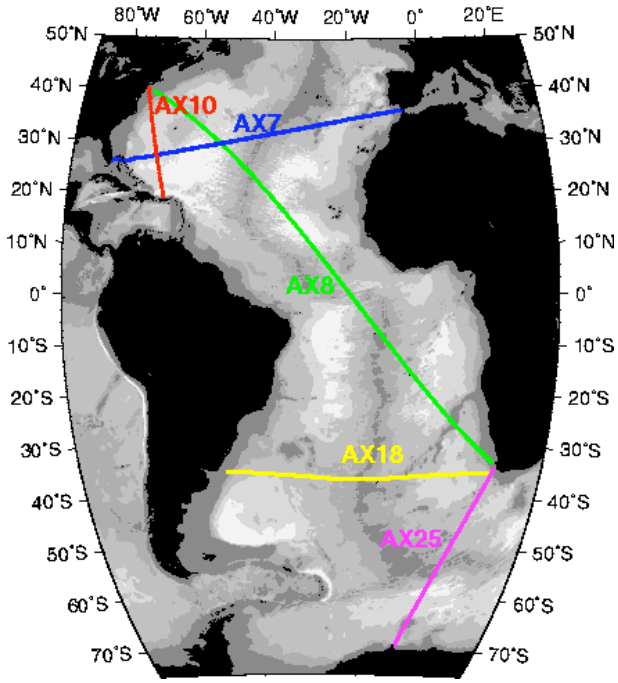

Figure 2. Location of the five high density XBT lines (AX07, AX08, AX10, AX18, and AX25) maintained by NOAA/AOML.

Rationale

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). This increased understanding is crucial to improving climate prediction models. This project provides critical data for initializing seasonal to interannual (SI) climate forecasts. The data resulting from this project helps to addresses this objective:

- Document the ocean's storage and global transport of heat and fresh water;

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 SI climate forecasts prepared by NCEP. Specifically, AOML manages a global XBT network that provides subsurface temperature data. Global coverage is now required as the forecast models not only simulate Pacific conditions but global conditions to improve prediction skill. Additional objectives of this project are to provide the resulting data to increase our understanding of the dynamics of the SI and decadal time scale variability and to provide data for model validation studies. Thus, this

project addresses both operational and scientific goals of NOAA's program for building a sustained ocean observing system for climate.

Data from these lines have been used extensively (Meyers et al, 1991; Taft and Kessler, 1991). 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, five XBT lines have been chosen to monitor properties in the upper layers of the Atlantic Ocean in high-density mode. The continuation of AX07 and AX10 and the implementation of AX08 and AX18 were recommended at the Meeting of the Ocean Observing System for Climate held in St. Raphael in 1999. The location of the lines recommended by the St. Raphael meeting and the GCOS *Implementation Plan* (GCOS-92) are based on specific advantages of each lines location. High-density line 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 high-density lines are required to have observations with adequate spatial and temporal resolution for climate studies. High-density observations in AX08, AX18, and AX25 provide data in poorly surveyed regions.

- The high-density line 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 high-density line 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 line was chosen to monitor the location of the Gulf Stream and its link to the NAO.
- The high-density line AX08, part 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 line are key to improving our understanding of the ocean and our ability to forecast climate. Temperature profiles obtained from this line will help to

monitor the main zonal (east-west) currents and undercurrents in the tropical Atlantic and to investigate their spatial and temporal variability.

- The high-density XBT line 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. The main objective of this line 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 line will be used to investigate the role of the South Atlantic in improving climate forecasts.
- The AX25 line was implemented to measure changes in 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 monitot the various frontal locations in the region.

Interagency and international partnerships

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.

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.

Data availability and project web sites

http://www.aoml.noaa.gov/phod/hdenxbt/
http://www.aoml.noaa.gov/phod/xbt.php
http://www.aoml.noaa.gov/phod/trinanes/SEAS/
http://seas.amverseas.noaa.gov/seas/

Data from the LD, FRX and most HD deployments are transmitted 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 for on the project web site listed above.

FY 2006 Accomplishments

SEAS System

During the last year the focus of our work has been to improve, update and support the SEAS 2K program. This includes ongoing development of the following software

modules: meteorological (MET) observations, automated MET observations, expendable bathy observation (XBT), and thermosalinograph (TSG) data. A flexible and powerful time-server background service was designed and created that provides essential time and position data to SEAS 2K from a wide variety of GPS sources. Figure 3 provides information of the SEAS 2K XBT data transmissions during FY2007.

In addition time and effort was spent in support of SEAS 2K, training and operational support is provided 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 below.

1. Meteorological System (VOS ships)

The MET software required several upgrades and corrections as determined by the Weather Service. It now self corrects for daylight savings time. If the ship computer is set to local time, it gives correct GMT time in the JJVV message. Additional help pages have been added, such as information about VOS climatological data formats.

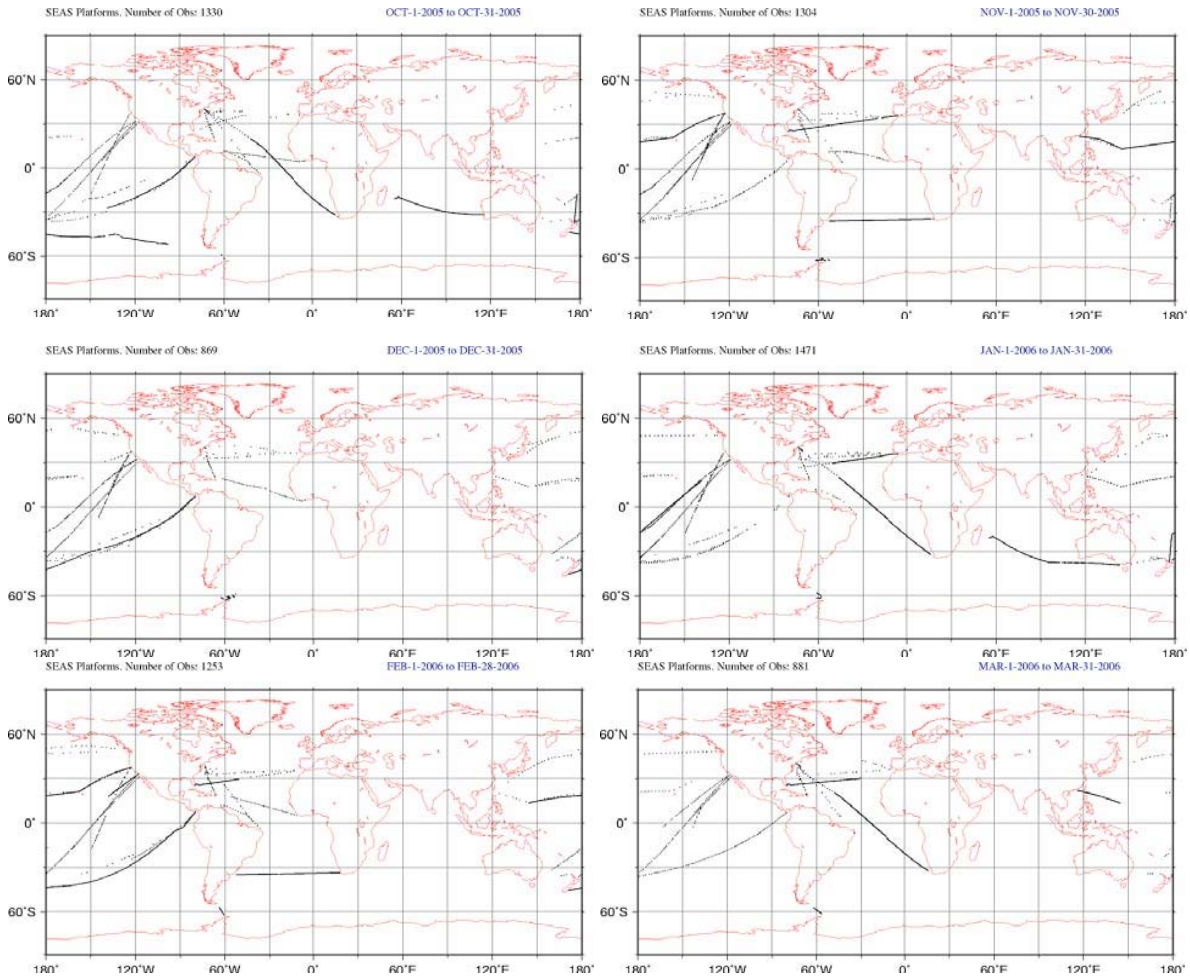

Figure 3a. XBT observations transmitted through the SEAS System for the first six months of FY2006.

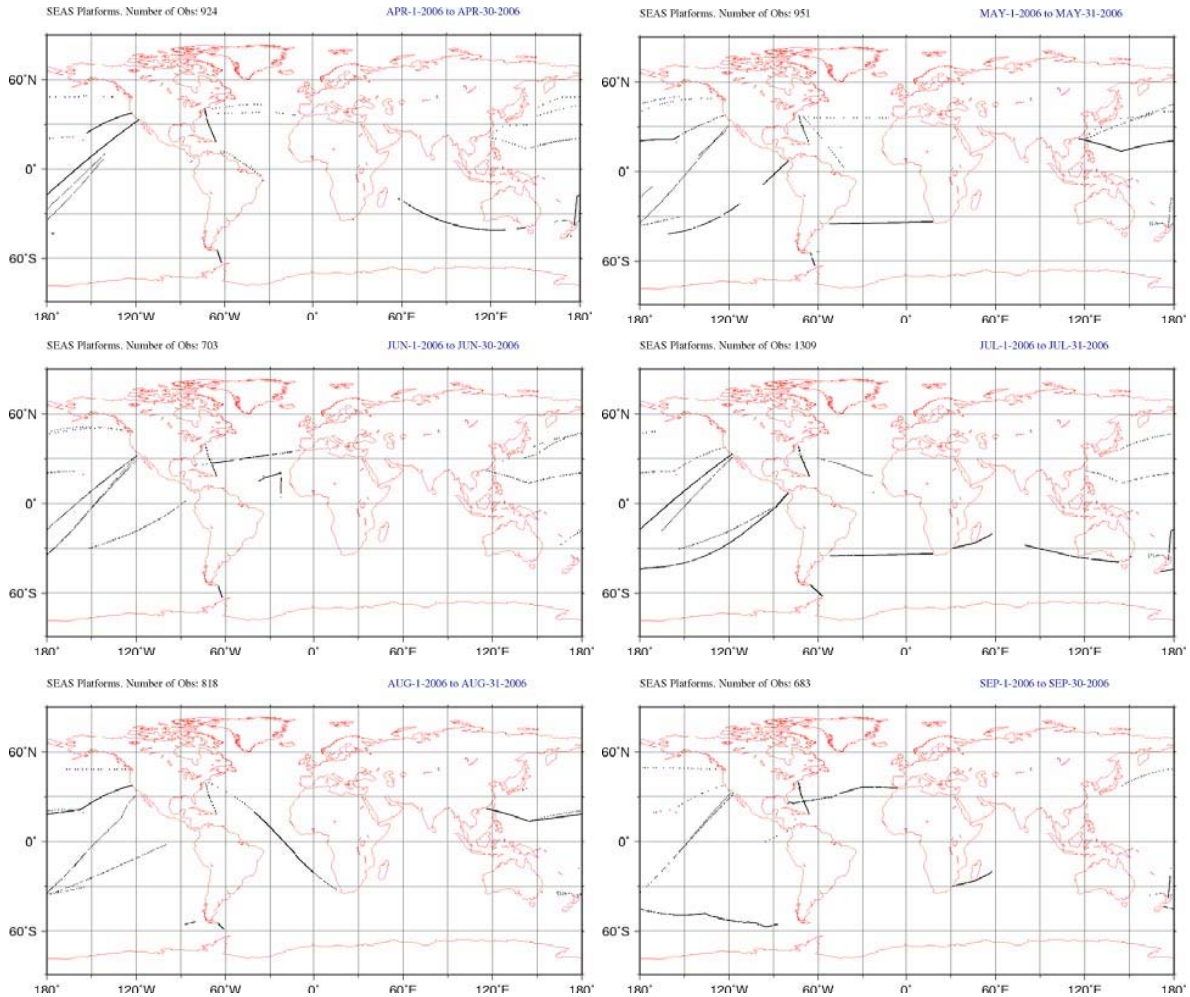

Figure 3b. XBT observations transmitted through the SEAS System during the last six months of FY2006.

The automated MET system is complete for integration with the Woods Hole Oceanographic Institute automated meteorological station. Automated MET is currently under development for the NOAA fleet that integrates SEAS2K with the Scientific Computing System (SCS). A software module has been written that collects data from the SCS system using socket transfer. Transferring these data into the Automated MET capability of SEAS 2K has been designed and is currently being tested. The data will then be transmitted off the ship using ship email.

The SEAS server software was modified to extract BBXX messages from the USCG that were in improperly coded bulletins. The messages were re-encapsulated in SXUS08 bulletins and delivered to the GTS.

2. *XBT System (SOOP ships)*

The XBT Auto Launcher System (XALS) is a multifaceted design that operates three different hardware systems: the hand launcher, the NOAA/AOML auto launcher and the Scripps oceanographic auto launcher.

The fully automated XALS schedules, drops and transmits XBTs, requiring little input from the operators. The XALS provides many features and options to the user: automatic or manual transmission of binary messages, alarms and alerts, and automatic input of meteorological and ship data. Some new features were added and minor bugs were corrected in the XBT program. Some of the upgrades were:

- Hardware checks were included that determine if the NOAA/AOML interface box is connected and will inform operator if it is not. This was a concern of the ship riders and requested by them at the AOML/GOOS meeting in Miami in April.
- A sophisticated re-drop feature was added that operates when running a system using a time plan (already functional for drops using a position plan). This code will engage when a drop is out of bounds from the last successful drop.
- An "End Cruise" button was added that allows the user to end a cruise gracefully with a button press. This button will zip all binary data and status files, clear directories of previous navigation data to insure that a new cruise will not be using data from previous cruises.
- An additional button was added to move the operation from auto launching setup to a hand launching setup.
- A MK21 Error detection code was added to determine if data had dropped out of the MK21 card during an XBT drop. In such cases the user is properly alerted and data collection halted.
- A new probe type, LMP5 (T-12), was included in the probe selection list along with code that calculates correct fall rates for this probe type.
- A new decoder is under development to receive e-mail with attached SEAS 2K delayed mode XBT files. The delayed mode data will be retrieved from the ships and e-mailed. This data will then be automatically unzipped and coded into NDC files. These NDC files will be checked against those transmitted in real-time and will replace bad or missing profiles.

3. *Time Server Service*

A Time Server Service was created as an essential part of the SEAS 2K system. The Time Server Service runs as a background service, which is different from the previous Time Serve that was a graphical interface. This new Time Server Service also increases the flexibility of the Time Server by allowing for 4 possible inputs for GPS. This includes Thrane and Thrane NMEA serial (4800 or 9600 baud), another Time Server on the network, and another server which would typically be the TSG Server software module. This Time Server distributes data to SEAS 2K and to the TSG Server. This software uses named pipes in a server client arrangement. The software system is flexible

and provides for multiple methods of cabling. In fact, if the GPS fails in the engine room the Time Server Service is capable of reading the GPS via internet from the bridge.

The Time Server Service has been successfully tested on the Cap Victor along with the TSG Server module. It is important to note that the SeaBird manufactured TSG junction box on the Cap Victor was unable to recognize the ship's GPS NMEA string, but that the SEAS 2K Time Server Service was able to read this and time/position stamp the TSG data correctly.

4. Thermosalingraph (TSG) System

The TSG transmission system was designed and created. This system has been tested successfully at sea on the Cap Victor in September 2006. This software is easy to setup and requires no user input once started. It 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 SEAS2K if necessary. The TSG data is transferred to the bridge over the ship intranet and can then be transmitted.

Low-Density/Frequently Repeated XBT Observations

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 (see Progress report for determination of the information content in long-occupied Voluntary Observing Ship (VOS) Expendable Bathythermograph (XBT) Transects, by G. Goni and R. Molinari): some LD lines contain time series as long as 30 years (longer than 50 years including mechanical BTs) with much higher horizontal resolution than is available from a fully implemented ARGO program.

	GOAL		ACTUAL	
Line	XBTs/year	XBTs per transect	AOML transects FY06 *	AOML XBTs FY06**
AX10	96	12	15	311
AX07	280	35	12	134
AX08	504	63	4	0
PX13	416	52	13	1143
PX37-PX10-PX44	544	48	15	519
PX26	468	39	15	461
PX08	408	60	17	867

Table I. Goals and actual deployments of XBTs in LD mode by NOAA/AOML. (*) includes HD transects. (**) LD/FRX deployments only.

This year LD sampling was reduced, FRX lines already begun were continued and several new FRX lines were initiated. In view of the SI 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 and PX08, PX10, PX13, PX26, PX37 and PX44 in the Pacific. In the Atlantic, AX04, AX29 and AX32 were discontinued and in the Pacific PX06, PX09 and PX18 were discontinued. Because the transition was started in January 2006 and finalized during the summer of 2006 some of the lines that were discontinued still appear in the FY2006 deployment report.

The current goal of this project is to have all the lines occupied at least 12 (16) times per year in LD (FRX) mode while deploying 4 (6) XBTs per day, this is 1 XBT every approximately 100km (60km). Some of these lines are also occupied in HD mode (which are carried four times a year) and need to be carried out a lesser number of times per year. The target for each of the lines in LD mode is shown in Table I. The goals have been reached in six of the seven transects. For one of the lines (AX08), we were not able to find ships willing to deploy XBTs. However, we have recently recruited one ship that will start sampling this line in LD mode in December 2006. Some of the lines (AX10, PX37-10-44, and PX26) are occupied in near FR mode. A total of 3435 XBTs were deployed by NOAA/AOML in LD/FRX mode from 28 participating ships during FY2006.

High-density XBT Observations

XBT deployments along HD lines proceeded as planned in previous years: 4 sections each year for AX7, AX10, AX8 and AX18, two sections per year for AX25 (Figure 2). Note that AX25 is occupied only twice each year due to ice coverage. Figure 4 shows all XBT deployments to date for each of the five HD lines. The exact locations of XBT deployments along each line during FY2006 are shown on the web. A summary of all the cruises conducted in fiscal year 2006 can be found in Table II. A total of nineteen HD cruises were conducted, 3612 XBTs deployed, 70 ARGO profilers, 67 SVP Drifting buoys and an average XBT failure rate of less than 8% (see Table II). Of note was that five HD cruises were conducted on AX7 due to a major equipment malfunction in September 2005, resulting in only three complete sections for FY2005. Because the AX7 line is so important for quarterly heat transport estimates, a replacement section during November 2005 (which falls in FY2006) was conducted: hence a total of five sections occurred during FY2006 along AX7.

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 AX98 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

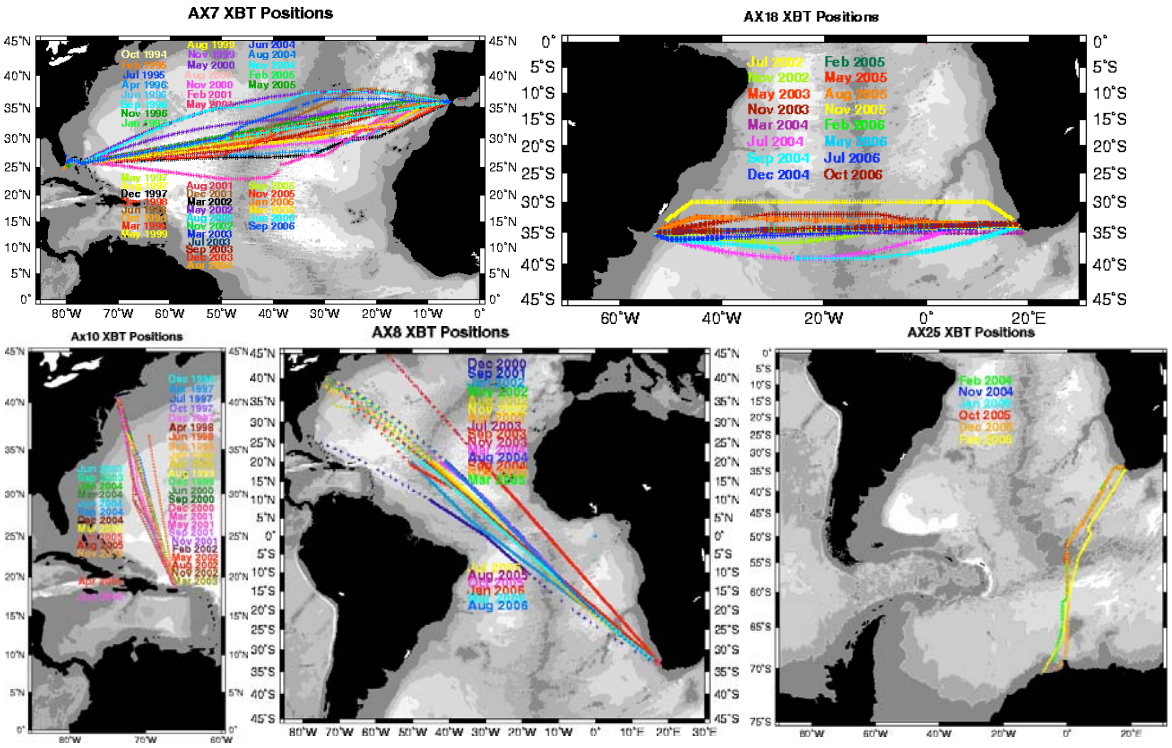

Figure 4. Location of XBT deployments for XBT lines AX07(top left), AX18 (top right), AX10 (bottom left), AX8 (bottom middle), and AX25 (bottom right) from the high-density XBT web

small island off the coast of Brazil. During fiscal year 2006 Brazilian researchers were deploying XBTs with sufficient frequency to be considered a new high-density XBT line and hence we have begun to recover and process these data. To date three cruises of data have been provided and processed by AOML: August 2004 (56 XBTs), February 2005 (59 XBTs) and August 2005 (49 XBTs) whose deployment locations are shown in Figure 5.

Line Designation	# Sections FY06	# XBTs	Avg # XBTs	Percentage Good	ARGO deployed	Drifters deployed
AX7	5	1124	224.8	88.3	18	18
AX10	4	391	97.8	89.5	4	0
AX8	4	1036	259.0	94.9	22	25
AX18	4	698	174.5	96.0	12	15
AX25	2	363	181.5	92.8	14	9
Total	19	3612		92.3	70	67

Table II. Summary of deployment information for HD lines maintained by AOML.

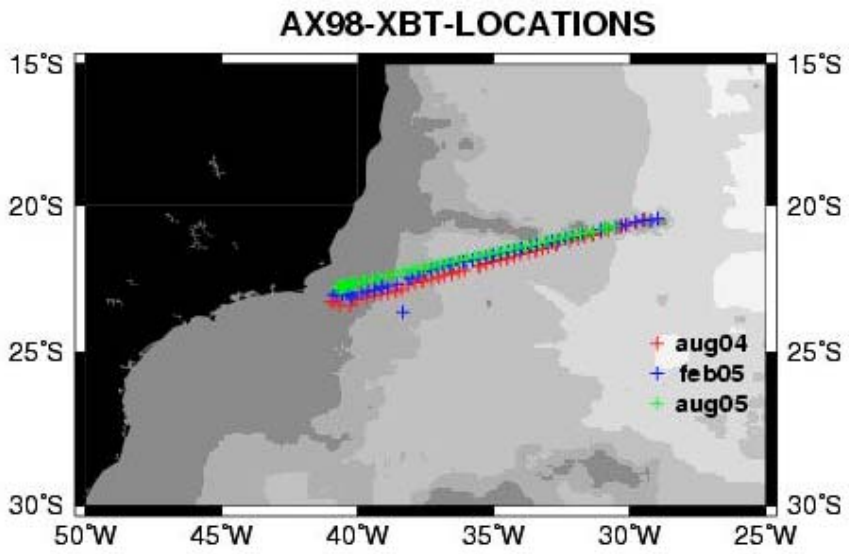

Figure 5. Deployment locations of XBTs on the line AX98 located off the coast of Brazil.

General

Real-time XBT data were transmitted via Inmarsat Standard C. Automatic quality control tests are applied to the data and those profiles that pass are distributed on the GTS. An operator reviews those profiles that fail the automatic quality control procedures and decides whether or not to send the data to the GTS. Full resolution data are stored on disks and obtained by ship greeters when the ship returns to port. The data are forwarded to AOML, placed in established formats and then sent to the National Oceanographic Data Center (NODC). The ratio of XBTs deployed to real time data transmitted is essentially 100%. 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. Note that the HD failure rate averaged about 8% in FY2006, due in part to aging autolaunching equipment and some intermittent instrument failure and not the XBTs themselves. All XBT data are archived at the NODC and a subset of all Atlantic XBT data are archived at a DAC located at AOML

These XBT data are used in real time for ENSO monitoring and prediction and the initialization of climate models at centers for environmental prediction and in delayed mode for research concerning 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.

International and Domestic Collaboration

By providing probes to international partners, AOML saves the cost of ship greeting for lines 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.

The international collaborators are:

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

We 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. All of the data were submitted to NODC.

These XBTs were deployed in the following transects:

Noumea: PX09, PX30, PX51
Brazil: Sao Paulo-Isla de Trinidade, Rio de Janeiro-Antarctica
France : AX05, AX20, AX11
Australia : IX12, IX28

Additionally, in support of the NOAA-funded "Surface pCO_2 Measurements from Ships" (Drs. Rik Wanninkhof and Richard Feely, PIs), we provided 1.5 pallets (486 XBTs) to NOAA/NMFS in Rhode Island to be deployed along the pCO_2 transects AX32 and AX02.

Research Highlights

1. Data from the AOML SOOP Program is available to researchers producing Quarterly reports on the "state of the ocean" using XBT data to estimate heat transport from two of its high-density lines and heat content from all XBTs and ARGO profiles (Figure 4). Quarterly reports are a means to present to managers and decision makers summary information on the state of the ocean, in this case the intensity of the temperature transported by the meridional overturning circulation and the ability of the current network to document heat content changes (see research analysis projects "Meridional Heat Transport Variability in the Atlantic Ocean" and "Global Heat Content" for more details). Temperature content and transport variability is an important indicator of climate variability since oceanic temperature transported poleward heats the atmosphere.

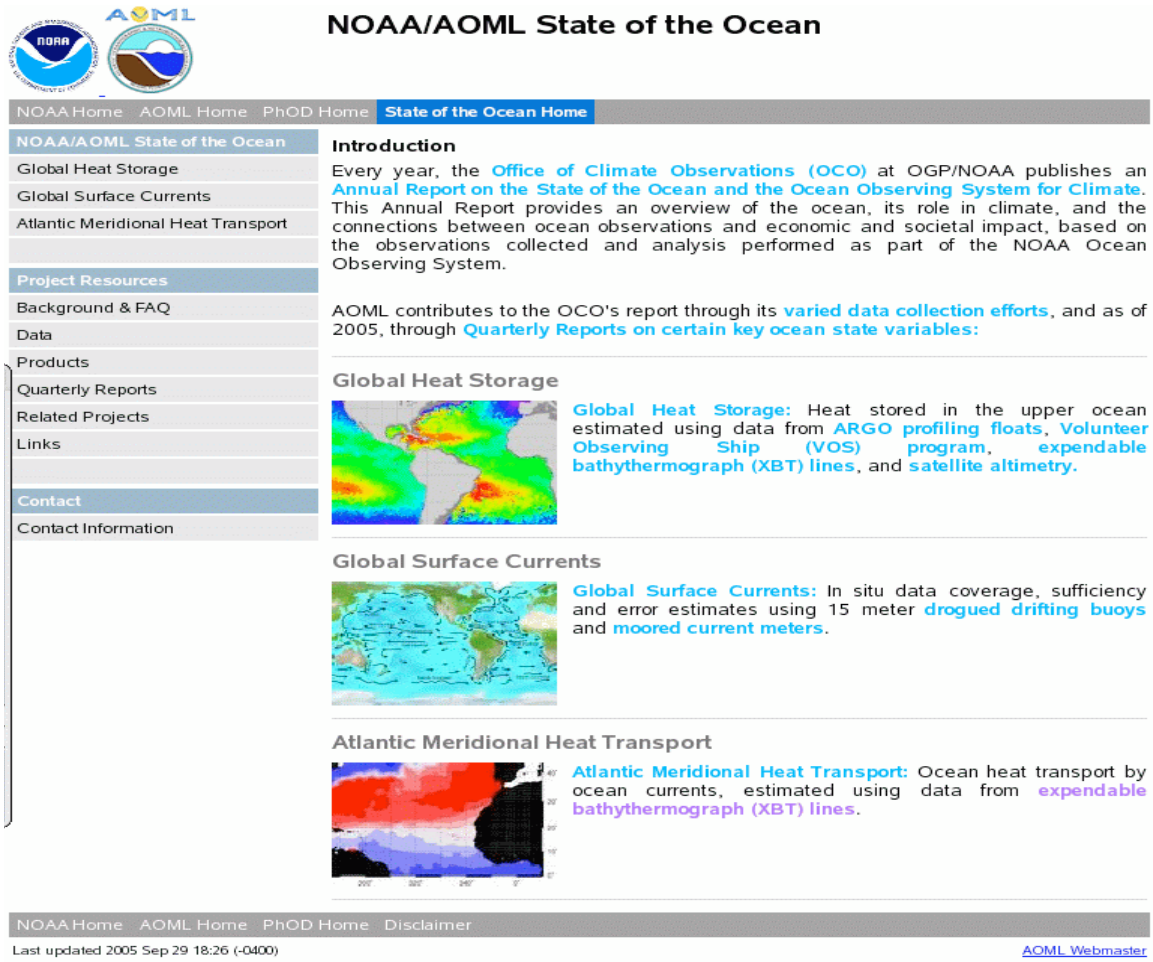

Figure 6: Main title page developed for the dissemination of products developed to provide input into the state of the ocean reports for NOAA's Office of Climate Observations.

2. Temperature sections obtained from the AX08 transects are being used to investigate the zonal currents in the tropical Atlantic (Figure 7). The currents are identified from the slope of the isotherms. A correlation was found between the slope of the isotherms and the dynamic height in the NECC region along each transect. The dynamic heights can also be found from altimetric measurement, where the sea height anomalies are added to the mean dynamic height (Levitus 2000) referenced to 800m. Time series of the location of the core of the NECC and its transports can then be derived from altimetric measurements. The key result that was found in this study is that the motion of the core of the NECC exhibits a semiannual and annual component, while the transport has only an annual component. Our results also indicate that the motion of the core of the NECC is mostly semiannual in the western side of the basin, while it is annual on the eastern side of the basin.

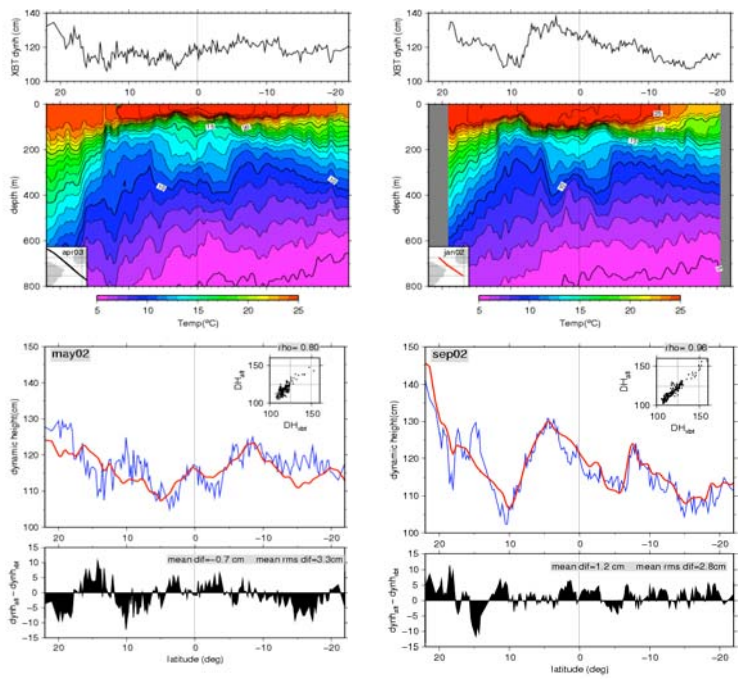

Figure 7. Temperature sections (second panels from the top) for two transects (September 2002 and May 2002, left and right, respectively) with the dynamic height (upper panels) derived from XBT deployments and climatological T-S relationships. The dynamic height derived from altimetry (in red) and XBTs (in blue) and their differences are shown in the lower panels.

3. XBT data are being used to determination of regional patterns of upper layer temperature variability in well sampled areas. Figure 8 shows an analysis of decadal temperature changes in the North Pacific (Robert Molinari, personal communication) in the form of a space-time diagram of the temperature at 150 m along the transect PX26. The decadal variability in the temperature, which can be seen as basin wide changes in the sign of anomalies after 1988 and 1998, are probably related to the Pacific Decadal Oscillation. Lines that cross the intense boundary currents and that have been occupied continuously for more than 10 years provide a unique source of information on the variability at time scales greater than interannual and, in some cases, decadal. It is speculated that data from other platforms may not be able to provide similar information because of the high advective speeds in these currents.

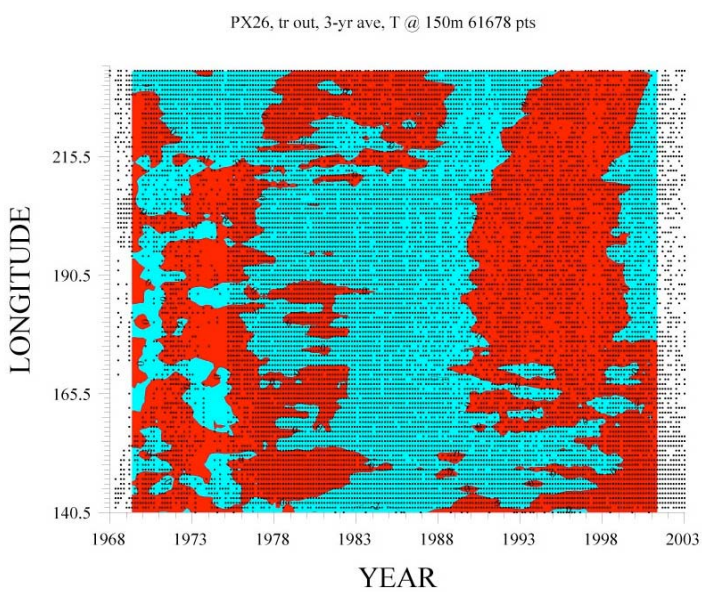

Figure 8. Decadal temperature anomalies showing warm (red) and cold (blue) periods at 150 m along the Pacific line PX26.

Publications:

Peer-reviewed

1. Baringer, M. O. and C. S. Meinen, 2006. Thermohaline Circulation *in* State of the Climate in 2005, K. A. Shein, ed., *Bulletin of the American Meteorological Society:* Vol. 87, No. 6, pp. s1–s102, doi: 10.1175/BAMS-87-6-shein.
2. Legeais, J.-F., S. Speich, M. Arhan, I. Ansorge, E. Fahrbach, S.L. Garzoli, and A. Klepikov. The baroclinic transport of the Antarctic Circumpolar Current south of Africa. *Geophysical Research Letters,* 32(24):L24602, doi:10.1029/2005GL023271 (2005).
3. Lentini, C., G.J. Goni, and D. Olson. Investigation of Brazil Current rings in the confluence region. J. Geophys. Res., Vol. 111, No. C6, C06013, doi:10.1029/2005JC002988, 2006.
4. Schmid, C. Impact of combining temperature profiles from different instruments on an analysis of mixed layer properties. *Journal of Oceanic and Atmospheric Technology,* 22(10):1571-1587 (2005).
5. Thacker, W.C., 2006. Estimating salinity to complement observed temperature, Part 1: Gulf of Mexico. *Journal of Marine Systems, In press.*
6. Thacker, W.C., and L.R. Sindlinger, 2006. Estimating salinity to complement observed temperature, Part 2: Northwestern Atlantic. *Journal of Marine Systems, In press.*
7. Lentini C., G. Goni and D. Olson. Investigation of Brazil Current rings in the Confluence region. Journal of Geophysical Research, 111, C6, DOI 10.1029/2005JC002988.

Submitted:

1. Baringer, Molly O. and Silvia L. Garzoli, 2006. Meridional Heat Transport using Expendable Bathythermographs. Part 1: Error Estimates, *Deep Sea Research, Submitted.*
2. Garzoli, Silvia L. and Molly O. Baringer, 2006. Meridional Heat Transport using Expandable Bathythermographs Part II: South Atlantic Ocean. *Deep Sea Research, Submitted.*

Technical/Progress Reports:

1. Baringer, M. O., C. S. Meinen and S. Garzoli, 2006. The Meridional Overturning Circulation and Oceanic Heat Transport, In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 68-73.
2. Baringer M., S. Garzoli, G. J. Goni, C. Thacker and R. Lumpkin, 2006. Quarterly Reports on the State of the Ocean: Meridional Heat transport Variability in the Atlantic Ocean. In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 265-268.
3. Baringer, M.O., G.J. Goni, and S.L. Garzoli, 2006. Atlantic high-density XBT lines. In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 181-182.

Ships of Opportunity

Robert A. Weller
Woods Hole Oceanographic Institution, Woods Hole, MA

Project Summary

Ships of Opportunity, also known as Volunteer Observing Ships or VOS, are merchant marine ships that make repeated ocean passages. We focus on 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. This provides 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). We also select ships that are used by other groups for deployment of XBTs (expendable bathythermographs) and profiling floats, as sharing of logistic support facilitates the work. Our goal is to obtain from the selected VOS time series of surface meteorology and ships velocity and 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 ASIMET (Air-Sea Interface Meteorological system) we developed. It consists of a central data logger and sensor modules that communicate with the central logger via RS-485. It has been developed to collect 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. It provides hourly averaged data for telemetry in near real time in addition to storing the one-minute data. The ASIMET hardware used in this project is also used on the surface buoys in the Ocean References Stations project. The ASIMET system produces high quality data, accurate enough to support calculation of monthly air-sea heat exchanges to an accuracy of better than 10 W

m^{-2}. The accurate 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) to provide the motivation for improvements to existing parameterizations and algorithms used in models and in preparing products from satellite data, 3) to provide the data needed to correct existing climatologies, 4) and to validate new model codes and remote sensing methods. The VOS data, due to the cross-basin, repeat sampling are a 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 failure rates of individual ASIMET sensor modules revealed where the present set of modules introduce reliability problems and negatively impact data return rates and flagged problems with anemometer performance. Examination of success at repeated pre- and post-deployment calibration and at getting close agreement (to roughly 2 W m^{-2}) in calibrated sensor modules has identified the incoming longwave radiation module as introducing the largest uncertainty in our heat flux estimates. In response we last year began efforts to improve the performance of these key sensors. We also last year increased work to analyze the surface meteorological and air-sea data collected in the past and on an ongoing basis and to meet the goals for utilization of VOS data. 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, that of flow distortion by the structure of the ship and its cargo.

The Ships of Opportunity Program is managed as three tasks: A) VOS Field Operations, B) Instrumentation Upgrades, and C) Data Processing.

Accomplishments

<u>VOS Field Operations</u>

The implementation of the ASIMET hardware on the VOS is the AutoIMET. AutoIMET was developed by the Woods Hole Oceanographic Institution to meet the need for improved marine weather and climate forecasting. It is a wireless, climate quality, high time resolution system for making systematic upper ocean and atmospheric measurements. This interfaces to the NOAA SEAS 2000 (Shipboard Environmental (Data) Acquisition System) that automatically receives meteorological data (from the AutoIMET) and sends in automated one hour satellite reports via Inmarsat C. This system will document heat uptake, transport, and release by the ocean as well as the air-sea exchange of water and the ocean's overturning circulation.

The basic deliverable is the data, supported by the appropriate metadata. Descriptions, technical information and data from the several VOS being serviced is posted on the site: http://uop.whoi.edu/vos/ Data (plots) are available for all ship sets. Data (numbers) are available via anonymous ftp for the last data set only: ftp.whoi.edu/pub/users/fbahr/VOS. Data from previous times are available from Frank Bahr at: fbahr@whoi.edu. There is a link to the site: http://frodo.whoi.edu where there is detailed information on the AutoIMET and ASIMET modules. Instrument design questions can be addressed to Dave Hosom at: dhosom@whoi.edu

Ship selection in the Atlantic and our interface to the NOAA SEAS system is via AOML (Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida). There is ongoing cooperation with Scripps Institution of Oceanography via the CORC (Consortium for Ocean Climate Research) program on Pacific ship scheduling; also we cooperate as well as Southampton Oceanography Centre (SOC) of Southampton UK on Computer Flow Dynamics (CFD) for evaluation of the flow turbulence around the ship and its effect on the sensor placement. A draft report from SOC is available (44 pages). Some logistic support is provided by the Southern California Marine Institute on ship turnarounds. There is ongoing cooperation with the Atlantic Marine Ocean and Atmosphere Laboratory (AOML) in Miami on the Atlantic VOS program. There is also ongoing cooperation with many sensor manufacturers and the VOS people at the German Weather Service (Deutsch Wetter Dienst) in Hamburg Germany.

We now support one ship in the Pacific and await assignment of a new ship in the Atlantic. During the year, several ships were in use but were discontinued due to route

assignments. The ships we collected data from this year are shown in Figure 1. The routes of these ships are shown in Figure 2.

Figure 1a. The VOS Horizon Enterprise

Figure 1b. The VOS Direct Tui.

Figure 1c. The VOS Sea-Land Express.

Figure 1d. The VOS Merkur.

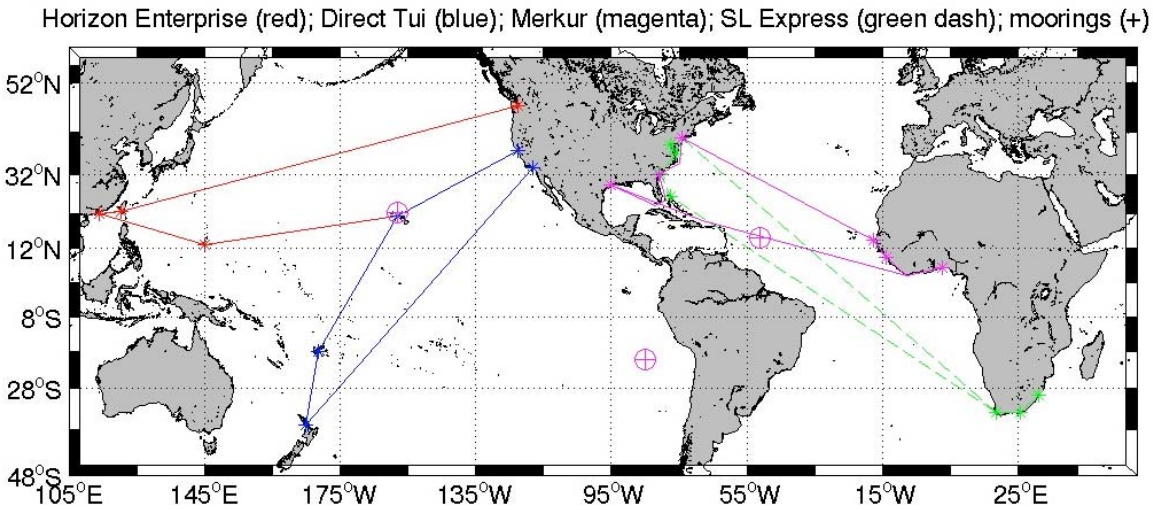

Figure 2. VOS routes for the Horizon Enterprise (red), Direct Tui (blue), which replaced the Columbus Florida, Merkur (magenta) and SeaLand Express (green). The Sealand Express route is presently open and waiting on a new ship assignment. Note the Ocean Reference Stations (circle with cross) being operated by WHOI.

Specific activities on these vessels during the reporting period are listed below. These illustrate the challenge of identifying stable platforms and the need for measurements systems that can be easily installed and removed.

June 2005. The Enterprise wind sensor had a problem and was replaced in Oakland CA.

June 2005. Visit Direct Tui in Los Angeles to install radio link in preparation for AutoIMET installation.

July 2005. AutoIMET installation on the M/V Merkur in Newark N.J. begun but not completed due to very short port stop.

August 2005. AutoIMET installation on the Direct Tui in Los Angeles CA.

August 2005. Repair wind and SST sensors on Horizon Enterprise. Installed battery for wind and SST to insure isolation from ship power surges.

September 2005. Complete installation on the M/V Merkur in Houston TX. Two sensors had problems wind and SST. Followed ship to Savannah GA and fixed wind sensor but not SST. Will meet ship on next cycle to fix SST.

October 2005. Meet the M/V Merkur in Savannah to repair SST.

January 2006. Maintenance of the Horizon Enterprise system in Tacoma WA. UPS had been turned off.

February 2006. System removed from the M/V Merkur in Houston TX because the ship has been sold and is no longer available for AutoIMET use.

February 2006. System removed from the CP Tui in Long Beach CA because the ship has been sold and is no longer available for AutoIMET use.

May 2006. Turnaround on the Horizon Enterprise in Tacoma WA and repair of the SST cable installation.

The challenges encountered this year in working to achieve two ships each in the Pacific and in the Atlantic have been significant. A first-order challenge is the short lifetime of a given ship on a given route. In addition, we have found that power supplied from the ship as well as the vibration and accelerations need to be addressed. We are doing so and having success. For now we have chosen to concentrate on the Pacific route, upgrade the hardware to address lessons learned, and to focus on analysis of the data we have collected. This approach will strengthen the effort by improving data return and by proving the utility of the data by using it in conjunction with data from the Ocean Reference Stations to improve our understanding of the surface meteorological and air-se flux fields. Our colleagues at NOC delivered a report on issue of making observations from VOS in the presence of flow distortion, which is listed below and attached as a PDF file.

Instrumentation Upgrades

The VOS provide a challenging operating environment in which to make high quality surface meteorological observations and we have moved to upgrade some sensor modules to address problems. At the same time, we have seen, since we started that

some of our 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. In particular, we have found our highest failure rates are associated with mechanical failures in the propeller/vane anemometer sensor and abrupt loss of data in the ASIMET relative humidity modules. A final problem has been calibration stability in the incoming longwave radiation modules. Work under this task has produced a low-power sonic anemometer sensor that is under test now as a replacement for the current mechanical propeller/vane sensor. A Kipp and Zonen longwave sensor has been used to replace the Eppley longwave sensor and a new front end (preamplifer for the thermopile voltage from the longwave sensor) circuit board has been developed to be used in an upgraded longwave module. Upgrades are being made to the ASIMET electronics. The present 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.

Data Analysis

This work under this task is yielding information about the spatial coherence of the surface meteorological fields by examining data from VOS track lines that pass close to our Ocean Reference Sites. Initial effort was focused on tracks from the R/V Merkur that passed within 500 km of the NTAS site (Fig. 3).

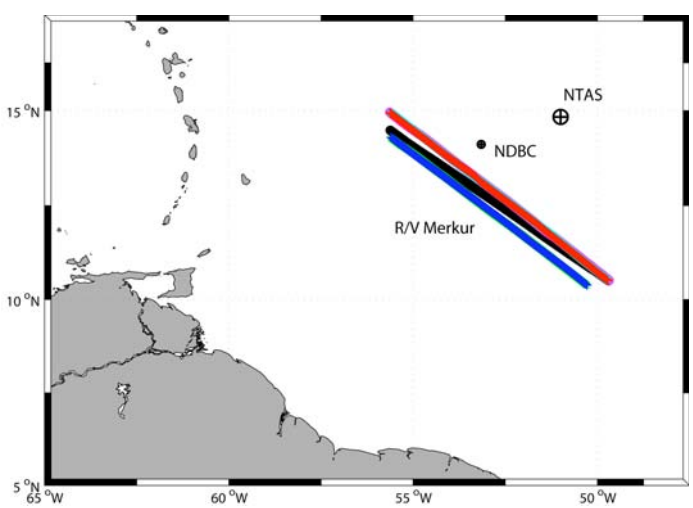

Figure 3. Ship tracks (color) for six "encounters" of the R/V Merkur passing within 50 km of the NTAS buoy. The NDBC 41041 station is also shown.

Auto-correlation functions for ship and buoy showed that typical de-correlation times are from 3 to 6 h (Fig. 4). Barometric pressure, dominated by the semidiurnal atmospheric tide, and shortwave radiation, dominated by the diurnal cycle, show the most similarity for ship and buoy results. Shipboard humidity, longwave radiation and wind showed longer correlation times and larger scatter compared to the buoy. This is the result of variation of the shipboard data on time scales of hours that is not seen in the buoy records, and was attributed to spatial variability.

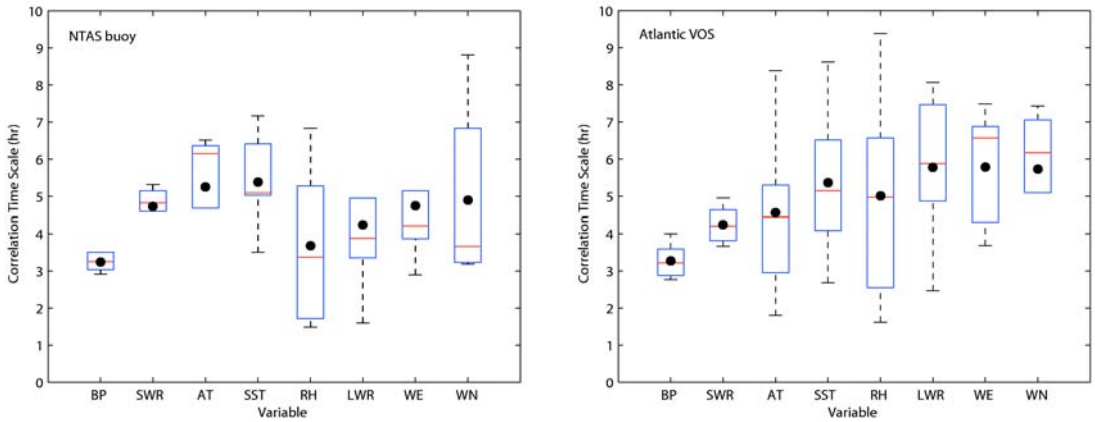

Figure 4. Correlation time scale for eight meteorological variables observed on the NTAS buoy (left) and the Atlantic VOS (right). Mean correlation time, as defined by the first zero-crossing of the autocorrelation function, for six "encounters" is shown along with box plots giving the median (red line), upper and lower quartile values (blue box) and extent of data within 1.5 times the inter-quartile range (dashed whiskers).

Publications and Reports

Plueddemann, A., F. Bahr, D. Hosom and R. Weller, 2006. Surface meteorology from volunteer observing ships, First Joint GOSUD/SAMOS Workshop, 2-4 May, Boulder, CO (poster).

Plueddemann, A., F. Bahr, D. Hosom and R. Weller, 2006. Surface meteorology from volunteer observing ships, NOAA Office of Climate Observation Annual System Review, Silver Spring, MD (poster).

Observations of Air-Sea Fluxes and the Surface of the Ocean. Report for Sub-contract Agreement A100239 between WHOI and the University of Southampton, Southampton Oceanography Centre.

06. Argo Profiling Floats:

a. The Argo Project

The Argo Project

Dean H. Roemmich[1], Russ E. Davis[1], Stephen C. Riser[2], W. Brechner Owens[3], Robert L. Molinari[4], Silvia L. Garzoli[4] and Gregory C. Johnson[5]
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[2] University of Washington, Seattle, Washington
[3] Woods Hole Oceanographic Institution, Woods Hole
[4] NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami FL
[5] NOAA Pacific Marine Environmental Laboratory, Seattle WA

PROJECT SUMMARY

The U.S. component of the international Argo Project (http://www.argo.ucsd.edu) is implemented through this award. The present report covers Year 5 of the 5-year project, and builds on progress made by previous awards (Phases 1 and 2) for pilot float arrays and data system development.

By the middle of 2007, Argo will have deployed a global array of 3000 profiling CTD floats (Roemmich and Owens, 2000, Roemmich et al, 2002, Gould, 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. The Argo array will provide unprecedented views of the evolving physical state of the ocean. It will reveal the physical processes that balance the large-scale heat and freshwater budgets of the ocean and will provide a crucial dataset for initialization of and assimilation in seasonal-to-decadal forecast models. 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.

Phase 1 (9/99 – 9/02) and Phase 2 (7/00 – 6/02) of US Argo provided a total of 187 CTD profiling floats in the Pacific, Atlantic and Indian Oceans. Objectives were 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). Technological developments in profiling floats were also implemented, including new generation salinity sensors, improved depth capability, and deployment techniques using fast ships and aircraft. Development of the U.S. Argo Data System was part of Phase 1, on a collaborative basis with international partners. Objectives are to make all Argo data publicly available within a day of collection, applying automated quality control procedures consistent with international Argo practices. Data appropriate for research applications and for comparison with climate change models are not available for several months since they need quality control by salinity experts and evaluation of data over many (10 day) float cycles. Phase 3 is a 5-year project (8/01 – 6/06) including full implementation of the US component of Argo. This report includes Phase 3/Year 5, which as of early October had deployed nearly 400 CTD profiling floats during CY2006 (Figure 1), with a deployment cruise underway at the time of this writing plus support for these deployments, data management activities and for national and international coordination of Argo. Other developments in 2006 included continued deployment of the operational floats employing Iridium telecommunications; deployment of floats equipped with oxygen sensors; and the

implementation of a new controller for profiling floats which will allow for incorporation of these and other, new technologies. Float deployments targeted the Atlantic, Pacific, Indian, and Southern Oceans. Priorities for US float deployment are set by the US Argo Science and Implementation Panel.

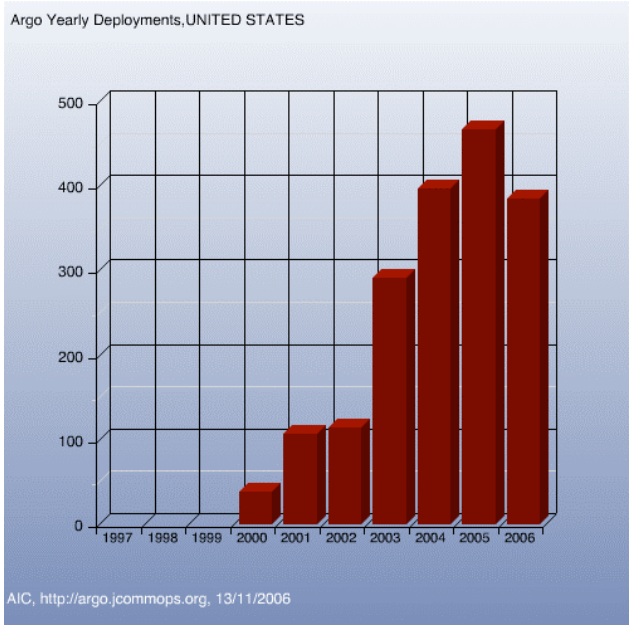

Figure 1: *Yearly deployments of United States Argo floats through October 2006. (As of 8 November 2006, 1313 are active – reporting at least once in the previous 30 days.)*

Float production and float deployment has been accomplished by four facilities – SIO (D. Roemmich and R. Davis - float production and deployment), WHOI (W.B. Owens – float production)/AOML (S. Garzoli – float deployment), UW (S. Riser – preparation and deployment of commercially manufactured floats), and PMEL (G. Johnson – 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 component institution. 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 needed to be on improving float performance, attention of the PIs will increasingly focus on exploiting the scientific value of Argo. The data system is also distributed, but by function rather than for load-sharing. AOML (R Molinari) is the national Argo data center, 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 recalibration of the salinity sensor carried out by PMEL (G. Johnson), using a high quality temperature/salinity climatology 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. US Argo PIs are involved in all of these components.

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).

ACCOMPLISHMENTS

It was reported in 2002 that, based on the performance of the pilot arrays deployed in Phases 1 and 2, design and production problems were detected in both SOLO and APEX floats that led to shortened instrument lifetimes. Extensive technical analysis and redesign was carried out over the first 9 months of 2002, leading to substantial improvements in float pumping and control subsystems. Large-scale float deployments were resumed in the 4th quarter, and by year's end about 1/3 of the Phase 3/Year 1 floats were deployed. Deployment of these modified designs have continued with promising results.

Deployment of the remaining Year 1 instruments plus most Year 2 instruments was completed in 2003. A significant disruption was caused by a recall of salinity sensors by SBE in August 2003. A problem associated with the pressure sensor had been detected by S. Riser at UW. Riser worked with the manufacturer to identify the fault. This resulted in the recall and a hiatus in the deployment of floats with SBE sensors that effectively lasted to the end of 2003.

There is enough data on the redesigned floats to confirm that significant improvements have occurred in float lifetimes, much of that due to the technical and engineering efforts of the U.S. partners. Figure 2 is a composite of the failure rates of all of the floats in the international program. The Argo program plan has a goal of a 10% failure rate over four years (146 cycles). Floats deployed in 2006 have not been deployed for a large number of cycles but these early results indicate that the U.S. float reliability has improved as a result of these technical improvements and may be approaching the goal of 10% failures over four years.

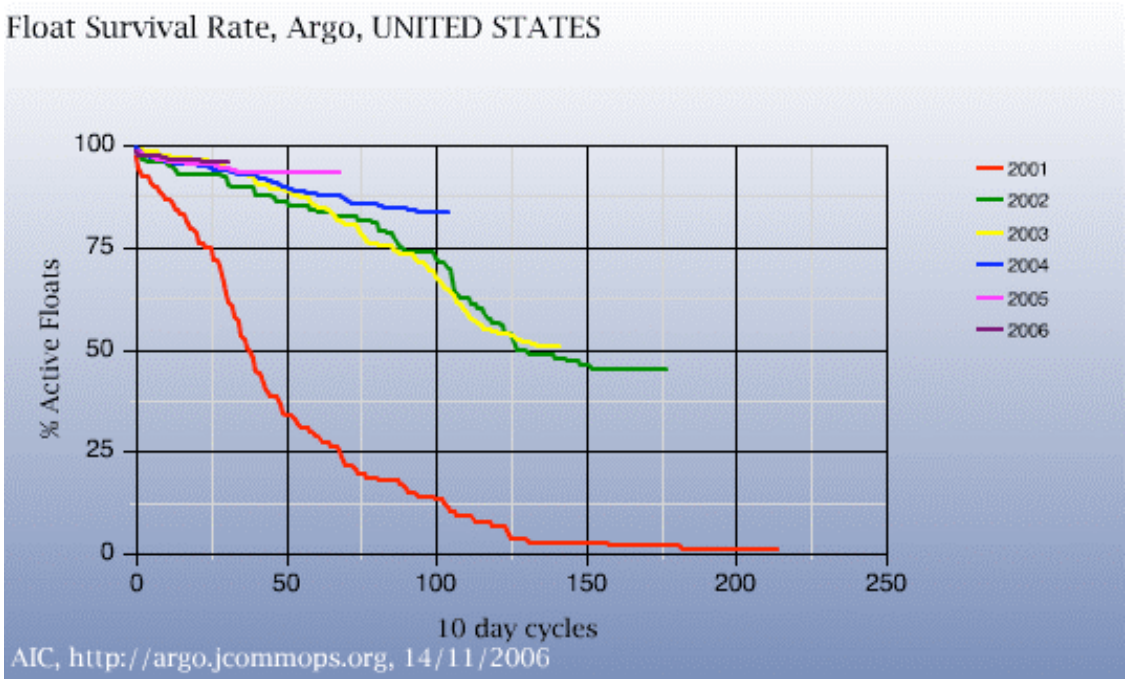

Figure 2: *Float Reliability*

All Argo profiles are now subjected to the internationally-agreed automated quality control procedures and are distributed via the GTS. The US Argo Data Center (AOML) provides all US data to the Global Argo Data Assembly Centers (GDACs) in Monterey, California and Brest, France in standardized Argo NetCDF format. The US delayed-mode data center (PMEL) provides suggested salinity recalibration information for US floats and has led the development of procedures that were endorsed by the Argo Science Team in March 2003 for incorporating delayed-mode quality control in the standard data files. The delayed-mode quality control procedures are now being implemented operationally on all U.S. profiles. After PI examination, the delayed-mode salinity data will be distributed by the U.S. Argo Data Center.

The US GDAC serves the global collection of Argo profiles through OPeNDAP servers, and Live Access Server from NOAA/PMEL. These servers integrate Argo data into the National Virtual Ocean Data System (NVODS), and the International Ocean Observing System Data Management and Communications (IOOS/DMAC) scheme.

The U.S. Program plays a strong role on the international Argo Data Management Team. Mark Ignaszewski (FNMOC) is now ADT co-chair. The PMEL technique for salinity recalibration has been distributed to international partners, along with assistance in getting it running, and it has been adopted internationally. AOML, participating on the ADMT, provides input to methodology development and leads efforts in product evolution. Finally, in the data management realm, AOML has provided assistance to other groups (e.g., China, South Korea and India) as they establish their real-time data management procedures.

Data management methodology is not static. Both AOML and PMEL continue to implement changes in the procedures required by the international Argo Data Management Team.

The international Argo array now includes over 2700 floats (Figure 3, from http://argo.jcommops.org). This represents slightly more than 90% of the 3000-float array planned. Float deployments increased dramatically in the past two years, especially in the remote sparsely sampled regions. Much of this was due to collaborations with the National Institute of Water and Atmospheric Research (NIWA) in New Zealand using the research vessel KAHAROA. AOML partnerships with Brazil, Argentina and South Africa have provided deployment opportunities in the South Atlantic Ocean in 2006 and the links with NIWA have continued enabling continued coverage of the remote and logistically difficult South Pacific and South Indian Oceans.

The northern hemisphere bias of the array has, basically, disappeared with 52% of the active floats now in the southern hemisphere. Data are being used by at least 12 operational centers worldwide, and by a broad community of researchers. The Argo Data Management System is operating, delivering profiles in near real-time to operational and other users via the GTS and the internet. The ability to produce scientific-quality data

has been demonstrated and is starting to be implemented for all floats with public internet distribution.

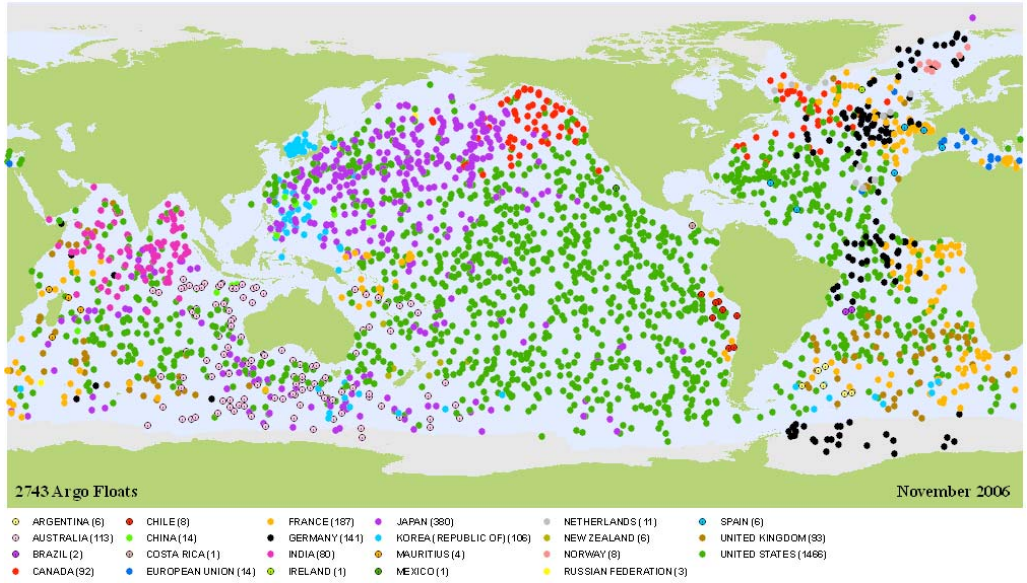

Figure 3: *The Argo Array as of 30 November 2006 (US floats in Green)*

Although the Argo Project is still young it has made possible a wide range of operational and research applications of Argo and pre-Argo profiling float data. This was clearly demonstrated at the First Argo Science Workshop held in Tokyo in November 2003 and co-sponsored by NOAA. There were 85 oral and poster presentations on topics ranging from the air-sea interaction below tropical cyclones, monsoonal and ENSO effects, seasonal mode water production, investigation of basin-scale ocean currents, global ocean heat and fresh water storage and the detection and attribution of climate change. These presentations can be accessed at http://www.argo.ucsd.edu/. U.S. PIs are conducting research in all of these areas and there is increasing use of Argo data in operational centers. The PI-led research is reflected in the attached bibliography.

The second international science workshop took place in March 2006, in conjunction with the Ocean Surface Topography Science Team workshop in Venice, Italy. Nearly one hundred and fifty papers (oral and posters) from 16 nations were presented during the Argo Workshop.

It is clear that Argo's contributions to the ocean observing system – including observations of subsurface salinity and extensive coverage of remote ocean areas (Figure 4) – are a profound improvement in our ability to characterize water masses and large-scale circulation, and to make accurate estimates of heat and freshwater storage and their transport by ocean currents..

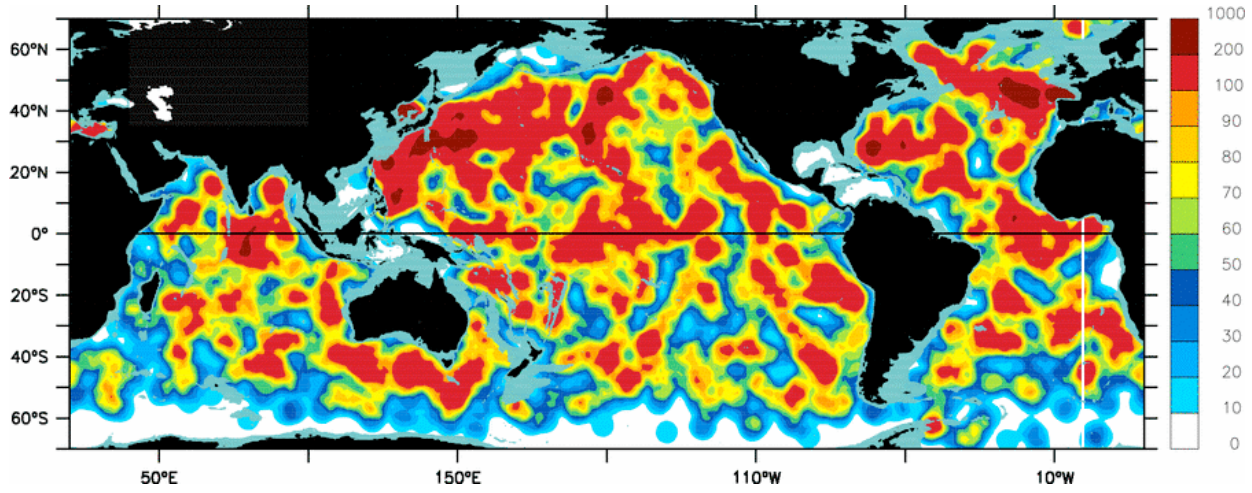

Figure 4: *Worldwide density distribution of the Argo profiling floats based on a global array of 3000 floats on a 3° x 3° grid.*

Argo's uniform distribution provides the ideal complement to satellite altimetry data (Willis et al, 2003) so as to address the issues of global heat and fresh water storage and sea level rise and for data assimilation into global models

National Security

The US Navy has a strong interest in accurate estimates and forecasts of the physical state of the ocean and the coupled air-sea system, because of the obvious impacts of wind, waves, currents, and temperature on virtually all aspects of naval operations. The Navy has experimental ocean state estimation and forecasting efforts, using both regional and global models, for which Argo provides a central contribution for ocean data assimilation. The Navy interest is further expressed by the hosting of one of the two Global Argo Data Centers (at FNMOC, Monterey), by NAVOCEANO participation as a provider of floats for international Argo, and by NAVOCEANO participation in air deployment of Argo floats. Phase 1 of US Argo was supported by ONR.

Science Education

Although the Argo project is still very new, it is proving to be an attractive educational asset for secondary, tertiary, and post-graduate levels. For secondary education, the web-based and real-time nature of the Argo data system, as well as Argo's strong climate-relevance, have been keys to engaging student interest in the oceans. Our consortium participates in a Pacific Island GOOS-sponsored initiative called SEREAD, (http://www.argo.ucsd.edu/FrEducational_use.html) that uses Argo data in existing secondary science curricula in Pacific Island countries. In post-graduate education, Argo is already providing primary data for dissertation research of graduate students in the

U.S. and other countries.

US Argo Consortium Relevant Web Sites

Argo Science 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/argo,
NOAA PMEL(Delayed Mode QC)) http://www.aoml.noaa.gov/phod/ARGO/HomePage/,
NOAA PMEL (General) http://floats.pmel.noaa.gov/floats
US GDAC http://www.usgodae.org

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Roemmich, D. and the Argo Science Team, 2002. Implementing Argo, the global profiling float array. Proceedings of *En Route to GODAE* Symposium, Biarritz, France, June 2002.

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Willis, J.K., Roemmich, D., Cornuelle, B., 2003. Combining altimetric height with broadscale profile data to estimate steric height, heat storage, subsurface temperature, and sea-surface temperature variability. Journal of Geophysical Research, 108(C9), 3292, doi:10.1029/2002JC001755.

REFEREED PUBLICATIONS

Argo data are now appearing in referred publications with increasing frequency. The Argo bibliography (http://www.argo.ucsd.edu/FrBibliography.html) lists 42 papers published so far in 2006 with an additional 15 in press or submitted. This compares with 27 papers published in each 2003 and 2004 and 49 papers published in 2005.

07. Ocean Carbon Networks:

a. Global Repeat Hydrographic/CO2/Tracer Surveys in Support of CLIVAR and Global Carbon Cycle Objectives: Carbon Inventories and Fluxes

b. Surface Water pCO2 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

d. Optimal Network Design to Detect Spatial Patterns and Variability of Ocean Carbon Sources and Sinks from Underway Surface pCO_2 Measurements

Global Repeat Hydrographic/CO_2/Tracer Surveys in Support of CLIVAR and Global Carbon Cycle Objectives: Carbon Inventories and Fluxes

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1.0 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) will reveal much about internal pathways and changing patterns that will impact the carbon sinks on decadal time scales.

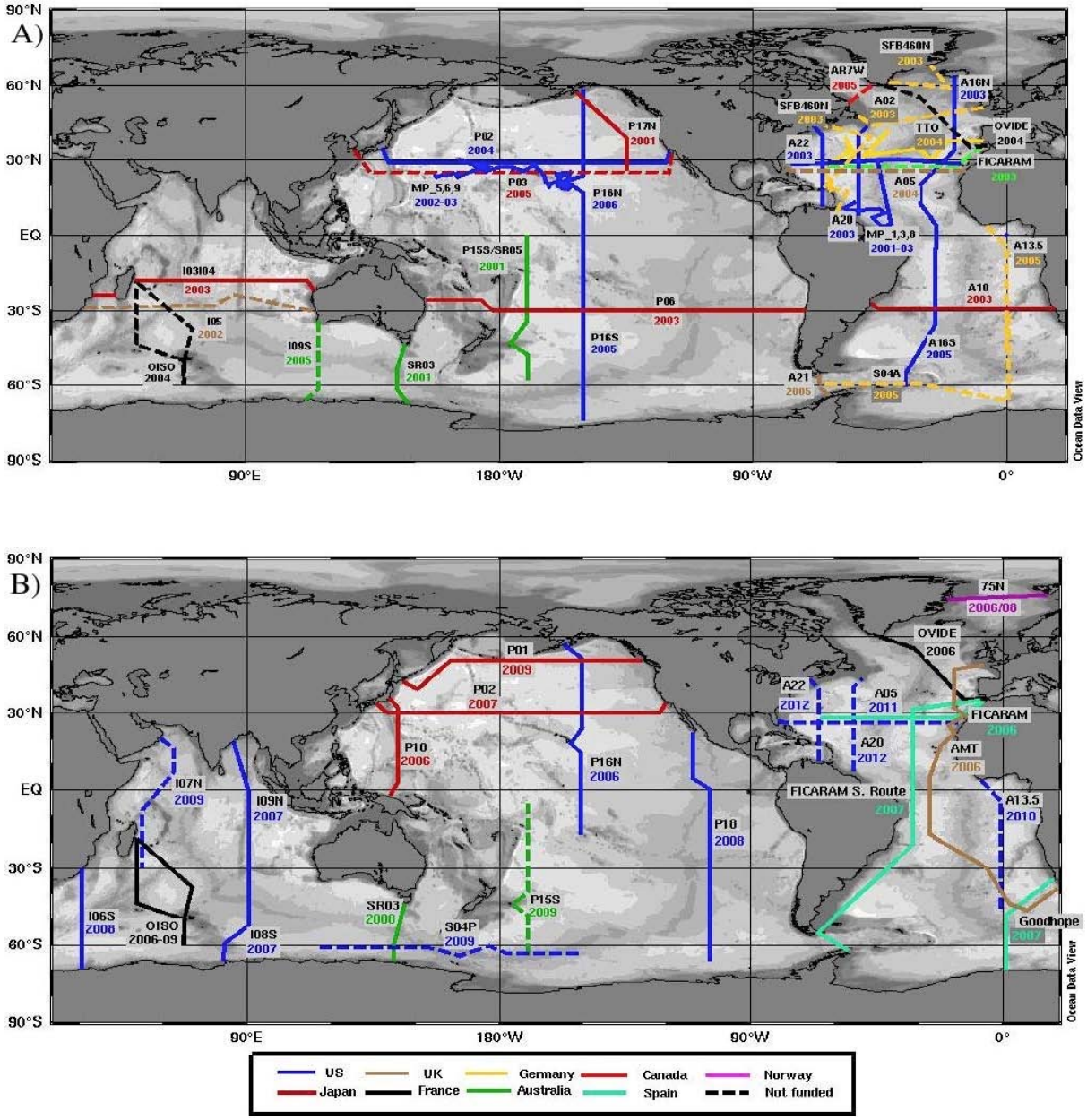

Figure 1. Global map of completed (A) and planned (B) Repeat Hydrography CO/tracer Program hydrographic sections with carbon system measurements. Solid lines indicate funded lines. Dashed lines indicate planned lines that are not fully funded at this time. The U.S. cruises are designated with blue lines. Solid lines are funded cruises.

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 2000m depth of the Argo array, Repeat Hydrography is the only global measurements program capable of observing these long-term trends in the ocean. The program will also provide 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.

Table 1. Sequence of Repeat Hydrography CO_2/tracer cruises in the oceans for the decade starting in June of 2003.

Schedule of US CO2/CLIVAR Repeat Hydrography Lines (as of 10/06)					
Dates	**Cruise**	**Days**	**Ports**	**Year**	**Contact/Chief Scientist**
					Overall Coordinator: Jim Swift, SIO
6/19/03-7/10/03	A16N, leg 1	22	Reykjavik-Madeira	1	Bullister, NOAA/PMEL
7/15/03-8/11/03	A16N, leg 2	28	Madeira - Natal, Brazil	1	Bullister, NOAA/PMEL
9/15/03-10/13/03	A20	29	WHOI - Port Of Spain	1	Toole, WHOI
10/16/03-11/07/03	A22	21	Port Of Spain - WHOI	1	Joyce, WHOI
6/13/04-7/23/04	P2, leg 1	41	Yokohama-Honolulu	2	Robbins, SIO
7/26/04-8/26/04	P2, leg 2	32	Honolulu - San Diego	2	Swift, SIO
1/11/05-2/24-05	A16S	45	Punta Arenas-Fortaleza	3	Wanninkhof/Doney; NOAA/AOML/WHOI
1/8/05-2/18/05	P16S	40	Tahiti-Wellington	3	Sloyan/Swift, WHOI/SIO
2/13/06-3/30-06	P16N	57	Tahiti-Alaska	4	Feely/Sabine, NOAA/PMEL
2007	I8S	38	Perth-Perth	5	Jim Swift, SIO
2007	I9N	34	Perth-Colombo	5	Janet Sprintall, SIO
2008	P18	32	San Diego-Easter Island	6	John Bullister, PMEL
2008	P18	35	Easter Island- Punta Arenas	6	Greg Johnson, PMEL
2008	I6S	42	Cape Town	6	
2009	I7N	47	Port Louis/Muscat	7	future planning
2009	S4P/P16S	42	Wellington-Perth	7	future planning
2009	S4P	26	Wellington-Perth	7	future planning
2010	I5	43	Perth - Durban	8	future planning
2010	A13.5	62	Abidjan-Cape Town	8	future planning
2011	A5	30	Tenerife-Miami	9	future planning
2011	A21/S04A	42	Punta Arenas-Cape Town	9	future planning
2012	A10	29	Rio de Janeiro-Cape Town	10	future planning
2012	A20/A22	29	Woods Hole-Port of Spain-Woods Hole	10	future planning

Years 1-6 are funded.

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 Objective 7 (Ocean Carbon Monitoring Network) of the Program Plan for Building a Sustained Observing Network for Climate. The sequence and timing for the sections (Figure 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 (Figure 2); 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. In addition, the proposed sections are selected so that there is roughly a decade between them and the WOCE/JGOFS occupations.

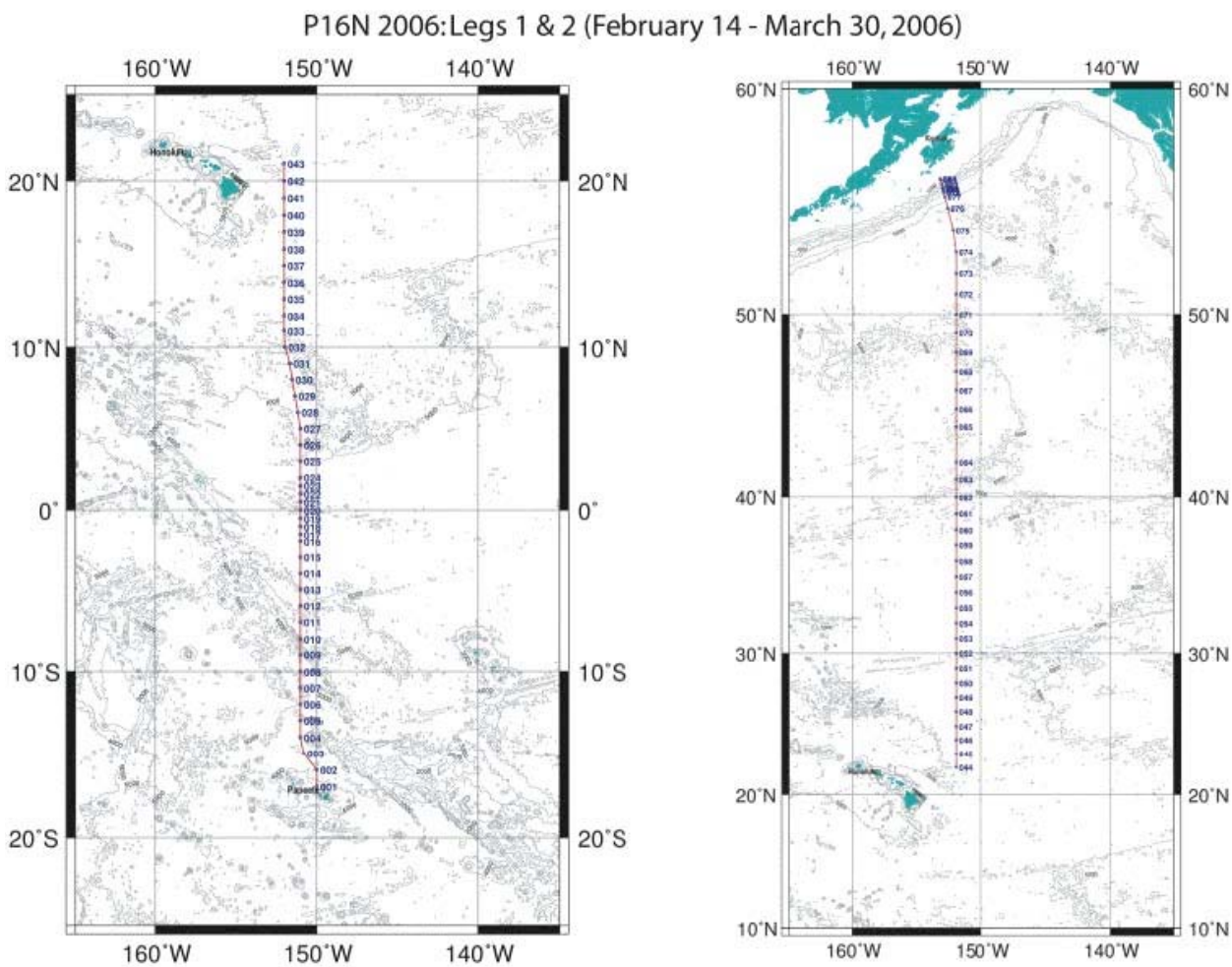

Figure 2. Cruise Track of Repeat Hydrography P16N along 152°W during Feb – Mar 2006 in the South and North Pacific.

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; Figure. 1). 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 will develop 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. The goal of this plan is to build and sustain the ocean component of 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.

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 IOC-SCOR Ocean CO_2 Panel (http://www.ioc.unesco.org/iocweb/co2panel/) and the Global Carbon Project (GCP; http://www.globalcarbonproject.org/) have 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.

2.0 FY 2006 PROGRESS REPORT AND ACCOMPLISHMENTS

2.1 P16N Cruise Results

A hydrographic/carbon/tracer survey in the South and North Pacific Ocean was carried out from *R/V Thomas G. Thompson*. The cruise departed from Papeete, Tahiti 13 February 2006. A meridional transect from 17°S to 57°N along 152° West was completed (Figure 2). NOAA scientists were responsible for all cruise planning and logistics and Drs. Sabine and Feely served as chief scientist for legs 1 and 2 of the cruise, respectively. Water samples were collected at 34 depths at each full water-column CTD/O_2 station and analyzed for salinity, nutrients, dissolved oxygen, four inorganic carbon parameters, radiocarbon, dissolved organic matter, colored dissolved organic carbon, chlorofluorocarbons, helium/tritium, carbon isotopes, chlorophyll, and a suite of bacterial measurements. Trace metal casts to 1000m were conducted at approximately every other station. Optical profiles were collected once each day. Near surface seawater and atmospheric measurements were also made along the cruise track. The cruise ended in Kodiak, Alaska on 30 March 2006.

2.2 CTD/O_2 and Bottle Salinity (Baringer, Johnson, and Langdon)

The PMEL and AOML hydrography groups worked together on this cruise. In preparation for this cruise PMEL readied and assembled the bulk of the rosette frames, Niskin bottles, CTD/O_2 units, altimeters, load cells, 12 kHz pingers, LADCPs, cabling, terminations, and other underwater equipment. We also acquired the necessary standard seawater, cruise supplies, and shipped the bulk of the CTD/O_2 and LADCP gear to Tahiti. While at sea, we acquired CTD/O_2 data, monitored sensor performance, and performed preliminary calibrations of the CTD/O_2 temperature, salinity, and oxygen sensors. The AOML group provided a salinity analyst who ran bottle salts for every bottle from which water was available to take a sample, and an electrical engineer who stood watch and assisted with CTD and LADCP operations. Since the cruise we have shipped the PMEL gear back to Seattle, had post-cruise calibrations run on the CTD/O_2 sensors, completed

final calibrations of CTD/O_2 temperature, salinity, pressure, and oxygen data (which are believed to be accurate to within 0.002°C, 0.003 PSS-78, 3 dbar, and 1.0 µmol kg-1 or better, respectively), revised the bottle salinity data quality flags, sent a list of suggested bottle oxygen flags to the bottle oxygen PI, submitted the final CTD/O_2 and salinity data and quality flags to the data center, and contributed to a cruise report documenting the final CTD/O_2 data calibration and processing.

In FY 2006 we wrapped up an analysis of data from the 2003 reoccupation of A16N and the three previous occupations on SubPolar Mode Water variability including analysis of regional substantial changes in oxygen and potential vorticity and their likely causes (ocean circulation). That paper (Johnson and Gruber, 2006) has now been accepted for publication. We also performed and published an analysis of abyssal changes in the South Atlantic using data from the 2005 reoccupation of A16S and the previous WOCE occupation to reveal a large and statistically significant warming of the bottom waters in the Argentine and Brazil Basins (Johnson and Doney, 2006).

In addition, we have begun an examination of deep temperature differences (Figure 3) for P16 that shows an abyssal warming over the 15-year time for almost the entire latitude range (all of the Pacific) occupied. Johnson is working with colleagues to analyze abyssal temperature changes in these and other repeat hydrographic sections. Analysis of data from these sections is the primary direct means to estimate the contributions of abyssal temperature variations to the global ocean heat budget. The global ocean heat budget is vital to climate change modeling and prediction. Early results suggest that abyssal temperature variations may contribute significantly, although probably not dominantly, to the global ocean heat budget.

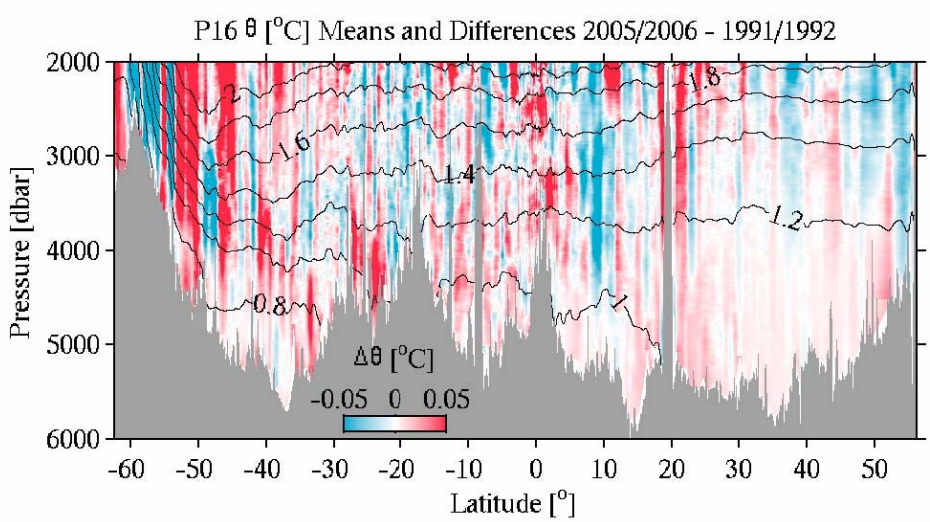

Figure 3. Potential Temperature (θ) means (solid black lines at 0.2 °C intervals) and differences (red warming and blue cooling) along WOCE Section P16 based on data from the 1991/1992 original occupations and 2005/2006 reoccupations.

2.3 Total Dissolved Inorganic Carbon (DIC) (Feely, Sabine and Wanninkhof)

The DIC analytical equipment was set up in a seagoing container modified for use as a shipboard laboratory. The analysis was done by coulometry with two analytical systems (PMEL-1 and PMEL-2) operated simultaneously on the cruise by Alex Kozyr (CDIAC) and Robert Castle (AOML) on leg 1 and Dana Greeley and David Wisegarver of PMEL on leg 2. Each system consisted of a coulometer (UIC, Inc.) coupled with a SOMMA (Single Operator Multiparameter Metabolic Analyzer) inlet system developed by Ken Johnson (Johnson, 1992; Johnson et al., 1985; Johnson et al., 1987; Johnson et al., 1993) of Brookhaven National Laboratory (BNL). Samples were drawn from the Niskin-type bottles into cleaned, precombusted 300-mL Pyrex bottles using silicone tubing. DIC values were reported for 2622 samples or approximately 92% of the tripped bottles on this cruise. Full profiles were completed at stations on whole degrees, with replicate samples taken from the surface, oxygen minimum, and bottom depths. Duplicate samples were drawn from 192 bottles and interspersed throughout the station analysis for quality assurance of the coulometer cell solution integrity. The average of the absolute value of the difference between duplicates was 0.85 $\mu mol\ kg^{-1}$ for both systems. No systematic differences between the replicates were observed. The coulometers were each calibrated by injecting aliquots of pure CO_2 (99.99%) by means of an 8-port valve outfitted with two sample loops (Wilke et al., 1993). The instruments were calibrated at the beginning of each station with a set of the gas loop injections. Secondary standards were run throughout the cruise on each analytical system; these standards are Certified Reference Materials (CRMs) consisting of poisoned, filtered, and UV irradiated seawater supplied by Dr. A. Dickson of Scripps Institution of Oceanography (SIO), and their accuracy is determined shoreside manometrically. On this cruise, the overall accuracy for the CRMs on both instruments combined was 0.8 μmol/kg (n=66).

The DIC data have been completed and submitted to CDIAC and CCHDO for distribution to the oceanic community. They have been integrated with the P16S cruise data (see Figure 4 above) and are of very high quality. A complete P16 section of the DIC data shows strong vertical and horizontal gradients in the concentrations consistent with anticipated circulation features (Figure 4). The black dots in the figure indicate the location of the carbon measurements. The previous occupation of this line was during the WOCE global survey in 1991. Figure 4 also shows the change in DIC between these cruises (approximately 15 years). Preliminary results indicate significant increases in DIC in the upper 1000 m in 2006 compared with 1991.

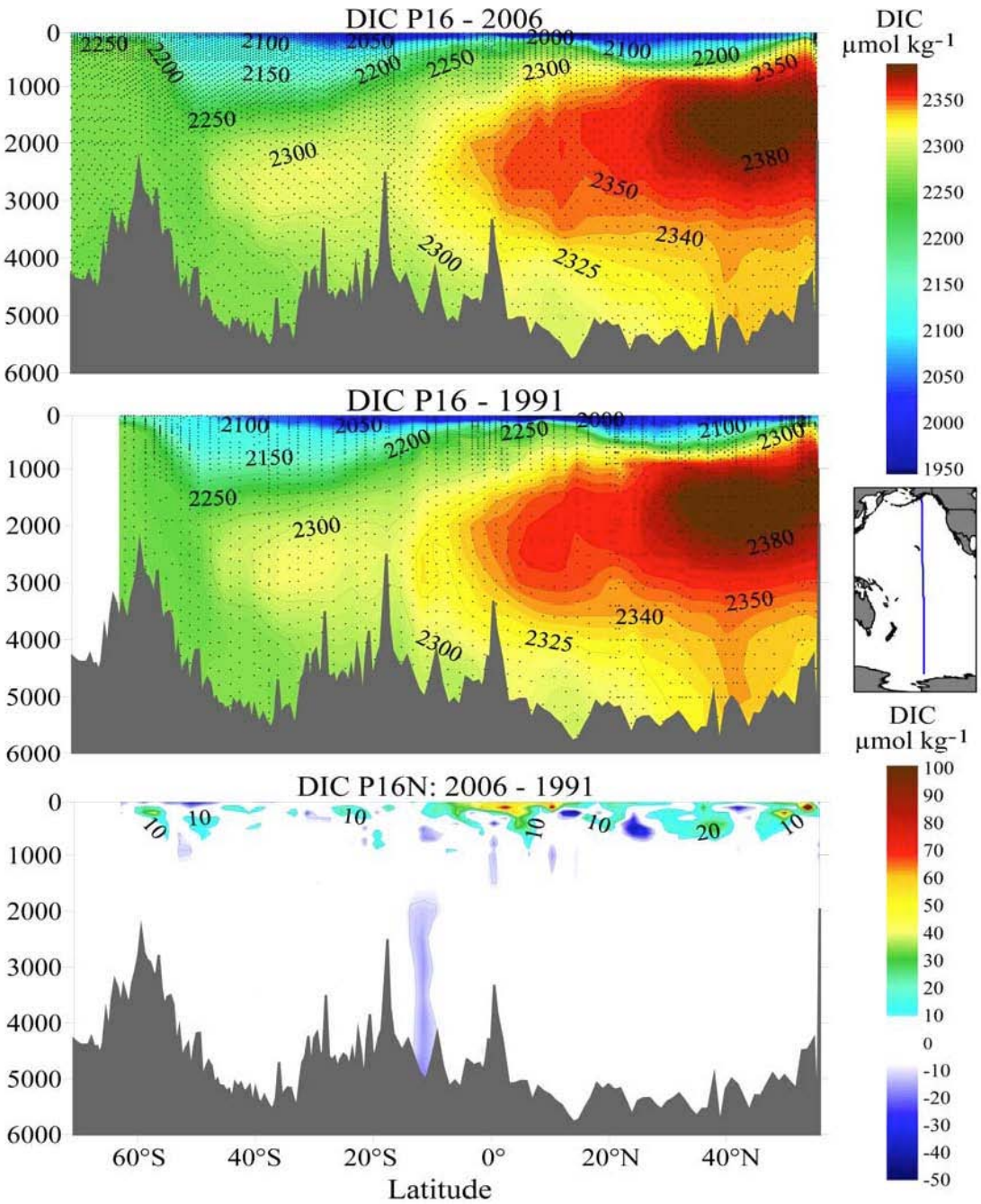

Figure 4. DIC in µmol kg^{-1} along the P16 section (top: 2005-2006; middle: 1991) in the Pacific Ocean along 150-152°W. The gridded difference plot is shown on the bottom panel. The increases in DIC are the result of a combination of processes including: anthropogenic CO invasion, and changes in circulation and biogeochemistry.

Table 2. Summary of number of DIC samples taken and the estimated precision for the P16 cruise	
	DIC
Number of samples	2622
Number of replicates	192
Average standard deviation (µmol kg^{-1})	0.85

2.4 Discrete pCO_2 (Wanninkhof)

Samples were drawn from the Niskin-type bottles into 500 ml volumetric flasks. About 5 ml of water was withdrawn to allow for expansion of the water as it warms. Saturated mercuric chloride solution (0.2 ml) was added as a preservative. The sample bottles were sealed with a screw cap containing a polyethylene liner. The samples were stored in coolers at room temperature generally for no more than 5 hours.

Samples were analyzed at a constant temperature of either 20°C or 12°C. The pCO_2 in intermediate waters of the North Pacific reach the highest values in the world's oceans and even with samples run at 12°C some analyses would exceed the working range of the detector of about 2000 ppm. The depth range of the very high pCO_2 concentrations gets progressively deeper going northward. Samples were not collected in the waters that would exceed the instrument range. For example, no pCO_2 samples were taken between 700 and 1200 db at station 53 and the range progressively increased from 175 to 1500 db at station 77.

When samples were taken on a particular cast, flasks were drawn on all the Niskin-type bottles including four duplicates. Two of the duplicates were analyzed at the two different temperatures. A total of 30 stations were sampled and the tally of samples is listed below.

Table 3. Summary of number of pCO_2 samples taken and the estimated precision for the P16 cruise
Number of stations sampled 30
Total number of unique pCO_2 samples 880
Good values (QC=2 or QC =6) 849
Questionable values (QC=3) 15
Bad values (QC=4) 16
Duplicate values (QC=6) 104

Table 4 shows the statistics for the three types of duplicates that were taken. The average difference: [ABS(sample 1-sample2)/(sample 1+sample 2)], std. dev. and number for the three types are listed below:

Table 4. Standard deviations of duplicate samples.		
Duplicates run at 20°C:	av. dif. =0.3 ±0.23%	n = 33 (one value omitted)
Duplicates run at 12°C:	av. dif. = 0.3 ±0.18 %	n= 23 (one value omitted)
Duplicates run at 12°C & 20°C*	av. dif = 0.7 ±0.75 %	n= 59 (two values omitted)
*For comparison of the duplicates run at 12°C, the 12°C results were normalized to 20°C		

The discrete pCO_2 system is patterned after the instrument described in (Chipman et al., 1993) and is discussed in detail in (Wanninkhof and Thoning, 1993) and (Chen et al., 1995). Once the samples reach the analysis 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 is run through the analyzer before and after every ten seawater samples. The cylinder serial numbers and mole fractions of CO_2 with balance artificial air of the standards are:

Table 5. Cylinder serial numbers and mole fractions of CO_2	
CA5998	205.1 ppm
CA5989	378.7 ppm
CA5988	593.6 ppm
CA5980	792.5 ppm
CA5984	1037.0 ppm
CA5940	1533.7 ppm

The standards were obtained from Scott-Marrin and referenced against primary standards purchased from C.D. Keeling in 1991, which are on the WMO-78 scale. 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.

Key reasons for the discrete pCO_2 measurements are to ascertain complete understanding of inorganic carbon system dynamics and to have a sensitive carbon system parameter to discern changes over time. The figure below shows the excellent agreement between the measured pCO_2 and calculated pCO_2 using total inorganic carbon (DIC) and pH. A weak trend is observed going northward (higher station numbers) that needs to be further investigated. Possibilities are that standardization of pH and/or pCO_2 are not entirely consistent or that other poorly constrained parameters such as the dissociation constants of Si and borate are biasing the use of pH in these internal consistency calculations. The much poorer agreement and larger standard deviation of the pCO_2 calculated from DIC and Total Alkalinity (TA) points to the strong need to include a third carbon system parameter if the data are to be used effectively to address the pressing concerns about biota in a high CO_2 /low pH ocean.

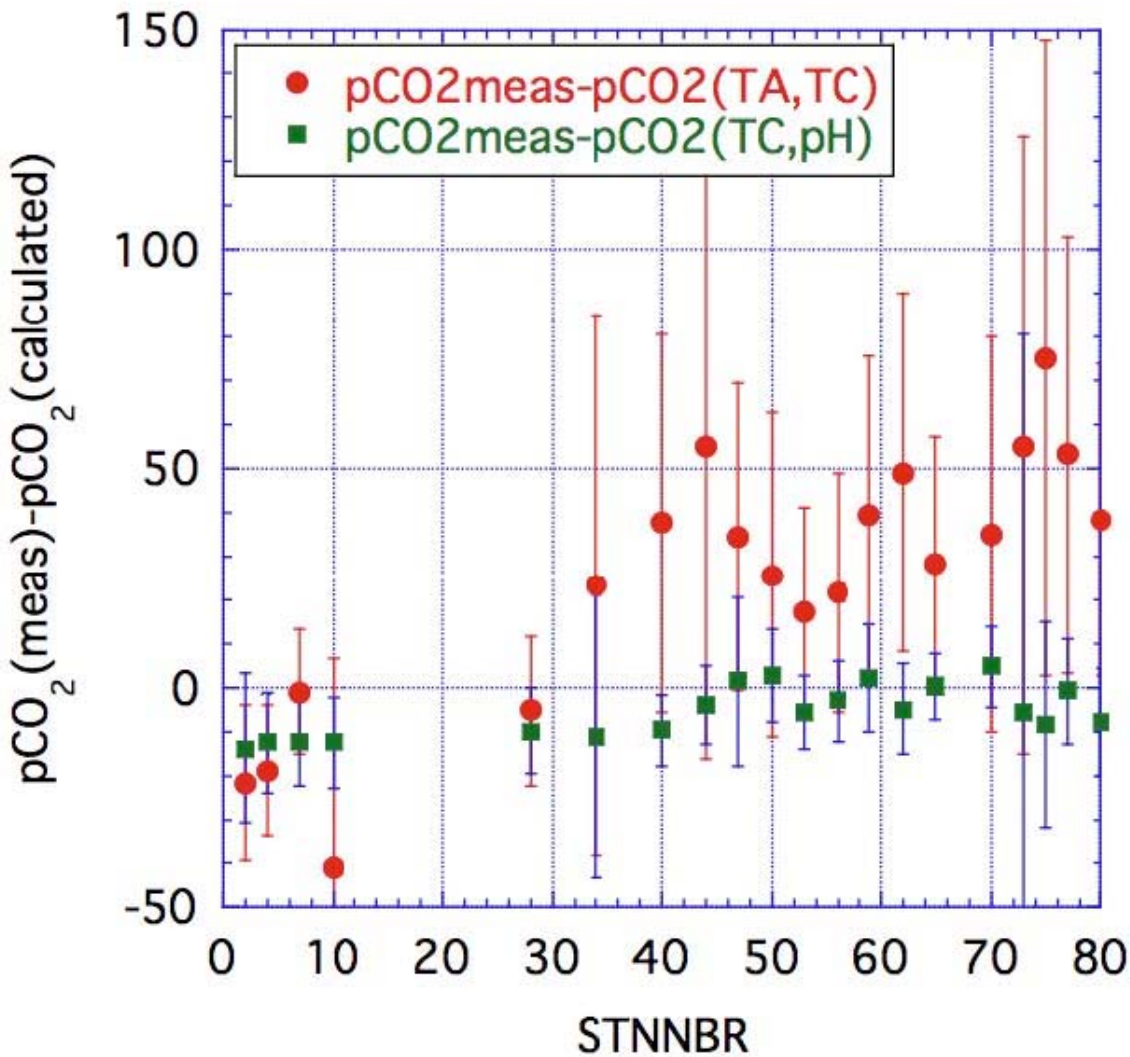

Figure 5. Station averaged (pCO_2 measured - pCO_2 calculated) versus station number (refer to Figure 2 for location). The red circles are the difference of pCO measured from those calculated with TA and DIC. The green squares are the difference with pCO measured from those calculated with pH and DIC. The error bars are the standard deviation of the differences for each station comprised of 25 to 35 samples.

2.5 Nutrients (Mordy and Zhang)

The major task for the nutrient group in FY-06 was the analysis of dissolved inorganic nutrients (nitrate, nitrite, phosphate and silicic acid) on the P16N cruise. This was a joint effort between nutrient laboratories at PMEL (Mordy) and AOML (Zhang), and involved several months of preparation (repairing the autoanalyzer, purchasing materials and supplies, shipping of hazmat and the autoanalyzer), several months at sea with two chemists running the autoanalzyer continuously, and several months of data reduction.

During the cruise, nutrient samples were collected from all Niskin-type bottles using 30 ml acid washed high-density polyethylene bottles that were rinsed at least three times with sample. All samples were allowed to warm to room temperature in the dark, and were analyzed within 2 hours of sample collection. Measurements were made in the temperature-controlled laboratory on the ship; nevertheless, temperatures variations were much greater (21±6°C) than on past cruises. The autoanalyzer used on P16N was a custom instrument made from various components. The reaction for phosphate was carried out using macro-sized glassware and coils from the Technicon AAII autoanalyzer. The other chemistries were carried out using micro-glassware from Alpkem. Analytical methods were from (Gordon et al., 1994), except that the reaction of phosphate occurred at 55°C with a much lower concentration of sulfuric acid (Zhang et al., 2001).

Standardization and analysis procedures specified by (Gordon et al., 1994) were closely followed, including calibration of labware (e.g. glass volumetric flasks and pipettes), preparation of primary and secondary standards, and corrections for blanks and refractive index. A mixed primary standard solution was prepared by dissolving high purity standard materials (KNO_3, KH_2PO_4 and Na_2SiF_6) in deionized water, and this standard was stored at room temperature. Because primary nitrite standard solutions are known to be unstable, they were prepared approximately every 10 days, and were stored in the refrigerator. Working standards were freshly made at each station by diluting 20 mls of the mixed primary standard and 1 ml of the nitrite stock solutions to 500 ml with low nutrient seawater. Standardizations were performed at the beginning and end of each analytical run. Replicates were collected from the deepest Niskin bottle(s). To check for station-to-station systematic errors (i.e., errors in standard preparation), at least one replicate was stored in the refrigerator, and analyzed a second time with the subsequent station. Each analytical run and the entire data set were corrected for any drifts or offsets in standards, blanks and refractive index. To estimate the overall precision of the analysis (Table 6), we calculated the relative standard deviation of replicate samples (not including replicates used to evaluate station-to-station systematic errors).

Vertical sections of silicic acid, nitrate and phosphate are shown in Figure 6. Along most of the section, surface concentrations were depleted. Equatorial upwelling resulted in low but measurable surface nutrients between ~5°S-10°N (~1500km to 3000km). Nutrient concentrations were also higher in the surface waters of the Alaskan Gyre as a result of deep winter mixing. Subsurface maxima of nitrate and phosphate were concomitant with the oxygen minimum in the upper 2000 m, and the distribution of these properties were a result of microbial remineralization of organic material (and to a lesser extent, processes such as denitrification and nitrogen fixation). The subsurface maximum of silicic acid was deeper than for nitrate and phosphate due to the slow dissolution of sinking siliceous material (skeletons of diatoms and radiolarians). Hydrothermal plumes rich in silicic acid emanate from Juan de Fuca Ridge, and also contributed to this maximum.

Table 6. Summary of number of nutrient samples taken and estimated precision on P16N.

	Phosphate	**Silicic Acid**	**Nitrate**	**Nitrite**
Number of samples	3212	3245	3145	3245
Number of replicates	149	150	146	22*
Percent deviation	1.6%	0.4%	0.5%	2%

* Samples with nitrite concentrations higher that 0.05 μM.

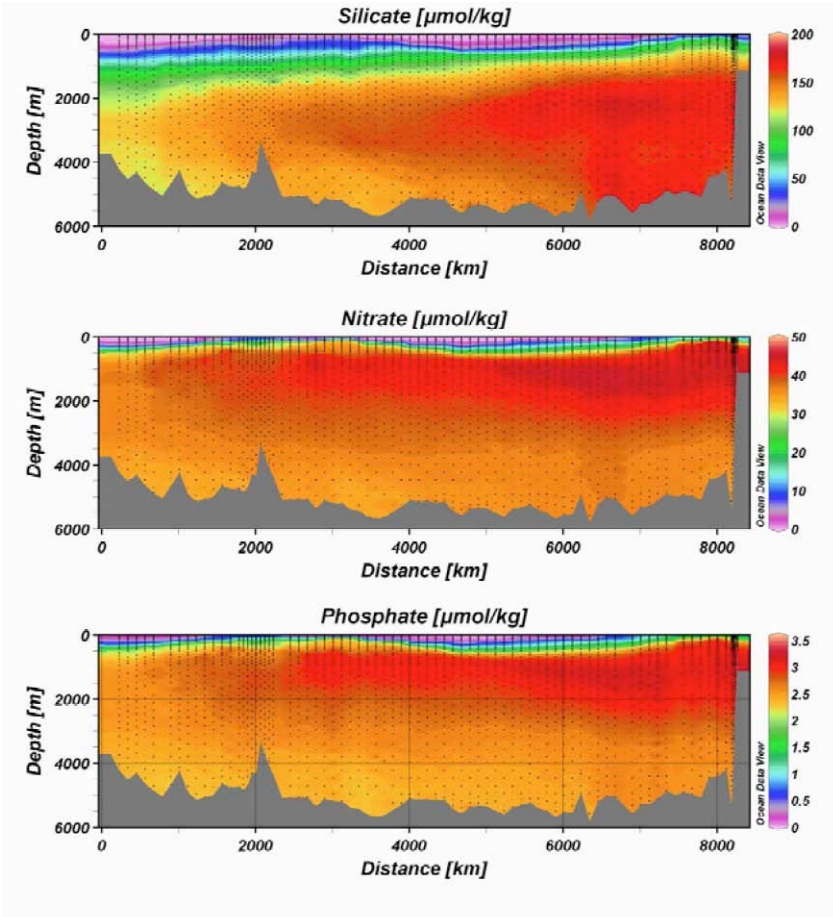

Figure 6. Vertical sections of nutrients along the P16N cruise track.

2.6 Oxygen (Langdon)

Samples were drawn from Niskin bottles into calibrated 140 ml iodine titration flasks using Tygon tubing with a Silicone adaptor that fit over the petcock to avoid contamination of DOM samples. Bottles were rinsed twice 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 µmol kg^{-1} concentrations, and a diagnostic check of bottle integrity. One-ml of $MnCl_2$ and one-ml of NaOH/NaI were added using a Repipetor, and the flask was stoppered and shaken. DIW was added to the neck of each flask to create a water seal. The flasks were stored in the lab in plastic totes at room temperature for 1-2 hours before analysis. Thirty-six samples plus 1-2 duplicates were drawn from each station except the shallow coastal stations where only 15-28 samples were drawn. Total number of samples collected was 2842; total number of samples flagged after initial shipboard reduction of quality control: Questionable (QC=3) 25: Bad (QC=4) 120: Not reported (QC=5) 7.

Dissolved oxygen analyses were performed with a MBARI-designed automated oxygen titrator using photometric end-point detection based on the absorption of 365 nm wavelength ultra-violet light. The titration of the samples and the data logging were controlled by a 386 PC running the Oxygen program written by Gernot Friedrich. Thiosulfate was dispensed by a Dosimat 665 fitted with a 5.0 ml buret. The whole-bottle titration technique of (Carpenter, 1965) with modifications by (Culberson and Knapp, 1991) was used, but with a more dilute solution of thiosulfate (10 g L^{-1}). Standard curves were run each day. The reagent blank was taken to be the intercept of the standard curve and compared to the reagent blank determined by the convention two titration method. The autotitrator and Dosimat generally performed well. Endpoints were noted to be noisy during periods of particularly bad weather. Thiosulfate molarities were calculated from titration of the standard iodate solution dispensed using a calibrated Wheaton bottle top dispensor and corrected to 20ºC. The 20ºC molarities were plotted versus time and were reviewed for possible problems. Blank volumes and thiosulfate molarities were smoothed (linear fits) at the end of the cruise and the oxygen values recalculate. Oxygen flask volumes were determined gravimetrically with degassed deionized water to determine flask volumes at AOML and corrected for the buoyancy factor. The Dosimat and Wheaton positive displacement dispenser used for dispensing the KIO_3 were calibrated in the same way. Liquid potassium iodate standard solution with a normality of 0.0100 was prepared and bottled at AOML prior to the cruise. A single batch was used during the cruise.

In addition to the photometric end-point technique, samples from several stations during leg 2 were analyzed using an amperometric detection method (Culberson and Huang, 1987) for comparison. This was done to test amperometric detection method for future standard use. The difference between the two techniques was on average <1 µmol kg^{-1}.

2.7 Chlorofluorocarbons (Bullister)

Samples for the analysis of dissolved CFC-11 and CFC-12 were drawn from ~1835 of the water samples collected during the P16N expedition. Efforts were made to sample CFCs from the same bottles sampled for carbon parameters (DIC, alkalinity, pCO_2 and pH) and other tracers. Twelve liter water sample bottles, specially designed to minimize CFC contamination, were used on the cruise. When taken, water samples for CFC analysis were the first samples drawn from the 12-liter bottles. Care was taken to coordinate the sampling of CFCs with other samples to minimize the time between the initial opening of each bottle and the completion of sample drawing. In most cases, CFC, helium-3, dissolved oxygen, DIC, alkalinity and pH samples were collected within several minutes of the initial opening of each bottle. To minimize contact with air, the CFC samples were drawn directly through the stopcocks of the 12-liter bottles into 100 ml precision glass syringes. The syringes were immersed in a holding bath of fresh water until analyzed.

For air sampling, a ~100 meter length of 3/8” OD Dekaron tubing was run from

the laboratory to the bow of the ship.

Concentrations of CFC-11 and CFC-12 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). For seawater analyses, water was transferred from a glass syringe to a fixed volume chamber (~30 ml). The contents of the chamber were then injected into a glass sparging chamber. The dissolved gases in the seawater sample were extracted by passing a supply of CFC-free purge gas through the sparging chamber and were concentrated on a cold-trap. The trap was then heated and its contents injected onto a pre-column and the main analytical column. The analytical systems were calibrated frequently using a standard gas of known CFC composition. Multiple injections of these loop volumes could be made to allow the system to be calibrated over a relatively wide range of concentrations. Air samples and system blanks (injections of loops of CFC-free gas) were injected and analyzed in a similar manner. The typical analysis time for seawater, air, standard or blank samples was ~10.5 minutes.

Concentrations of the CFCs in air, seawater samples and gas standards are reported relative to the SIO98 calibration scale (Prinn et al., 2000). Concentrations in air and standard gas are reported in units of mole fraction CFC 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 (pmol kg^{-1}). CFC 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 response of the detector to the range of moles of CFC-12 and CFC-11 passing through the detector remained relatively constant during the cruise. Full-range calibration curves were run at intervals of 10 days during the cruise. These were supplemented with occasional injections of multiple aliquots of the standard gas at more frequent time intervals. Single injections of a fixed volume of standard gas at one atmosphere were run much more frequently (at intervals of ~90 minutes) to monitor short-term changes in detector sensitivity. The precisions of measurements of the standard gas in the fixed volume (n=395) were ± 0.44% for CFC-12, and 0.56% for CFC-11.

The efficiency of the purging process was evaluated periodically by re-stripping high concentration surface water samples and comparing the residual concentrations to initial values. These re-strip values were approximately <1 % for all 3 compounds.

The average atmospheric concentrations determined during the cruise (based on sets of 5 air analyses made daily, n=23) were 252.9 +/- 4.4 parts per trillion (ppt) for CFC-11 and 547.2 +/- 5.0 ppt for CFC-12.

The estimated precisions for the CFC-11 and CFC-12 seawater analyses are shown in the following tables.

Table 7. Summary of number of CFC-11 samples taken and the estimated precision for the P16 cruise	
	CFC-11
Number of samples	1835
Number of replicates	38
Average standard deviation	0.004 pmol kg^{-1} (or 0.45%), whichever is greater

Table 8. Summary of number of CFC-12 samples taken and the estimated precision for the P16 cruise	
	CFC-12
Number of samples	1835
Number of replicates	38
Average standard deviation	0.003 pmol kg^{-1} (or 0.36%), whichever is greater

A small number of water samples had anomalously high CFC 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 during the sampling or analysis processes. Measured concentrations for these anomalous samples are included in the preliminary data, but are given a quality flag value of either 3 (questionable measurement) or 4 (bad measurement). A quality flag of 5 was assigned to samples that were drawn from the rosette but never analyzed due to a variety of reasons (e.g. power outage during analysis).

A composite section of CFC-12 concentrations along P16S in 2005 and P16N in 2006 is shown in Figure 7. The strong latitudinal gradient in surface CFC-12 concentrations primarily reflects the latitudinal gradient in surface temperature, since the solubility of CFCs is greater at cold temperatures. CFC-12 concentrations in general decrease with depth, reflecting the relative isolation of deeper waters from recent exchange with the atmosphere. There especially strong penetration of CFC-12 in mode and intermediate waters in the southern hemisphere south of 40°S, indicating the potential of this region to take up atmospheric gases, including CO_2.

Figure 8 shows the concentration of dissolved sulfur hexafluoride (SF_6) along P16N in 2006 (SF_6 measurements were not made on P16S in 2005). The spatial resolution for SF_6 measurements was relatively coarse in this pilot study on P16N, with at

total of ~130 SF_6 samples analyzed during the expedition. Atmospheric concentrations of SF_6 have been increasing rapidly in the atmosphere during the past 2 decades. Along with the CFCs, this compound has the potential to be an extremely useful tracer of ocean circulation and mixing processes, for estimating anthropogenic CO_2 uptake and for multi-tracer dating of water masses (Bullister et al., 2006). At present, typical concentrations of dissolved SF_6 in surface waters are ~1000 times lower that CFC-12. We hope to develop our analytical techniques to make SF_6 measurement more routine on future repeat hydrography cruises.

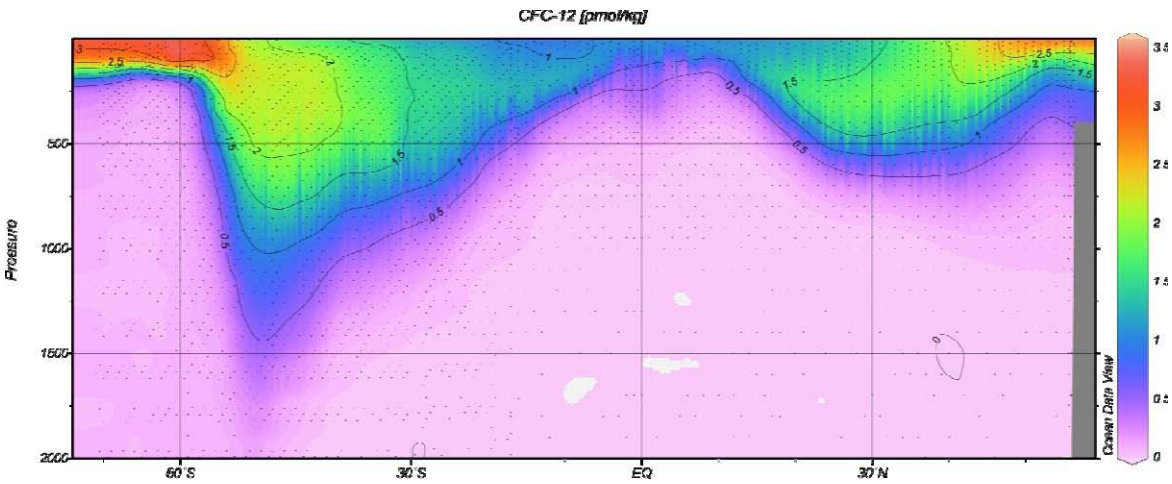

Figure 7. CFC-12 concentrations along P16S in 2005 and P16N in 2006**.**

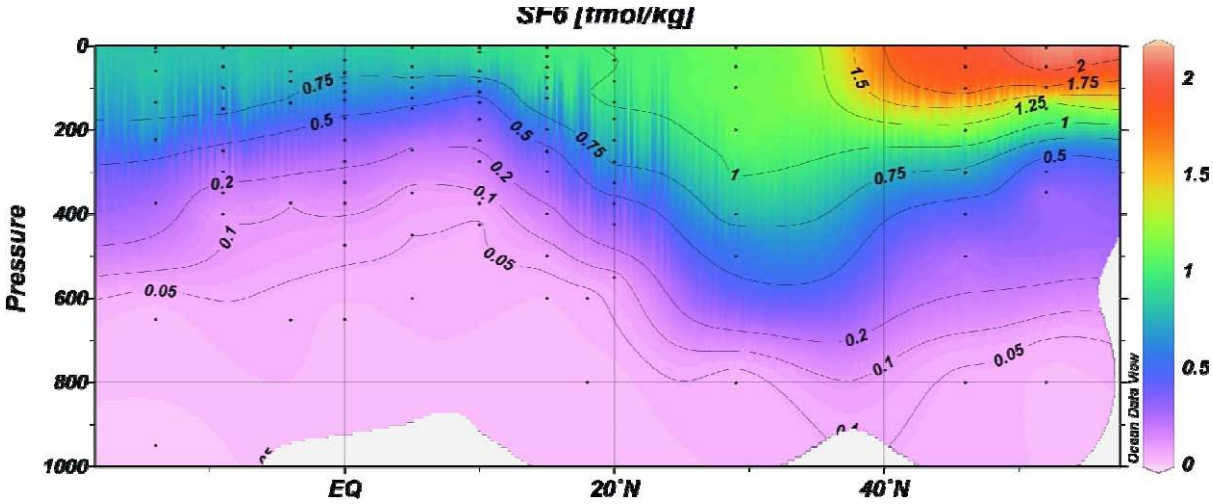

Figure 8. Concentration of dissolved sulfur hexafluoride (SF6) along P16N in 2006

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Relevant Meetings and Presentations in FY06

Sabine:

IOCCP SSG Meeting, Broomsfield, CO, October 1, 2005 (organizer and chair of meeting)
Geological Society of America Annual Meeting, Salt Lake City, UT, Oct. 17-18, 2005 (invited talk: The $CaCO_3$ Cycle and its Role in Global Climate Change)
IOCCP/CLIVAR Repeat Hydrography Workshop, Shonan Village, Japan, Nov. 14-16, 2005 (co-organizer and discussion session leader)
PICES section on Carbon and Climate meeting, Shonan Village, Japan, Nov. 17, 2005
Guest lecture at Art Institute of Seattle, Seattle, WA, April 19, 2006 (talk on global climate change and ocean acidification).
OCO annual review, Silver Spring, MD, May 10-12, 2006 (invited talk: The Global Ocean Carbon Cycle: Inventories, Sources and Sinks)
NACP Science Steering Group Meeting, Silver Spring, MD, May 18-19, 2006 (report to SSG on ocean carbon components)
North Atlantic Synthesis Meeting, Laugarvatn, Iceland, June 26-July 2, 2006
Ocean Carbon and Climate Change Scientific Workshop, Woods Hole, MA, July 10-12, 2006
OCCC and Ocean Carbon and Biogeochemistry SSG meeting, Woods Hole, MA, July 13, 2006
Global Carbon Project SSG meeting, Mexico City, Mexico, Aug. 30-Sept. 4, 2006

Feely:

IOCCP SSG Meeting, Broomsfield, CO, October 1, 2005

IOCCP/CLIVAR Repeat Hydrography Workshop, Shonan Village, Japan, Nov. 14-16, 2005

PICES section on Carbon and Climate meeting, Shonan Village, Japan, Nov. 17, 2005

Ocean Sciences Meeting, Honolulu, HI February 2006 - Decadal Variations in Ocean Interior Circulation and Biogeochemistry: Results From the CLIVAR/CO2 Repeat Hydrography Program, Feely and Talley co-chairs.

OCO annual review, Silver Spring, MD, May 10-12, 2006 (poster: The Repeat Hydrography CO_2/Tracer Program) Ocean Carbon and Climate Change Scientific Workshop, Woods Hole, MA, July 10-12, 2006

North Atlantic Synthesis Meeting, Laugarvatn, Iceland, June 26-July 2, 2006

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Surface Water pCO_2 Measurements from Ships

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Project Summary:

The oceans are the largest sustained sink of anthropogenic carbon taking up on average about 1.6 10^{15} gram (= 1.6 gigaton) of carbon each year. Changes in this sink will be determined by monitoring regional and seasonal patterns of carbon uptake and release. Determination 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 are outfitting 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. While this is the largest coordinated effort, it is by no means the only one. Success in constraining the sources and sinks depends critically on international coordination and partnerships. 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 Iceland, France, the United Kingdom, Australia, New Zealand, and Japan on reciprocal data exchange and logistics support.

Documenting carbon sources and sinks relies critically on other efforts undertaken under sponsorship of the Office of Climate Observations (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.

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

have pCO_2 systems on them: NOAA ship *Ronald H. Brown*, NOAA ship *Ka'imimoana*, RVIB *Palmer*, cruise ship *Explorer of the Seas*, container ship *Cap Victor,* container ship *Skogafoss*, container ship *Oleander*, and UNOLS research ship RV *Atlantic Explorer* (ship owned and operated by BIOS) 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.

FY 2006 Progress:

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.

SHIP	# Cruises	# Data Points	% Recovery*
R/V Brown	12	47,551	86.1%
M/V Skogafoss	7	31,210	61.0%
Explorer of the Seas	46	67,177	80.0%
RVIB Palmer	7	84,909	98.0%
R/V Ka'imimoana	4	54,537	85.0%
R/V Atlantic Explorer	6 months	38,920	86.1%
M/V Cap Victor	6	96,239	91.0%
M/V Oleander	8 months	63,120	67.6%

Table 1:VOS Data Summary FY-2006.

* 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 undertaken in which General Oceanics Inc. of Miami, FL will build the underway pCO_2 systems to our specifications. Substantial time and effort is involved by participants at AOML and RSMAS to assist in building, trouble shooting and improving instrument design. A prototype has been completed and we will oversee production of the first 12 units and provide product support. Participants in the NOAA project ordered six systems of the first production run.

2. With the retirement of Steven Cook, the GOOS/TSG (thermosalinograph) component is taken over by Gustavo Goni who will lead the installation and maintenance of TSG units aboard three ships of the program: the *Oleander*, the *Skogafoss* and the *Cap Victor*. One key

accomplishment has been the installation of the SEAS 2000 software in the *Cap Victor*. The system, which has been upgraded to a micro TSG and dedicated computer, is currently storing data which is retrieved when the ship is serviced in port. The other two will be upgraded this summer. we will also set up a robust quality control and data management system for temperature and salinity for the ships we use, thereby assuring improved data quality of these critical support measurements for the pCO_2 program. AOML has implemented quality control procedures for historical (delayed mode) and real-time mode observations, based on the ten GOSUD (Global Ocean Surface Underway Data Pilot Project) real time control tests and on additional AOML tests. The quality control tests implemented by AOML are among the most complete for TSG observations, which will assure the quality of the data transmitted to the data centers. The quality control of data in delayed-time mode is already being carried out for three ships of the SOOP. The real-time mode was implemented for the TSG data of the *Explorer of the Seas*: (*www.rsmas.miami.edu/rccl*).

3. In addition to leading the effort on the *Palmer* the LDEO group has provided two critical data packages towards to overall goal of this project. The data produced by the NOAA-supported groups as well as those from international collaborators from Japan, Iceland, Germany and France, were processed into a single format at the Lamont-Doherty Observatory. A compilation of all coastal data was assembled that is the cornerstone of an assessment of the role of the coastal ocean in carbon dynamics (Chavez and Takahashi, 2006). The comprehensive dataset that was used to create the global pCO_2 climatology comprised of 3 million data points from over a dozen research groups was sent to the Carbon Dioxide Information and Analysis Center (CDIAC) at the Oak Ridge National Laboratory, for the permanent archive and ready access to the public. The data are being examined by the CDIAC staff, and the release date has not been determined pending on the consent of European contributors for releasing their data.

4. The RSMAS group jointly maintains the pCO_2 system on the *Skogafoss* and has analyzed discrete surface samples for Total Alkalinity (TA) and Total Inorganic Carbon (TC) that have been collected on select cruises. These state variables provide the opportunity to further elucidate the factors that control the surface water pCO_2 and can provide a physical basis for the CO_2 flux map analysis.

Several opportunistic collaborations have increased our data holdings. The AOML/GOOS group has provided a TSG for the *Atlantic Companion* maintained by the Leibnitz oceanographic Institute in Kiel. As part of this arrangement this group will share the pCO_2 and TSG data of the line.

A pCO_2 system was lent to Prof. Brain Ward of Old Dominion to outfit a cruise in the North Atlantic. This high resolution data set augments our high latitude data. We continue close interactions with the University of Bergen in data exchange for the North Atlantic and interpretation to improve flux maps in this region.

The responsibilities of the different groups are summarized in the flow diagram below.

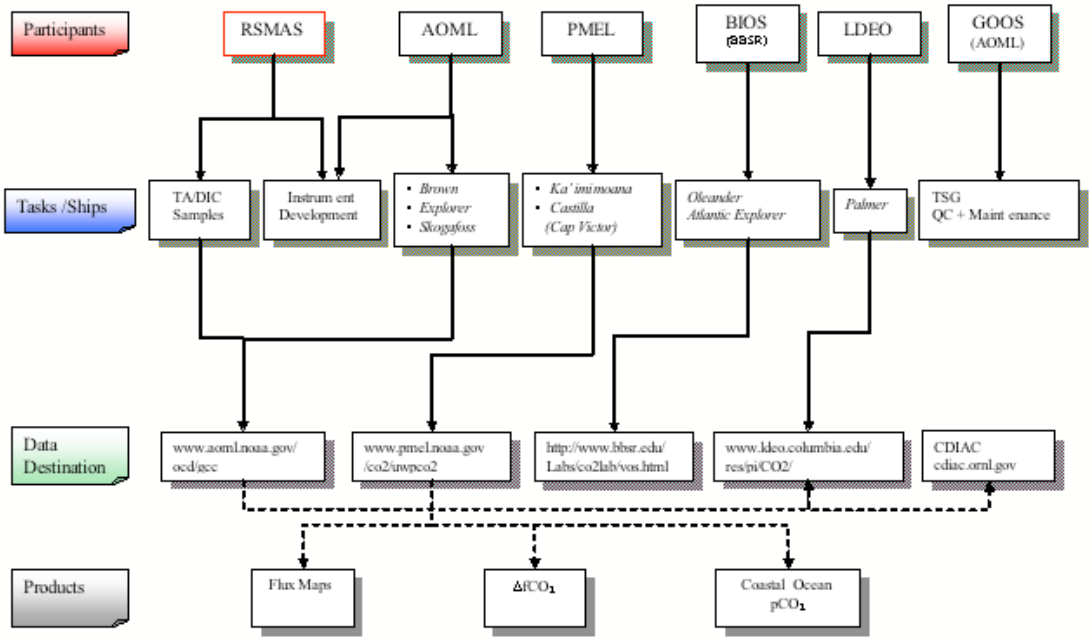

Figure 1: Organizational chart of the VOS project.

A short summary of the efforts on each ship are listed below:

***NOAA* ship *Ronald H. Brown*- AOML lead**

Causes for non-return: The underway pCO_2 system on the *Brown* enjoyed over a 85 % data return. Trips had to be made to Boston for fixing a clogged air line and to Charleston to replace a waterbath The thermosalinograph on the *Brown* yielded poor data on several of the cruises complicating data reduction. Overall returns from the ship continue to be excellent (see *Table **1***)

Description: The cruise tracks for each cruise of the *Brown* for FY 2005 and FY 2006 are shown at http://www.aoml.noaa.gov/ocd/gcc/rvbrown_data2005.php . The cruises include the annual deployment of moorings in the eastern Equatorial Pacific. *Figure **2*** shows the trends for three years encompassing the last occupation and a El Nin˜o and La Nin˜a year showing the large changes from year to year. Feely et al. (2006), quantify these fluxes and show that the Equatorial Pacific is the region that contributes most to the flux variability.

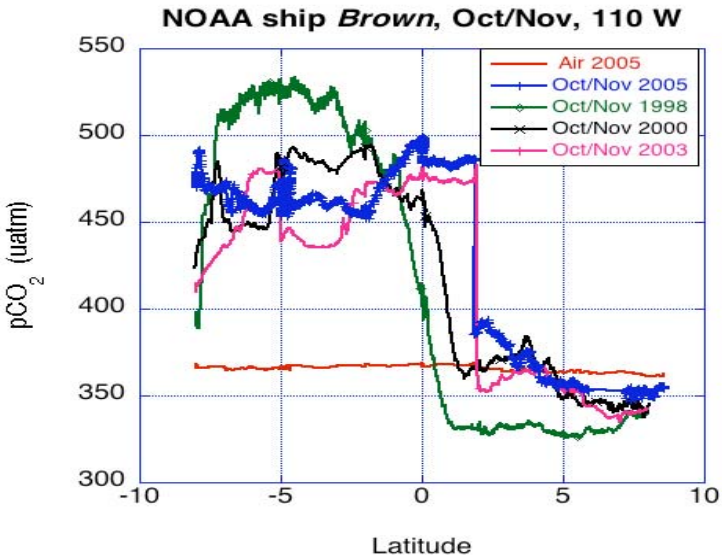

Figure 2: pCO2 data from the R/V Brown for the years 2002 to 2005

NOAA ship *Ka'imimoana*- PMEL lead

Data Site: http://www.pmel.noaa.gov/co2/uw
Number of cruises: 4
Number of pCO_{2w} data points: 54,537
% Data return: 85%.

Causes for non-return: The underway pCO_2 system on the *Ka'imimoana* yielded a 85 % data return during 2005-2006. There were periodic system failures due to problems associated with water vapor removal. There were also problems associated with low water and gas flow. The thermosalinograph information must be integrated into the data files after the cruises, which complicates data reduction.

Description: During 2005-2006 the *Ka'imimoana* was involved in studies in the Equatorial Pacific between 95°W and 165°E (*Figure **3***). The cruise data can be obtained from our website located at**:** http://www.pmel.noaa.gov/co2/uw. A summary of the cruise results from November 1997 through August 2006 is shown on the frontispiece and in *Figure **4***. The results show weak seasonal and strong interannual variability of CO_2 fluxes from the oceans to the atmosphere. These results are described in detail in Feely et al (2006). The most recent data will undergo further contextual checks by LDEO scientists before it is submitted to CDIAC for archiving.

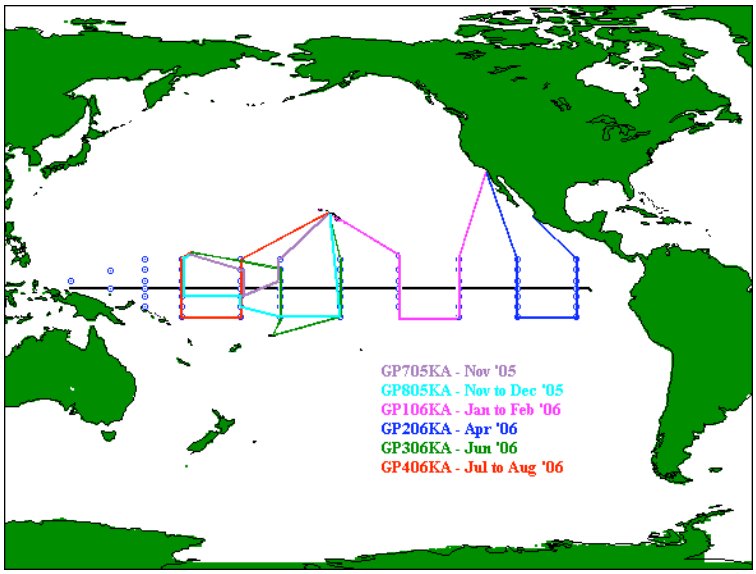

Figure 3: Ka'imimoana track lines occupied during FY 2006.

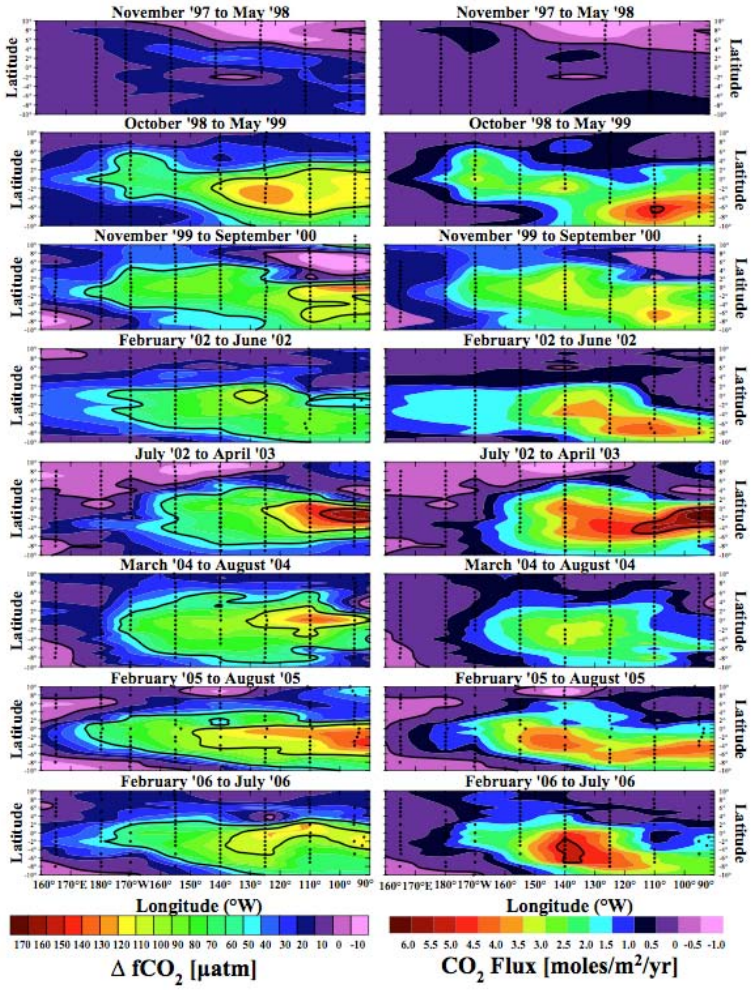

Figure 4: Time-Series of surface water pCO2 levels in the tropical Pacific resulting from Ka'imimoana repeat observations from 1997 thru 2006.

RVIB *Palmer*- LDEO lead

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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. During transits to her homeport we have been able to make measurements along long transects over other parts of global oceans. (see *Figure* ***5***) and an additional 85,000 data points have been processed and added to our database during this 2005-06 funding period. The expeditions of the Palmer during 2005-06 were mostly in the high-latitude Pacific Sector of the Southern Ocean between latitudes 40°S and 75°S. We continue to acquire the surface ocean pCO_2 and associated SST and salinity data aboard the RVIB Palmer during this coming investigation period.

Upgrading of our pCO_2 system was started two years ago with the support from NOAA. It has been completed successfully for the past two years. More automation has been added, and the at-sea performance of the upgraded system has been excellent

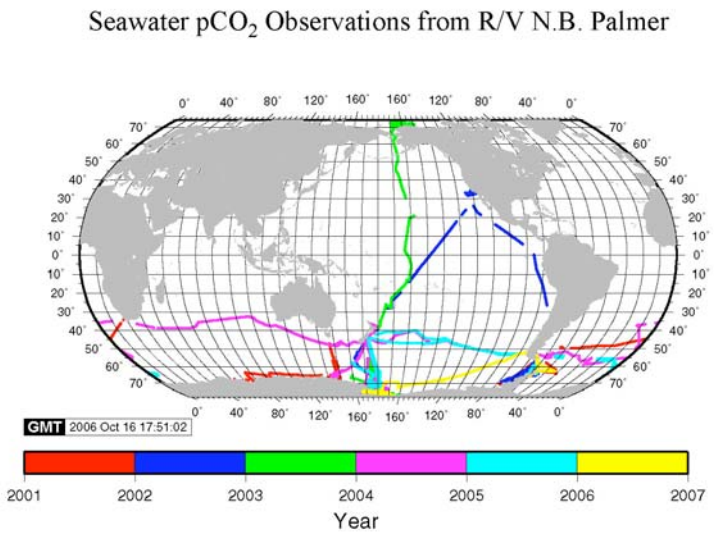

Figure 5: The locations of surface water pCO_2 measurements made aboard the RVIB Palmer since 2001. Colors indicate the years when the measurements were made. The 2005-06 observations are mostly in the New Zealand-Ross Sea and Drake Passage areas.

Cruise ship *Explorer of the Seas*-AOML lead

Causes for non-return: Some loss of data occurred because of water delivery problems to the equilibrator. Because of the shallow intake the seawater entrains air during heavy seas and the system is turned of during these conditions. Slow flushing of lines means that we omit data from the first 10-minutes after the standard run.

Description: After four years of sailing in the Caribbean the ship changed its route to sail to Bermuda during the summer time with alternating cruises from New York to Bermuda and from New York to the Eastern Caribbean. During the wintertime the original cruise track in the Eastern and Western Caribbean are occupied. This yields excellent temporal and spatial coverage. The area has been used as a test bed to create flux maps utilizing remote sensing (see research highlights). During the performance period a near-real time data display was instituted where daily pictorial updates of concentrations along the cruise track in color-code like in *Figure 6* below and a display of temperatures and concentrations are provided on the website: http://www.aoml.noaa.gov/ocd/gcc/explorer_realtime.php for system checks and quality control.

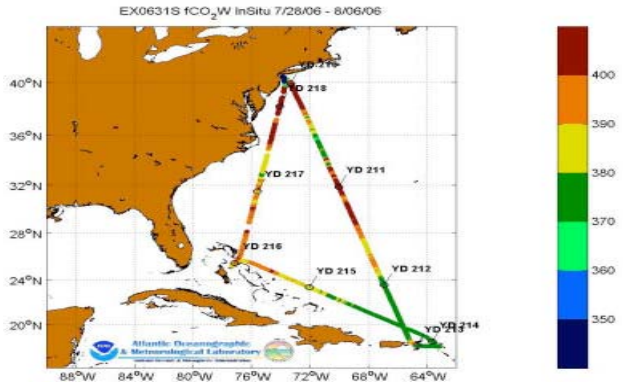

Figure 6: Summer Cruise Tracks of the Explorer of the Seas with surface water pCO_2 levels for late summer 2006.

Container Ship *Skogafoss*- AOML & RSMAS lead

Causes for non-return: This has system run unattended or with untrained observers except for 2 cruises when AOML or RSMAS personnel were onboard. Data gaps have occurred for a variety of reasons, including failure by ship's personnel to open the seawater valves, leaks in the system that caused an automatic shutdown, and a malfunctioning drain pump. The problems have resulted in frequent trips by AOML and RSMAS personnel to the ship.

Description: The *Skogafoss* sails between Iceland and Boston and covers a critical high latitude region that has been shown to be a large CO_2 sink. Large seasonal variations are observed as shown in *Figure 7*. During the early spring, pCO_2 values well above atmospheric levels are measured over most of the ocean transect due to entrainment of deep water to the surface. In late spring, values decrease significantly as a result of high biological productivity during this time.

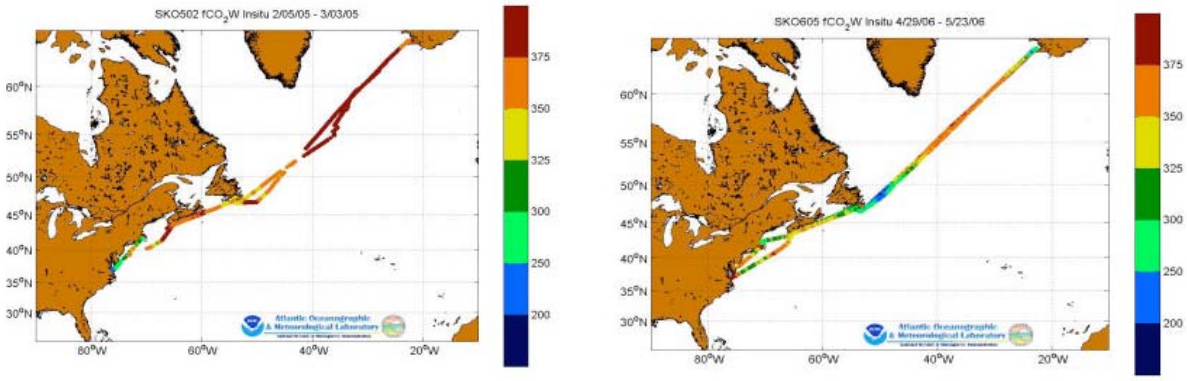

Figure 7: pCO_2 levels along the transect of the Skogafoss in February 2005 and May 2006 (figures from http://www.aoml.noaa.gov/ocd/gcc/skogafoss_introduction.php)

Container Ship *Oleander*- BIOS lead

Causes for non-return

The pCO_2 system was installed on the MV *Oleander* in February 2006. Over the last 8 months, the total data collected was 63,120, with a 67.6% data recovery. The remaining 32.4% had some caveats associated with flow rates through the licor. The MV *Oleander* system uses a LiCOR 7000 NDIR detector, and there are a few minor unresolved issues of comparability to systems with a LiCOR 6262 NDIR detector.

On the MV *Oleander*, the equilibrator is located in the Engine Room near the seawater system and TSG. It is located ~5' below the water line, requiring the equilibrator waste seawater to free drain into a waste reservoir, which in turn will be drained by a new pump back into the seawater line downstream of the tap off to the pCO_2 system. The pump has failed twice with shutdown of the system after overflow into the ship's bilges. We have added a second, stronger pump to ensure that the waste water is pumped overboard. There have also been several ship power problems. We have installed a UPS line, but the power outage has exceeded the UPS battery life on one occasion. The primary filter on the seawater intake line has also needed to be cleaned each week; otherwise rust and debris from the *Oleander*'s internal plumbing clogs the line and slows the flow rate into the equilibrator.

The average temperature of the engine room has been ~47°C with the CPU failing due to temperatures over 60°C. We have modified the dry box, adding new fans, and replaced the CPU with one that has a higher temperature threshold. The replacement of the CPU caused a problem with the GPS comport that is currently being addressed. The engine room air is quite dirty requiring cleaning of all filters each week. We have also had problems with the Superlogic Module boards; these modules have had to be replaced. The condenser tubes have clogged with salt crystals causing a shutdown of the system. The condenser tubes have been replaced.

The seawater and atmospheric pCO_2 data will also be served at the following site (http://www.bbsr.edu/Labs/co2lab/vos.html).

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.

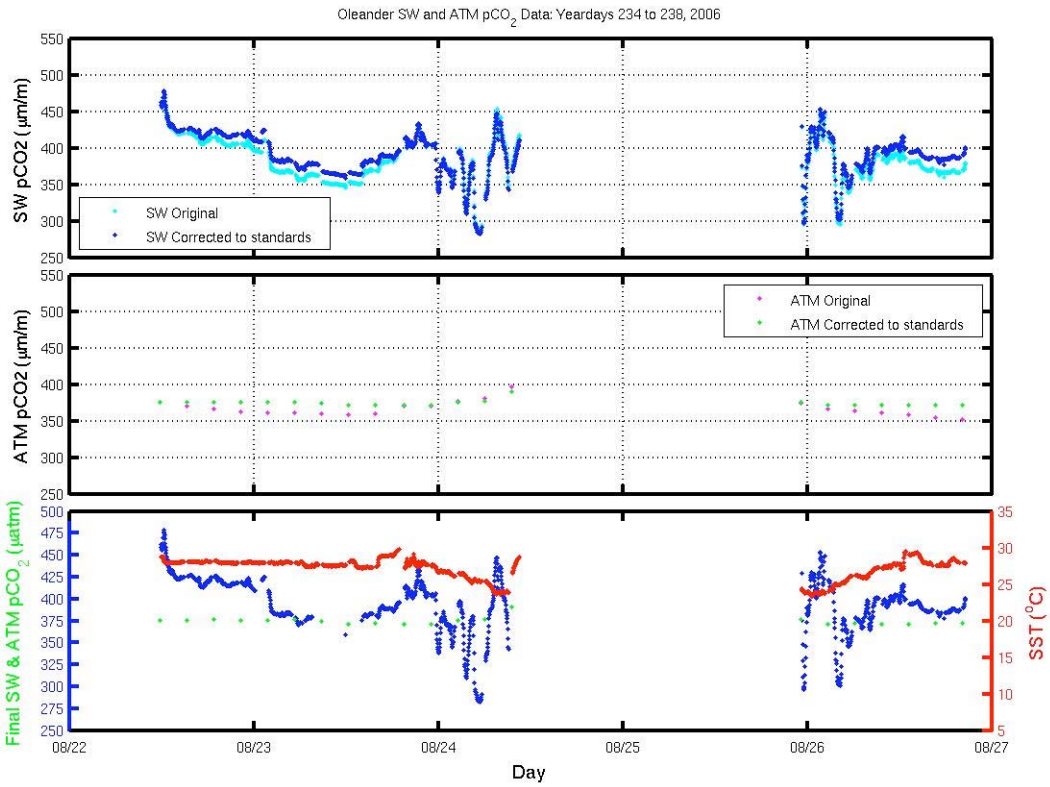

Figure 8: Example of Oleander data during a crossing from New Jersey to Bermuda, and back again in August 2006. The data gap is when the ship on 8/25 was in port

Atlantic Explorer - BIOS lead

Causes for non-return

The pCO_2 system was installed on the RV *Atlantic Explorer* in April 2006. Over the last 6 months, the total data collected was 38,920, with a 86.1% data recovery. The remaining 13.9% were flagged due to problems associated with the Valco multiposition valve and distribution of standards through the system. A permanent airline remains to be installed during the December shipyard visit for the *Atlantic Explorer*.

The major problem with the *Atlantic Explorer* system has been intermittent problems with the Valco multiposition valve. The valve has been replaced. We have had problems with the Ivisco valve that controls the flushing of the lines with freshwater. This valve has failed twice due to salt crystal buildup. We have also had problems with clogging of the flow meter impeller. We have also had problems with the Superlogic Module boards due to faulty power feed; these modules have had to be replaced. The acrodisk have also been clogged and in need of regular cleaning. We have also had a few problems with the GPS system, with a faulty 232 to 424 converter, and faulty comport. The seawater and atmospheric pCO_2 data will also be served at the following site (http://www.bbsr.edu/Labs/co2lab/vos.html).

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. In 2007, the *Atlantic Explorer* is scheduled for 173 days.

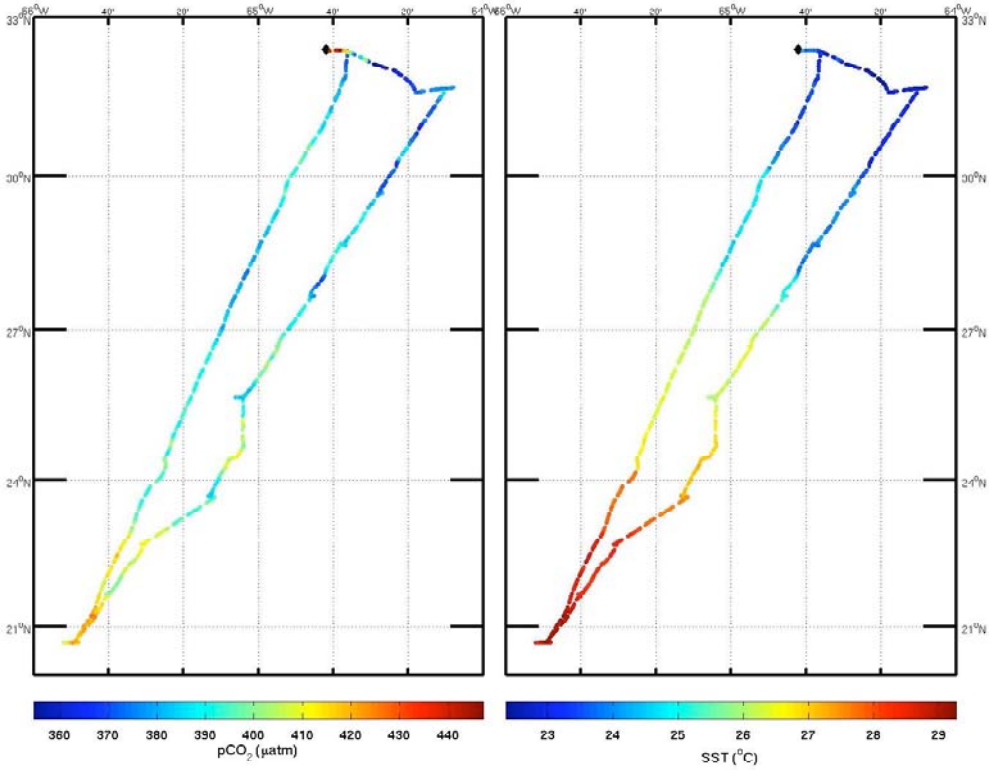

Figure 9:Example of Atlantic Explorer data during a transect across the North Atlantic subtropical gyre in May 2006.

Container ship *Cap Victor* - PMEL lead

Causes for non-return: The underway pCO_2 system on the *Cap Victor (formally Columbus Waikato)* resulted in a 91 % data return during 2005-2006. There were minor system failures due to problems associated with water vapor removal.

Description: During the fall of 2005 and 2006 the *Cap Victor* was involved in studies in the tropical and subtropical Pacific (***Figure 10***). This research is done in collaboration with

Drs. Paul Quay of the University of Washington and Bronte Tilbrook of the CSIRO in Hobart, Australia. In addition to supporting our underway pCO_2 measurements, they are also collecting samples for carbon isotope measurements (Quay) and DIC and nutrients (Tilbrook). For this reason, we have combined resources to place ship riders on each of the cruises. They maintain the underway systems and collect the discrete samples. The cruise data can be obtained from our website located at: http://www.pmel.noaa.gov/co2/uw.

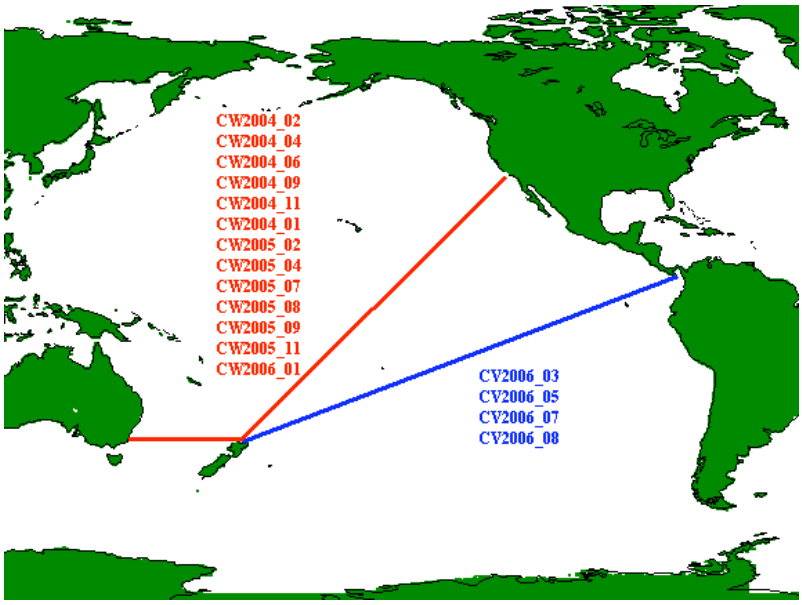

Figure 10:Cruise Tracks of the Columbus Waikato (red) and Cap Victor (blue) occupied during FY2004-2004.

A summary of the cruise results from Fall 2005 thru September 2006 is shown in Figure 11 and Figure 12. The results show strong seasonal variability of CO_2 fluxes in the southern and northern subtropic, but out of phase by 6 months. These results are described in the AGU/ASLO abstract by Cosca et al., (2006). The data will undergo further contextual checks by LDEO scientists before it is submitted to CDIAC for archiving. The *Cap Victor* was relocated to the Atlantic in the Fall of 2006.

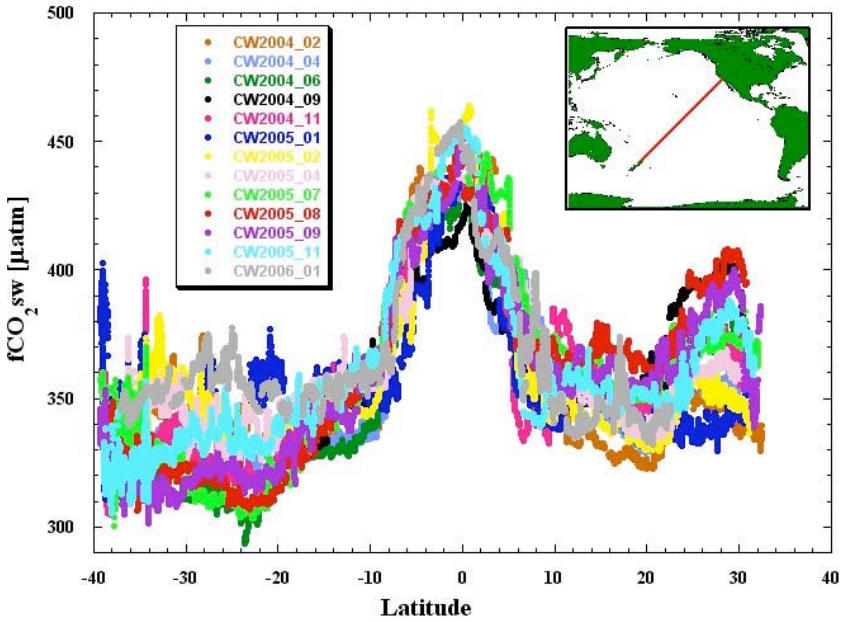

Figure 11:Time-Series of surface water pCO2 levels in the tropical and subtropical Pacific Resulting from Columbus Waikato repeat observations from 2004 to 2006..

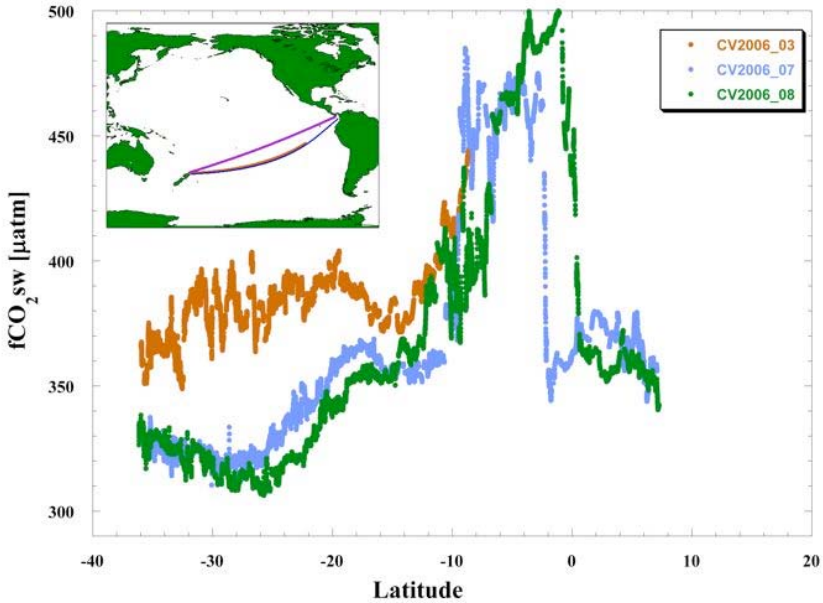

Figure 12:. Time-Series of surface water pCO2 levels in the tropical and subtropical Pacific Resulting from Cap Victor repeat observations in 2006.

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 standards that are traceable to the WMO scale. The first units were delivered in the summer of 2003, within a year of receipt of program funding. We are actively involved in assuring uniform instrumentation, through a technology transfer with the manufacturer General Oceanics who is building instruments to our specifications, uniform operating protocol, and uniform data reduction procedures.

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.

For the thermosalinograph data the AOML/GOOS group developed a data quality control computer code using OpenSource, FreeSoftware and multiplatform solutions, which allow great freedom for the future of the project. It injects the data into a PostgreSQL database where it is then subjected to different quality control procedures. Probably the major advantage to have the dataset in a relational database, such as PostgreSQL, is the use of indexes for fast sub samples by any criteria, for example QC flags, range limits, time windows or grouped values by sensors or area or ships. On this way, from the same real dataset, could be created virtually infinite metadata sets with the same storage demand and a small development effort. We are planning to install a DAP server, which will allow the direct access to the database from traditional scientific tools, such as MatLab, Python, Grads, Ferret, and others. The core of the system management is done in Python, which has modules for the direct database access, scientific procedures and easily deal with dates between other advantages which allow a robust and fast development. Details on each of the quality control steps can be found in : *www.aoml.noaa.gov/phod/tsg/data/qc_sheet.pdf*.

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 an 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 set period agreed on by the PIs, 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. 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 Lamont group processed and added to its database the measurements made during cruises of the R/V Laurence M. Gould, which is supported by NSF as a part of the Long-Term Research in Environmental Biology (LTRE) program. For the 2005-06 period, the Gould transited across the Drake Passage every month, and these

observations are ideally suited to document seasonal variability in the area. During the present reporting period of 2005-06, about 100,000 new surface water pCO_2 data have been added to the database. A total of 284,000 surface water pCO_2 data have been obtained since the beginning of the program in 2002.

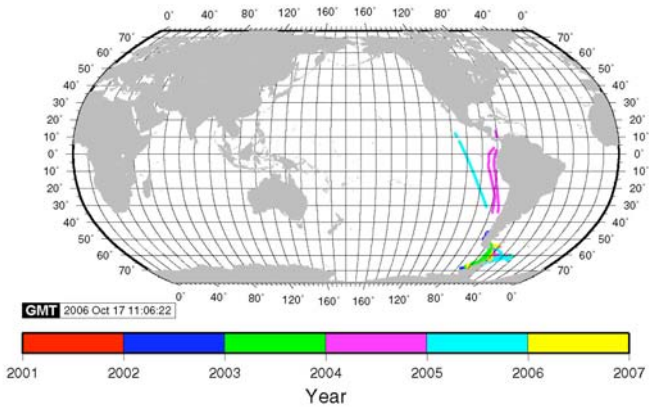

Figure 13: The locations of the surface water pCO2 measurements obtained aboard the RV Gould during this project, March, 2002 through August, 2006. The years of the measurements are color coded.

During the performance period two important data products were submitted to CDIAC. A compilation of coastal data from this group and other investigators was provided that is the cornerstone for the chapter 17 of the SOCCR report (*Chavez and Takahashi, 2006*). All the data that are used for the global pCO_2 climatology comprised of 3 million data points was sent to CDIAC as well.

CDIAC has just implemented a Live Access Server (LAS) for the data with funding from a companion effort. The LAS at http://cdiac3.ornl.gov/underway/servlets/dataset is being populated. Investigators, and the oceanographic community use the data extensively. This data is also used for national and international assessments such as the IPCC.

<u>Research highlights;</u>

1. It is widely recognized that robust methods to interpolate CO_2 measurements in time and space are needed to produce CO_2 flux maps from measurements along a line. Publications by *Lueger et al*. (2006) for the North Atlantic and *Wanninkhof et al*. (2006) for the Caribbean Seas show how temperature can be utilized to produce regional flux maps. The algorithms are area specific but show a robust predictive capacity and provide a way to utilize remote sensing to produce flux maps with high spatial and temporal resolution. The data used to create the algorithms were obtained on the ships funded under this effort.

2. Air-Sea CO_2 fluxes in the Caribbean: Air-sea fluxes in the Caribbean Sea are determined from 2002-2005 based on data from an automated system onboard the cruise ship

Explorer of the Seas. The partial pressure of CO_2 in seawater, pCO_{2sw}, are used to develop algorithms of pCO_{2sw} based on sea surface temperature (SST) and position. Regressions are applied to assimilated SST data and remotely sensed winds on a 1° by 1° grid to estimate the fluxes on weekly timescales in the region. The positive relationship between pCO_{2sw} and SST is lower than the iso-chemical trend suggesting counteracting effects from biological processes. The relationship varies systematically with location with a stronger dependence further south. Furthermore, the southern area shows significantly lower pCO_{2sw} in the fall compared to the spring at the same SST, which is attributed to differences in salinity. The annual algorithms for the entire region show a slight trend between 2002 and 2004 suggesting an increase of pCO_{2sw} over time. This is in accord with the increasing pCO_{2sw} due to the invasion of anthropogenic CO_2. The annual fluxes of CO_2 yield a net invasion of CO_2 in the ocean that ranges from -0.04 to -1.2 mol m^{-2} yr^{-1} over the three years. There is a seasonal reversal in the direction of the flux with CO_2 entering into the ocean during the winter and an evasion during the summer. Year-to year differences in flux are primarily caused by temperature anomalies in the late winter and spring period resulting in changes in invasion during these seasons (Reference: *Wanninkhof et al. 2006*).

3. As part of our continuing effort to understand decadal changes in the carbon fluxes of the equatorial Pacific, we developed seasonal and interannual pCO_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. The data were gathered onboard research ships from November 1981 through June of 2004. The data were collected during repeat transects of the equatorial Pacific between 95°W and 165°E, and included five El Niño periods (1982–1983, 1986–1987, 1991–1994 and 1997–1998 and 2002–2003) and three La Niña periods (1988–1989, 1995–1996 and 1998–2000). 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 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 Nin˜o – Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and weaker seasonal variability. There is also a slight increase (~27%) 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. These increases are consistent with the recent rebound of the shallow water meridional overturning circulation in the tropical and subtropical Pacific after the PDO shift. (Reference: Feely et al., 2006)

4. Using the observations made since the 1970's we have investigated increases in pCO_2 in surface water in the North Pacific Ocean. In 19 areas that are located in the open North Pacific, the surface water pCO_2 values have been increasing at a rate similar to the mean atmospheric CO_2 increase of about 1.5 ppm/yr. Although surface waters are out of equilibrium with atmospheric CO_2 because of the seasonal swing of SST, biological production and deep-water upwelling, the ocean surface waters appear to take up CO_2 from the air keeping up with the atmospheric CO_2 increase. In contrast, in four areas

located near and within the Bering and Okhotsk Seas, the surface water pCO_2 have been decreasing with time, in spite of the fact that surface water temperatures have been increasing. This may be attributed to an increase in photosynthesis in the high latitude North Pacific, that has been reported by Gregg et al. (2003) on the basis of remote-sensed ocean colors. (Reference: Takahashi et al., 2006)

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APPENDIX

Underway CO_2 Measurements aboard the RVIB Palmer and Data Management of the Global VOS Program

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1. INTRODUCTION:

This report describes the progress made during the period September 1, 2005, through October 1, 2006 under the NOAA grant NA03OAR4320179 which is entitled "CICAR-Underway CO_2 measurements aboard the RVIB Palmer and data management of the global VOS program".

2. PROJECT OBJECTIVES:

The sea-air net flux of CO_2 is governed by the difference between pCO_2 in surface ocean water and that in the overlying atmosphere and by the gas transfer rate across the sea-air interface. The former depends primarily on the physical, chemical and biological processes occurring within the sea (such as seawater temperature, biological productivity and upwelling of deep waters), and the latter is controlled mainly by ocean-atmosphere interactions including wind-induced turbulence above and below the interface. 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. The results will give us an improved understanding of geographical and interannual variability of the sea-air CO_2 transfer flux.

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. Although the Palmer spends a large fraction of year in the Weddell and Ross Seas, Antarctica, she has taken a few long trans-oceanic cruises over warmer oceans during the past three years. Therefore, in addition to seasonal and interannual observations over the high latitude Southern Oceans, we have been able to make measurements along long transects over other parts of global oceans. (see Fig. 1). We continue to acquire the surface ocean pCO_2 and associated SST and salinity data aboard the RVIB Palmer during this coming investigation period.

Our proposed work is a part of a consortium of investigators who operate their respective pCO_2 systems aboard other research and commercial vessels. The consortium includes the following groups: Richard Feely and his PMEL/NOAA group investigate mainly the equatorial Pacific aboard the NOAA ships; Rik Wanninkhof and his group at AOML/NOAA are primarily responsible for measurements over the Atlantic Ocean; Nick

Bates of Bermuda Institute of Ocean Sciences (BIOS), Bermuda, makes measurements in the western North Atlantic between Bermuda and N. America; Frank Millero and his group at the University of Miami investigates coastal waters and Caribbean. Pooling of the data among the participants will allow us to cover a large part of the global oceans. The data produced by the NOAA-supported groups as well as those from international collaborators from Japan, Iceland, Germany and France, are being processed into a single format at the Lamont-Doherty Observatory, and are made accessible to the participants via our web site (www.ldeo.columbia.edu/CO2). In addition, we have assembled a global surface water pCO_2 data from national and international investigators, and transferred it to the Carbon Dioxide Information and Analysis Center (CDIAC) at the Oak Ridge National Laboratory, for the permanent archive and ready access to the public. Research papers on the interpretation of the data are being written with collaborating researchers.

3. PROGRESS TO DATE:

3-a) 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 locations of our data obtained aboard the RVIB Palmer since the beginning of this project in 2001 are shown in Figure 1. The dates, location and number of measurements, which have been added to the web site during the present funding period, are listed in Table 1. A total of about 425,000 surface water pCO_2 measurements were processed during the first 4.5 years of this project (January, 2001 – April, 2005), and additional 85,000 have been processed and added to our database during this 2005-06 funding period. The expeditions of the Palmer during 2005-06 were mostly in the high-latitude Pacific Sector of the Southern Ocean between latitudes 40°S and 75°S.

3-b) Upgrading of the underway pCO_2 system aboard the RVIB Palmer;

Upgrading of our pCO_2 system was started two years ago with the support from NOAA. It has been completed successfully for the past two years. More automation has been added, and the at-sea performance of the upgraded system has been excellent.

Figure 1- The locations of surface water pCO_2 measurements made aboard the RVIB Palmer since 2001. Colors indicate the years when the measurements were made. The 2005-06 observations are mostly in the New Zealand-Ross Sea and Drake Passage areas.

Seawater pCO_2 Observations from R/V N.B. Palmer

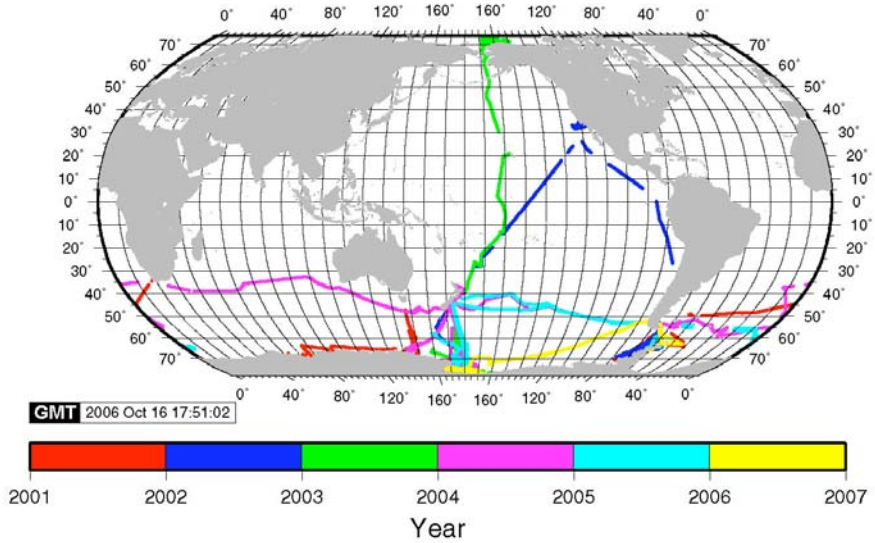

Table 1 – List of the RVIB N. B. Palmer expeditions and the number of surface water pCO_2 measurements obtained since the inception of this project in 2001 through May, 2005.

CRUISE DESIGNATION	PROJECT NAMES	DATES	NO. OF PCO_2 OBS.
NBP 01/1	East Antarctic Margin	30 Jan - 20 Mar 2001	12,300
NBP 01/2	South West Pacific	01-19 Apr 2001	6,541
NBP 01/3	SO-GLOBEC	23 Apr - 06 Jun 2001	20,446
NBP 01/4	SO-GLOBEC	21 Jul - 01 Sep 2001	14,960
NBP 01/5	Antarctic Peninsula	07 Sep - 26 Oct 2001	27,312
NBP 01/6	SO-GLOBEC	09 Nov- 01 Dec 2001	10,317
NBP 01/7	Antarctic Peninsula	05 Dec 01 - 12 Jan 02	22,627
NBP 02/1	Antarctic Peninsula	18 Jan - 04 Mar 02	24,542
NBP 02/2	GLOBEC III	09 Apr - 21 May 2002	25,327
NBP 02/4	GLOBEC IV	31 Jul - 09 Sep 2002	29,640
NBP 02/5	Transit along W. South America	23 Sep - 19 Oct 2002	8,317
NBP 02/6	USCG Inspection	30 Oct - 08 Nov 2002	6,732
NBP 02/7	Reconst. of Paleo S. Pac.	10 Nov - 06 Dec 2002	5,702
NBP 02/9	ANSLOPE, from Lyttleton to McMurdo	11 Dec 2002 - 03 Jan 2003	6,925
NBP 03/1	Ross Ice Shelf Survey	5 - 30 Jan 2003	8,062
NBP 03/1A	Ross Sea Research	2-20 Feb 2003	7,227

Table 1 – continued

CRUISE DESIGNATION	PROJECT NAMES	DATES	NO. OF PCO_2 OBS.

NBP 3/4A	Alaska North Slope	06 Jul - 18 Aug 2003	17,136
NBP 03/5	Southern Ocean near 175E	26 Oct - 13 Dec 2003	7,427
NBP 3/5A	Ross Sea Research	18 Dec 2003 - 02 Jan 2004	4,501
NBP 04/1	Western Ross Sea	20 Jan - 19 Feb 2004	12,299
NBP 04/2	ANSLOPE III	26 Feb - 11 Apr 2004	17,708
NBP 04/3	Transit New Zealand to Chile	16 Apr - 12 May 2004	9,463
NBP 04/4	Transit Chile to South Africa	18 May - 19 Jul 2004	22,755
NBP 04/6	Transit South Africa to New Zealand	27 Jul - 20 Aug 2004	14,227
NBP 04/8	ANSLOPE IV	06 Oct - 10 Dec 2004	21,958
NBP 04/9	Antarctic Research	15 Dec 2004 - 23 Jan 2005	14,443
NBP 05/1	Transit McMurdo to Chile	17 Jan - 16 Feb 2005	5,736
NBP 05/1B	Transit New Zealand to Chile	03 Mar - 24 Mar 2005	7,494
NBP 05/2	Tidewater Glaciers	31 Mar - 24 Apr 2005	8,235
TOTAL 2001-2005 (Previous Reporting Periods)			***424,170***
NBP 05/5	Antarctic Research	23 Jun - 14 Jul 2005	3,983
NBP 05/6	Maud Rise	20 Jul - 18 Sep 2005	19,066
NBP 05/7	Transit Chile to New Zealand	23 Sep - 21 Oct 2005	9,554
NBP 05/8	Biology Effects	26 Oct - 12 Dec 2005	18,387
NBP 06/1	Ecology of Phytoplankton	17 Dec 2005 - 30 Jan 2006	16,174
NBP 06/2	Paleo History of S. Pacific	02 Feb - 21 Feb 2006	7,740
NBP 06/3	Paleo History of Larsen Ice Shelf	12 Apr - 05 May 2006	10,005
TOTAL 2005-2006 (Current Reporting Period)			***84,909***

3-c) pCO_2 Data Processing and Management:

The Lamont group is responsible for quality control (QC) and management of the surface water pCO_2 data acquired by the members of the VOS consortium, so that the participants of the VOS program are able to access the data which are listed in an uniform 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 set period agreed on by the PIs, 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.

3-d) Data from the NSF's LTRE Program in the Drake Passage Area:

As a part of the VOS program, we processed and added to our database the measurements made during cruises of the R/V Laurence M. Gould, which is supported by NSF as a part of the Long-Term Research in Environmental Biology (LTRE) program. For the 2005-06 period, the Gould transited across the Drake Passage every month (Fig. 2), and these observations are ideally suited to document seasonal variability in the area. During the present reporting period of 2005-06, about 100,000 new surface water pCO_2 data have been added to our database (Table 2). A total of 284,000 surface water pCO_2 data have been obtained since the beginning of the program in 2002 (Table 2).

Figure 2 – The locations of the surface water pCO_2 measurements obtained aboard the

RV Gould during this project, March, 2002 through August, 2006. The years of the measurements are color coded.

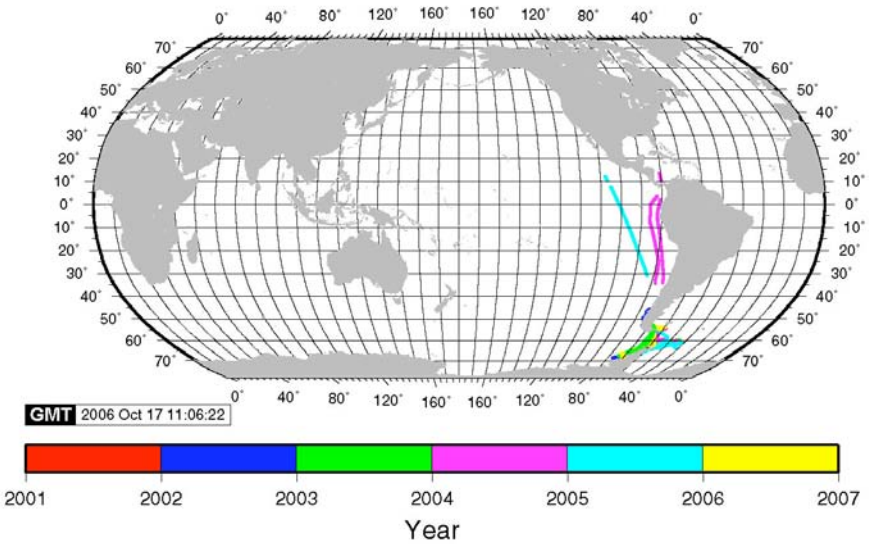

Table 2 – List of the R/V Laurence M. Gould expeditions and the number of surface water pCO_2 observations added to the VOS database since the inception of this project in 2002.

Cruise No.	Project Name	Dates	No. Obs.	Annual Total
2002				
02/1	Antarctic Penninsula	07 - 18 Mar 02	2731	
02/2	Palmer Shuttle	22 Mar - 02 Apr 02	1879	
02/3	GLOBEC III	07 Apr - 20 May 2002	8659	
02/4	Palmer Shuttle	21 Jun - 22 Jul 2002	4815	
02/5	GLOBEC IV	29 Jul - 18 Sep 2002	6787	
02/6	Palmer Shuttle	23 Sep - 07 Oct 2002	2332	
02/8	Open Cape Shirreff	03 Nov - 17 Nov 2002	3137	
02/9	Scotia Arc GPS Project	23 Nov - 23 Dec 2002	8209	**38,549**
2003				
03/1	LTER	31 Dec 2002 - 08 Feb 2003	13831	
03/2	GLOBEC	13 Feb - 07 Mar 2003	4167	
03/2	Palmer Shuttle	12 Mar - 29 Mar 2003	5721	
03/4	Biological Research	05 Apr - 07 May 2003	9334	
03/4A	Biological Research	10 May - 05 Jun 2003	4629	
03/5	Palmer Shuttle	15 Jun - 29 Jun 2003	2618	
03/5A	Palmer Shuttle	15 Aug - 04 Sep 2003	5774	
03/6	Palmer Shuttle	23 Sep - 06 Oct 2003	2495	
03/7	Palmer Shuttle	10 - 22 Oct 2003	3450	
03/8	Palmer Shuttle	07 - 18 Nov 2003	3758	
03/9	Antarctic Penn Research	23 Nov - 29 Dec 2003	12288	**68,065**

Table 2 (Continued)

Cruise No.	Project Name	Dates	No. Obs.	Annual Total
2004				
04/1	Antarctic Penn Research	01 Jan - 07 Feb 2004	12556	
04/2	Antarctic Penn Research	12 Feb - 24 Mar 2004	14222	
04/3	Antarctic Penn Research	28 Mar - 12 Apr 2004	2100	
04/4	Antarctic Penn Research	16 Apr - 10 May 2004	5510	
04/5	Antarctic Penn Research	14 - 24 May 2004	3797	
04/6	Palmer Shuttle	30 May - 09 Jun 2004	2609	
04/7	Palmer Shuttle	13 - 27 Jun 2004	2835	
04/8	Transit Chile to Louisiana	06-16 Jul 2004	3849	
04/10	Transit Louisiana to Chile	25 Aug - 12 Sep 2004	4539	(Inside EEZ)
04/11	Palmer Shuttle	25 Sep - 12 Oct 2004	3165	
04/12	Palmer Shuttle	17 - 30 Oct 2004	2091	
04/13	Palmer Shuttle	08 - 18 Nov 2004	4014	
04/14	Palmer Shuttle	24 Nov - 31 Dec 2004	10916	**72,203**
2005				
05/1	LTER Palmer Penn.	31 Dec 2004 - 05 Feb 2005	14091	
05/2	Paleohistory of Larsen Shelf	11 Feb - 12 Mar 2005	11411	
05/3	Palmer Shuttle	15 Mar - 28 Mar 2005	2398	
05/4	Acoustic Census in W Antarc.	02 Apr - 15 Apr 2005	1377	
05/5	Evolution of Antarctic Fishes	20 Apr - 12 May 2005	3674	
05/6	Evolution of Antarctic Fishes	18 May - 09 Jun 2005	3126	
05/7	Tracers, Bio and Gas Exch.	13 Jun - 28 Jun 2005	2837	
05/8	Hazardous Waste Pickup	03 Jul - 31 Jul 2005	4440	
05/9	Palmer Shuttle	16 Aug - 02 Sep 2005	3876	
05/11	Support of Palmer Station	17 Sep - 29 Sep 2005	2436	
05/12	Support of Palmer Station	23 Oct - 03 Nov 2005	3032	
05/14	Support of Palmer Station	08 Nov - 22 Nov 2005	3900	
05/15	Support of Palmer Station	27 Nov - 26 Dec 2005	6462	
				63,060
2006				
06/1	Support of Palmer Station	02 Jan - 08 Feb 2006	10538	
06/2	Support of Palmer Station	14 Feb - 16 Mar 2006	8137	
06/3	Support of Palmer Station	21 Mar - 04 Apr 20006	3072	
06/4	Support of Palmer Station	26 Apr - 07 May 2006	2601	
06/5	Support of Palmer Station	14 May - 15 Jun 2006	11145	
06/6	Support of Palmer Station	20 Jun - 02 Jul 2006	3840	
06/8	Support of Palmer Station	06 Aug - 16 Aug 2006	2932	
				42,265
	Grand Total			**284,142**

3-e) Data from the NOAA's AOML and PMEL:

During the current funding period, we have received a large number of surface water pCO_2 data from the AOML group of NOAA. These data have been examined at Lamont and added to our database. The cruise designations, dates and the number of pCO_2 measurements obtained are listed in Table 3. Since the location map for these NOAA data are shown in the AOML and PMEL CO_2 websites, they are not duplicated here. For the current funding period, we have received from the AOML/NOAA (R.

Wanninkhof PI), about 33,000 pCO_2 observations made aboard the R/V Ron Brown and 112,000 made during the Explorers of Seas program. These have been quality-controlled and added to the database of about 275,000 pCO_2 observations obtained during previous funding periods.

No new data for the PMEL program (R. A. Feely and C. Cosca) aboard the Ka'imimoana and for the Bermuda program (N. Bates) have been received for the 2005-06 period.

Table 3 - Surface water pCO_2 data received from the AOML/NOAA and PMEL/NOAA groups for quality control and archiving.

Previous Reporting Periods (2002-2004) :

SHIP	CRUISE NO.	PROJECT NAME	DATES	pCO_2 Obs.
AOML/NOAA				
Ron Brown	RB-04-01	NTAS Mooring	12-24 Feb 2004	2,301
Ron Brown	RB-04-02A	Saharan Dust Leg A	29 Feb-15 Mar 2004	2,539
Ron Brown	RB-04-02B	Saharan Dust Leg B	17-26 Mar 2004	1,776
Ron Brown	RB-04-03	Windward Passage	29 Mar-12 Apr 2004	2,668
Ron Brown	RB-04-04A	Ocean Expl. Transit	29 Apr-03 May 2004	612
Ron Brown	RB-04-04B	Ocean Expl. Mount.	08-24 May 2004	2,818
Ron Brown	RB-04-05	Ocean Expl. Titanic	27 May-10 Jun 2004	2,486
Ron Brown	RB-04-06	NURP Deep Sea Corals	17-28 Jun 2004	2,032
Ron Brown	RB-04-07A	New England Air Qual	05-23 Jul 2004	3,347
Ron Brown	RB-04-07B	New England Air Qual	26 Jul - 12 Aug 2004	2,920
Ron Brown	RB-05-01A	CLIVAR A16S Trans.	20 Dec 04 - 05 Jan 05	1,332
Ron Brown	RB-05-1B	Clivar A16S	11 Jan - 22 Feb 2005	7.829
Subtotal				**32,363**
Expl. Seas*	EX0401	Weekly Cruises in Caribbean Sea and Western Trop. Atlantic	From 02 March 2002 through 03 April 2005	
		2002: 30 Files		39,262
		2003: 39 Files		76,322
		2004: 50 Files		82,025
Expl. Seas	EX0517	2005: 28 Files		44,834
Subtotal				**242,443**
PMEL/NOAA				
Ka'imimoana	KA2004_1	TAO-TOGA Array	27 Mar-24 Apr 2004	3,696
Ka'imimoana	KA2004_2	TAO-TOGA Array	28 Apr-31 May 2004	3,589
Ka'imimoana	KA2004_3	TAO-TOGA Array	18 Jun-14 Jul 2004	2,999
Ka'imimoana	KA2004_4	TAO-TOGA Array	12 Jul-15 Aug 2004	3,466
Subtotal				**13,742**

*/ Cruise Ship "Explorer of the Seas"

Table 3 – continued

2005-2006 Period:

SHIP	CRUISE NO.	PROJECT NAME	DATES	pCO_2 Obs.
AOML/NOAA				
Ron Brown	RB-05-01C	Clivar A16S Transit Leg C	01-03 Mar 2005	766
Ron Brown	RB-05-02	Plueddermann Moorings	10-18 Mar 2005	1,560
Ron Brown	RB-05-03A	Ocean Explorations Lost City	18 Jul-03 Aug 2005	1,406
Ron Brown	RB-05-03B	Ocean Explorations Stepping Stone	10 Aug-03 Sep 2005	2,926
Ron Brown	RB-05-03SB	SeaBeam Patch Test	12-15 Jul 2005	612
Ron Brown	RB-05-03T	Ocean Explorations Transit	06-09 Sep 2005	in prep.
Ron Brown	RB-05-04	Western Boundary Time Series	11-24 Sep 2005	2,332
Ron Brown	RB-05-05	Stratus Mooring	04-20 Oct 2005	2,805
Ron Brown	RB-05-06	TAO Cruise	27 Oct-25 Nov 2005	5,169
Subtotal				**17,576**
Ron Brown	RB-06-01	Plueddermann Moorings	16 Feb- 03 Mar 2006	2,697
Ron Brown	RB-06-02	Western Boundary Time Series	12-28 Mar 2006	3,056
Ron Brown	RB-06-03	Ocean Explorations	11-30 Apr 2006	3,461
Ron Brown	RB-06-04	Tsunami Source Potential in the Caribbean	03-19 May 2006	3,035
Ron Brown	RB-06-05a	AMMA African Monsoon Sahara Dust	27 May - 17 Jun 2006	3,993
Subtotal				**16,224**
Expl. Seas*	Ex0501-Ex0548	Weekly Cruises in Caribbean Sea and Western Trop. Atlantic 44 Files	From24 Jan 2005 through 11 Dec 2005	67,231
Expl. Seas*	Ex0549-EX0636	Weekly Cruises in Caribbean Sea and Western Trop. Atlantic 31 Files	From 12 Dec 2005 through 11 Aug 2006	45,037
Subtotal				**112,268**
PMEL/NOAA				
No Additional Files				
Subtotal				**0**

*/ Cruise Ship "Explorer of the Seas" in 2005 15 files were added for total of 44 files.

4. DATA DISTRIBUTION, ANALYSIS AND SYNTHESIS:

During this funding period, we completed two major data sets for public release. First, we have assembled a surface water pCO_2 database for the global oceans, and submitted it to the CDIAC, Oak Ridge, TN, for archiving and distribution to the public. This data set is about 450 megabytes long and contains about 3 million surface water pCO_2 measurements and related observations (such as temperature, salinity and pressure) made by a large number of national and international investigators. This is the most extensive and complete surface water pCO_2 dataset that has ever been assembled. It covers the period 1968-2006, and includes open ocean data as well as coastal water data. The data assembled are only those measured using equilibrator-CO_2 analyzer systems, and have been quality controlled based upon the stability of the system performance, reliability of calibrations for CO_2 analysis and internal consistency of data. The overall uncertainty of the pCO_2 values listed are estimated to be ± 2.5 μatm on the average.

Second, we have compiled a dataset for pCO_2 measurements made within 800 km around North America and used the results for the preparation of the SOCCR report (Chavez and Takahashi, in press). The database thus assembled has been distributed to all the participants of the Coastal Ocean Carbon Cycle Workshop convened at PMEL in Seattle, WA, October, 2006. Our analysis shows that the coastal waters within 80 km for the shore of North America emits CO_2 at a mean rate of 19 (± 22) Tera grams of carbon per year (Tera grams = 10^{12} grams = million metric tons). This is about 1% of the mean annual ocean uptake rate of 2 Peta grams of carbon per year (Peta grams = 10^{15} grams = billion metric tons).

In collaboration with other researchers, we have analyzed the data and the results have been published in scientific journals. A list of 2005-06 publications that are based upon the surface water observations made during this and previous grants is provided below.

Published in 2005-06:

Rangama, Y., Boutin, J., Etcheto, J., Merlivat, L., Takahashi, T., Delille, B., Frankingnoulle, M. and Bakker, D. C. E. (2005). Variability of the air-sea CO_2 flux inferred from shipboard and satellite measurements in the Southern Ocean south of Tasmania and New Zealand. Jour. Geophys. Res., 110, C09005, doi:10.1029/2004JC002619, 2005.

Li, Z., Adamec, D., Takahashi, T. and Sutherland, S. C. (2005). Global autocorrelation scales of the partial pressure of oceanic CO_2. Jour. Geophys. Res., 110, C08002, doi:10.1029/2004/C002723.

Patra, P. K., Maksyutov, S., Ishizawa, M., Nakazawa, T., Takahashi, T. and Ukita, J. (2005). Interannual and decadal changes in the sea-air CO_2 flux from atmospheric CO_2 inverse modeling. Glob. Biogeochem. Cycles, 19, GB4013, doi:10.1029/2004GB002257, 2005

Takahashi, T., S. C. Sutherland, R. A. Feely, and R. Wanninkhof (2006), Decadal change of the surface water pCO_2 in the North Pacific: A synthesis of 35 years of observations, J. Geophys. Res., 111, C07S05, doi:10.1029/2005JC003074.

Feely, R. A., T. Takahashi, R. Wanninkhof, M. J. McPhaden, C. E. Cosca, S. C. Sutherland, and M. Carr (2006), Decadal variability of the air-sea CO_2 fluxes in the equatorial Pacific Ocean, J. Geophys. Res., 111, C08S90, doi:10.1029/2005JC003129.

McKinley, G. A., Takahashi, T., Butenhuis, E., Chai, F., Christian, J. R., Doney, S. C., Le Quere, C., Lima, I., Murtugudde, R., Shi, L. and Wetzel, P. (2006). North Pacific carbon cycle response to climate variability on seasonal to decadal time scales. Jour. Geophys. Res., 111, C07S06, doi:.10.1029/2005JC003173.

Chavez, F. and Takahashi, T. (in press). Coastal oceans, Chapter 15, in the State of Carbon Cycle Report (SOCCR), 2004-2006, Inter Government Agencies.

5. FUTURE WORK:

Two at-sea projects are being planned: a) R/V Marcus Langseth of LDEO and b) Icebreaker Healy of USCG.

a) Program aboard the R/V M. Langseth:

Lamont-Doherty Earth Observatory has acquired a new research vessel named R/V Marcus Langseth (about 2000 tons) with supporting funds from the NSF, and she will start her research cruises in early 2007. We are planning to put together an underway pCO_2 system using available spare parts supplemented with some new purchases. The pCO_2 system will be operational in early 2007, and will be added to the VOS program. R/V Langseth is operated primarily as a marine geophysics ship in various parts of the global oceans. Often, she will stay in a small area over deep oceans as well as over coastal areas for a month for detailed geophysical survey. This will give us an opportunity to observe local time-variability in surface water pCO_2 over different parts of the oceans.

b) Program aboard the Icebreaker Healy of USCG:

In spite of the fact that the oceanographic conditions in the Arctic have been changing rapidly, CO_2 observations are extremely scarce especially during winter months. We do not know whether the Arctic Sea is a sink or source for atmospheric CO2 on the annual average. We have started asking the USCG the availability of space aboard the Icebreaker Healy for our pCO2 system. New funding will be sought for such a project if the USCG responds favorably to our request.

High-resolution Ocean and Atmosphere pCO_2 Time-Series Measurements

Christopher L. Sabine[1], Francisco Chavez[2] and Nicholas R. Bates[3]
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[2] Monterey Bay Aquarium Research Institute, Moss Landing, CA
[3] Bermuda Institute of Ocean Sciences, Bermuda

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/.

ACCOMPLISHMENTS

Measurements and Network Development

The moored pCO_2 systems 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 once per day and plots of the data are posted to the web. In addition to the moored pCO_2 data collected as part of this project, MBARI has been collecting nutrient and chlorophyll measurements on the 125°W, 140°W, 155°W, 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 FY06, PMEL/MBARI maintained the eight sites from FY05 (Figure 1). There were a total 12 servicing visits to these sites in FY06. To facilitate these service visits, three additional TAO buoy hulls were modified and two new PMEL pCO_2 systems were built. The new pCO_2 systems were needed to replace older systems or systems that were lost at sea earlier in the year.

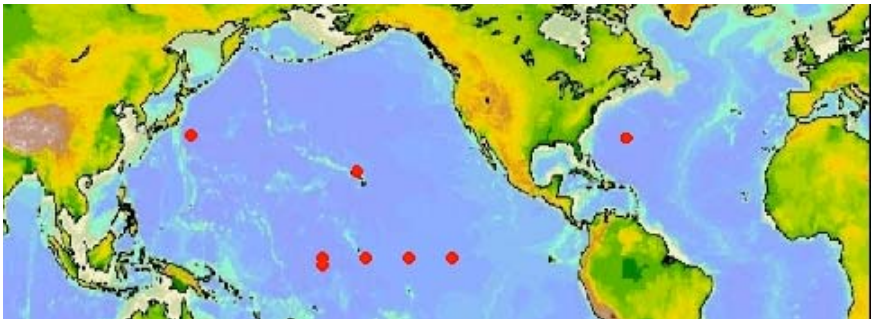

Figure 1. Map of moored pCO_2 systems currently deployed as part of this program.

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. Two systems are located in the North Pacific and North Atlantic subtropical gyres on Woods Hole buoys. These systems are co-located with the Hawaii and Bermuda shipboard time-series study sites. One system is located off of Japan in a modified TAO 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 beginning of FY06, the PMEL built system at this location collected atmospheric measurements, but lacked seawater measurements due to a valve failure in mid September 2005.

This system was replaced on January 31, 2006. The system functioned well until the buoy went adrift on July 8, 2006. At the time the buoy went adrift, probably due to vandalism, the equilibrator was damaged and the system ceased to collect seawater measurements. The buoy was redeployed on August 31, 2006, but due to deployment error, the equilibrator was jammed above the sea surface and is unable to collect seawater measurements. The system continues to collect good atmospheric measurements. This system is scheduled to be replaced April 2007. The percent data return (only counting times when both seawater and atmospheric measurements were considered good) is as follows, FY06: 44% and Lifetime: 52%.

140°W, 0° - This PMEL-built system was recovered and redeployed in late September 2005. The seawater measurements after the redeployment were implausibly high and it is believed that the there was a problem with the installation of the equilibrator. Although the seawater values were compromised, the system collected good atmospheric measurements during the entire deployment. The system was recovered and redeployed on January 16, 2006. The system operated properly until the buoy broke free, probably due to vandalism, on May 14, 2006. A new buoy was deployed on September 23, 2006 and the system is currently fully operational. The percent data return (only counting times when both seawater and atmospheric measurements were considered good) is as follows, FY06: 35% and Lifetime: 56%.

155°W, 0° - This MBARI-built system, which was deployed in June 2005 was the first deployment for a system MBARI redesigned to collect the same measurements as the PMEL systems. The system developed leaks in a stainless steel swage fitting allowing water to enter the housing making the system inoperable. The problem could not be identified until the system was recovered in June 2006 and returned to the laboratory for diagnostic testing. Extensive testing and a revision of deployment protocols are being put in place before the next cruise to this location. The percent data return is as follows, FY06: 0% and Lifetime: 35%.

170°W, 2°S - This MBARI-built system, which was deployed in June 2005, was the first deployment for the MBARI redesigned system. The system developed leaks in a stainless steel swage fitting allowing water to enter the housing making the system inoperable. The problem could not be identified until the system was recovered in June 2006 and was returned to the laboratory. The replacement system deployed in June 2006 did not leak, but much of the data quality was poor. The cause of the problem is under investigation. In October 2006, the system was again replaced and appears to be operating properly. The percent data return is as follows, FY06: 20% and Lifetime: 16%.

170°W, 0° - This PMEL-built system was fully operational until the recovery and redeployment on June 24, 2006. During the deployment in June, the surface buoy was dragged across the surface while the anchor was being deployed. This forced water up past the equilibrator into an area of tubing that could not drain properly. This trapped water prohibited the equilibrator from working properly. Although the seawater values were compromised, the system collected good atmospheric measurements during the entire deployment. The buoy was visited by the ship in October 2006 and the system is now operational. The percent data return (only counting times when both seawater and atmospheric measurements were considered good) is as follows, FY06: 73% and Lifetime: 87%.

Nutrient and Chlorophyll - Bottle samples are collected and processed by MBARI personnel from the NOAA ship *Ka'imimoana* twice a year on sections at 125°W, 140°W, 155°W and 170°W. Approximately 2000 samples were collected during the cruises in FY06. Approximately 10% of the samples were discarded due to improper sampling and loss during analysis. The percent data return is as follows, FY06: 90%.

HOT/BATS on WHOI designed buoys

MOSEAN buoy at Hawaii Ocean Time-series site (158°W, 22°N) – This system was fully operational for almost all of FY06. The November 2005 scheduled recovery was postponed due to bad weather. Another ship was not available for the recovery/deployment until February 2006. With the unanticipated delay in servicing, the system battery died on January 20, 2006, just 22 days before the successful recovery. The redeployed system is fully operational. The percent data return is as follows, FY06: 93% and Lifetime: 83%.

Bermuda Testbed Mooring (64.2°W, 31.7°N) – A moored pCO_2 system was first deployed on the BTM on October 22, 2005. The system was fully operational for the entire FY06. The system was successfully recovered and redeployed in July 2006. The system is currently operational. The percent data return is as follows, FY06: 100% and Lifetime: 100%.

OceanSITES Flux Moorings

Kuroshio Extension Observatory (144.5°E, 32.3°N) – The mooring at this location was redeployed with a PMEL-built moored pCO_2 system in May 2006. The equilibrator cycle in this system failed on deployment. We believe that water became trapped above the equilibrator during the deployment. The rest of the system, including the atmospheric measurements, is operational.

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 FY06, we had problems with water getting trapped above the equilibrator. Three changes were implemented in the fall of 2006 to prevent this problem from happening in the future. To eliminate the possibility of water being forced up into the equilibrator during the violent times of the buoy deployment and the anchor drop, the systems are now being deployed in stand-by mode. While in stand-by mode, a valve is closed to prevent water from entering the equilibrator. Once the anchor has reached the bottom and the buoy has settled, the system is called via Iridium and put into run mode.

In the event that water does enter the space above the equilibrator, the design of the equilibrator has been modified so that the water will fall back out of the tubing. The equilibrator tubing diameter was increased to allow water to fall more freely out and a tubing guide was added to the buoy tower to

ensure that the tubing is properly installed and supported. We have had three deployments since we have implemented these changes and all of them have been successful.

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. As of this report, all PMEL data through January 2006 have been finalized and submitted to CDIAC for public release. We anticipate being able to maintain or improve upon the one year final data release for the foreseeable future.

Analysis and Research Highlights

The moored CO_2 data is providing valuable information on CO_2 variability in surface seawater over a wide range of timescales that have not been fully examined. For example, we are seeing significant differences in the monthly to seasonal variability between the North Pacific and North Atlantic subtropical gyres (Figure 2). As these time-series records grow they will document the full range of differences between these basins. Since both of the sites shown in Figure 2 are co-located with shipboard time-series measurements, these variations can be directly compared to variability in a number of physical and biogeochemical parameters as well as variations in biological composition and activity.

We are also beginning to realize the importance of understanding the biological contributions to CO_2 variability in the equatorial Pacific thanks to the shipboard analyses of nitrate and chlorophyll collected as part of this project. Figure 3 shows a time-series of averaged nitrate and chlorophyll data along the 155°W line. The long-term variations in these parameters correlate very closely with the long-term variations in pCO_2 at this site.

Many publications have focused on CO_2 variability in the equatorial Pacific associated with the El Niño/Southern Oscillation, but the time-series moorings in the equatorial Pacific have shown that

Timescales of Variability	Range (ppm)
Long-term (annual rate)	~1.7-2.5
Interannual (ENSO)	~80-100
Seasonal	~20-30
Sub-seasonal (weeks to months)	~50-60
Diurnal	~20-40

variability at other timescales may be nearly as important as the ENSO variability (table 1). Manuscripts are currently in preparation discussing the significance and mechanisms controlling these other timescales of variability.

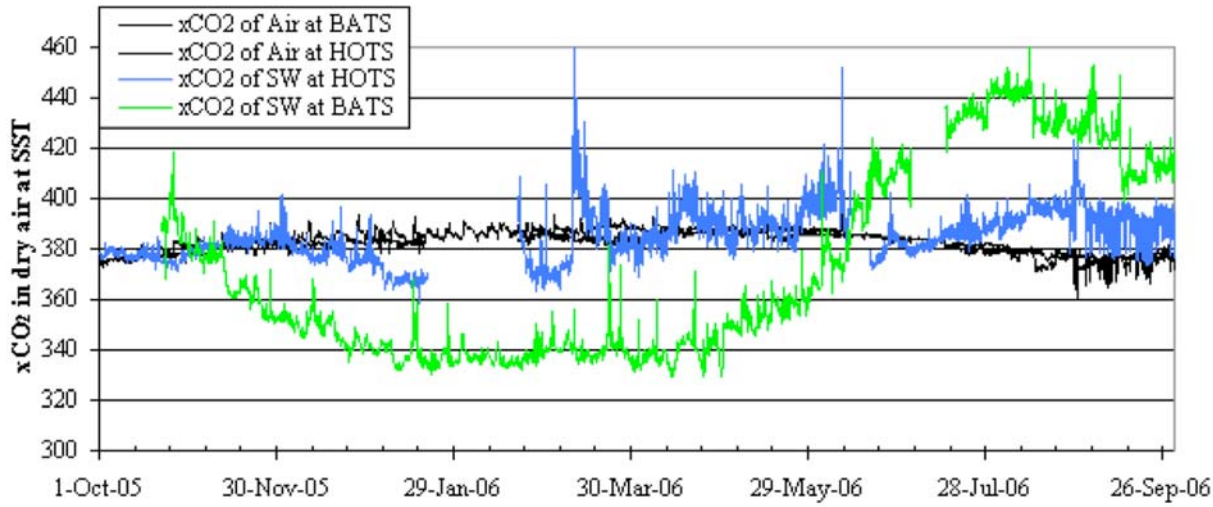

Figure 2. Time-series of CO_2 measurements from the subtropical North Pacific (HOT mooring) and the subtropical North Atlantic (BATS mooring) over the last year.

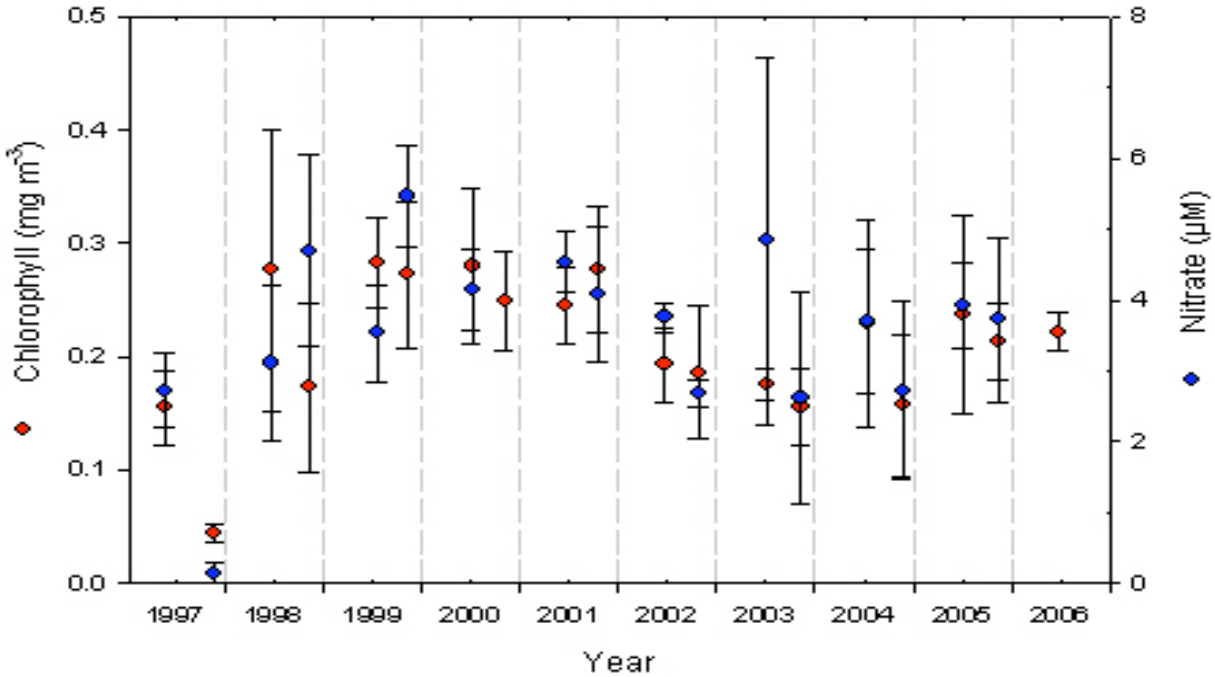

Figure 3. Average sea surface chlorophyll and nitrate levels along 155°W during the spring and autumn cruises from 1997 until 2006.

PUBLICATIONS AND REPORTS

Relevant Publications in FY06

Sabine, C.L. (2006): Global Carbon Cycle. In *Encyclopedia of Life Sciences*, John Wiley & Sons, Ltd., Chichester, http://www.els.net/ (doi: 10.1038/npg.els.0003).

Sabine, C.L., and N. Gruber (2006): Introduction to special section: North Pacific Carbon Cycle Variability and Climate Change. *J. Geophys. Res.*, 111(C7), C07S01, doi: 10.1029/2006JC003532.

Johnson, K. S., L. J. Coletti and F. P. Chavez (2006) Diel nitrate cycles observed with in situ sensors predict monthly and annual new production. *Deep-Sea Research I*, **53**, 561–573.

Ryan, J. P., I. Ueki, Y. Chao, H. Zhang, P. S. Polito, and F. P. Chavez (2006), Western Pacific modulation of large phytoplankton blooms in the central and eastern equatorial Pacific, *Journal of Geophysical Research*, 111, G02013, doi:10.1029/2005JG000084.

Pennington, J.T., Mahoney, K.L., Kuwahara, V.S., Kolber, D.D., Calienes, R., Chavez, F.P. (2006) Primary production in the eastern tropical Pacific: A review. *Progress in Oceanography* 69: 285-317.

Behrenfeld M. J., K. Worthington, R. M. Sherrell, F. P.Chavez, P. Strutton, M. McPhaden and D. M. Shea (2006) Controls on tropical Pacific ocean productivity revealed through nutrient stress diagnostics. *Nature*, 442, 1025-1028.

Relevant Meetings and Presentations in FY06

Sabine:

OCO annual review, Silver Spring, MD, May 10-12, 2006 (invited talk: The Global Ocean Carbon Cycle: Inventories, Sources And Sinks)

ASLO summer meeting, Victoria, BC Canada, June 8-9, 2006 (talk: Temporal Variability In Equatorial Pacific CO_2 Fluxes)

Ocean Carbon and Climate Change Scientific Workshop, Woods Hole, MA, July 10-12, 2006

Chavez:

Invited presentation at Ocean Sites steering committee meeting February 17-20, 2006, Honolulu, Hawaii.

Oral presentations (2) at AGU/ASLO Ocean Sciences meeting February 20-24, 2006, Honolulu, Hawaii. Authored or co-authored 12 abstracts.

Keynote speaker-Consecuencias biologicas de El Niño y El Viejo- at Biannual Mexican Oceanography Conference, 15-19 May, 2006, Manzanillo, Mexico.

Optimal Network Design to Detect Spatial Patterns and Variability of Ocean Carbon Sources and Sinks from Underway Surface pCO_2 Measurements

Joellen L. Russell[1], Colm Sweeney[2] and Anand Gnanadesikan[3]
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[2] Cooperative Institute for Research in Environmental Sciences, Boulder, CO
[3] NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ

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 (Fig. 1), updating and expanding the preliminary effort of Sweeney et al. (2002).

International Linkages:

Research strategies for global carbon cycle studies have been developed by various working groups of programs like the International Geosphere-Biosphere Programme (IGBP), the World Climate Research Programme (WCRP), the International Human Dimensions Program (IHDP), and the Intergovernmental Oceanographic Commission (IOC) working together. Our project is in support of the need for global-scale coordination of international carbon observation and research efforts in order to achieve the goal of a global carbon synthesis. This study fulfills one component of the 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. By providing an optimal network design for a global pCO_2 measurement program, we will directly contribute to the International Ocean Carbon Coordination Project (IOCCP). We will also contribute to regional efforts such as CARBOOCEAN in the Atlantic and the PICES Working Group 13 in the North Pacific that are coordinating observations.

Relationship to NOAA's Program Plan for Building a Sustained Ocean Observing System for Climate: (Objective 8: Ocean Carbon Monitoring Network)

Optimal design of the pCO_2 sampling network design using both the global database of pCO_2 measurements and simulations of future climate from GFDL's Earth System Model will help NOAA cost-effectively develop the infrastructure necessary to build, with national and international partners, the ocean component of a global climate observing

system. The goal of this data and model-based pCO_2 sampling network design is to quantitatively assess the optimum sampling strategy based on the ongoing long-term observational requirements of the operational forecast centers, international research programs and major scientific assessments.

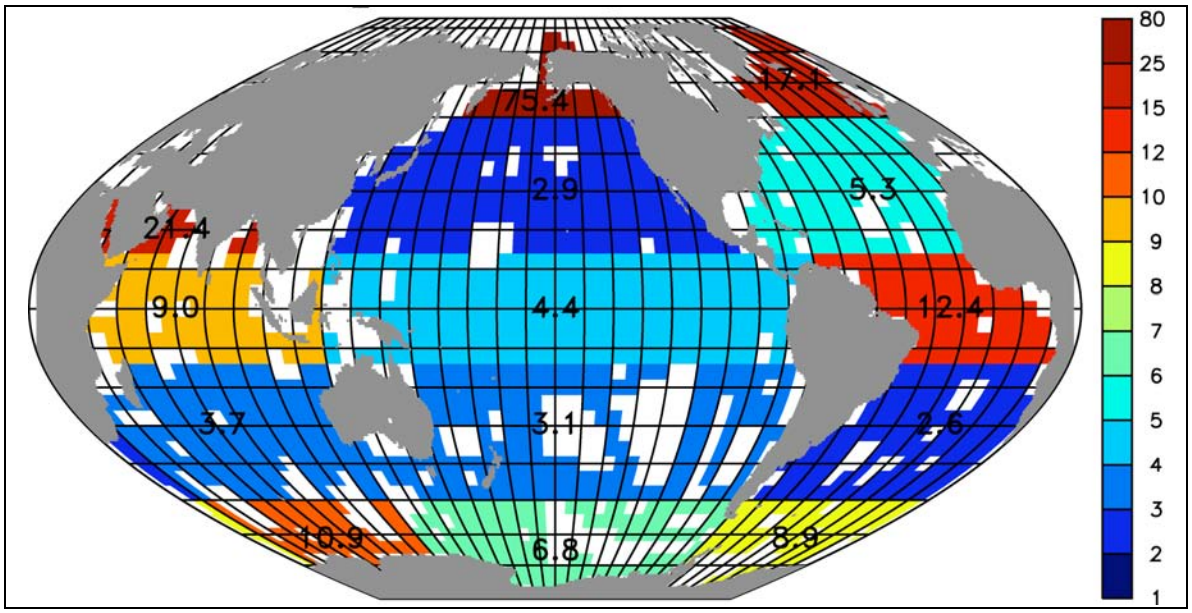

Fig 1. – Target ΔfCO_2 to estimate a regional CO_2 flux within ± 0.1Pg-C/yr for the major oceanic regions.

Specific questions to be addressed include:

- Which seasons most affect the variability of surface pCO2?
- Which sampling locations (boundary currents, open ocean, etc.) will be most representative of large-scale seasonal, interannual and decadal changes in the surface ocean pCO_2 and air-sea CO_2 flux?
- Are there sampling locations that will respond earlier to climate change and will provide the initial detection of changes in surface pCO_2 concentrations and the associated fluxes?

Sweeney et al. (2002) study suggests that a desired uncertainty of ±0.1 Pg C/yr in the basin-scale mean annual estimates for net sea-air CO_2 flux may be achieved by evenly time-spaced measurements of pCO_2 **6–15 times a year** throughout the regions of the world ocean with evenly spaced sampling **200–1500 km apart** (or 2–20 degrees longitude, depending on region and latitude). We have recalculated these targets using both high-resolution measurements made throughout the World Ocean (Fig. 2) and the NOAA/GFDL Earth System Model, and have determined that **4-12 measurements per year**, located **300-1200 km** apart will optimize our sampling network (given the currently available amount of data) to best capture the variability in surface water pCO_2 and the resulting air-sea fluxes on seasonal to decadal time frames.

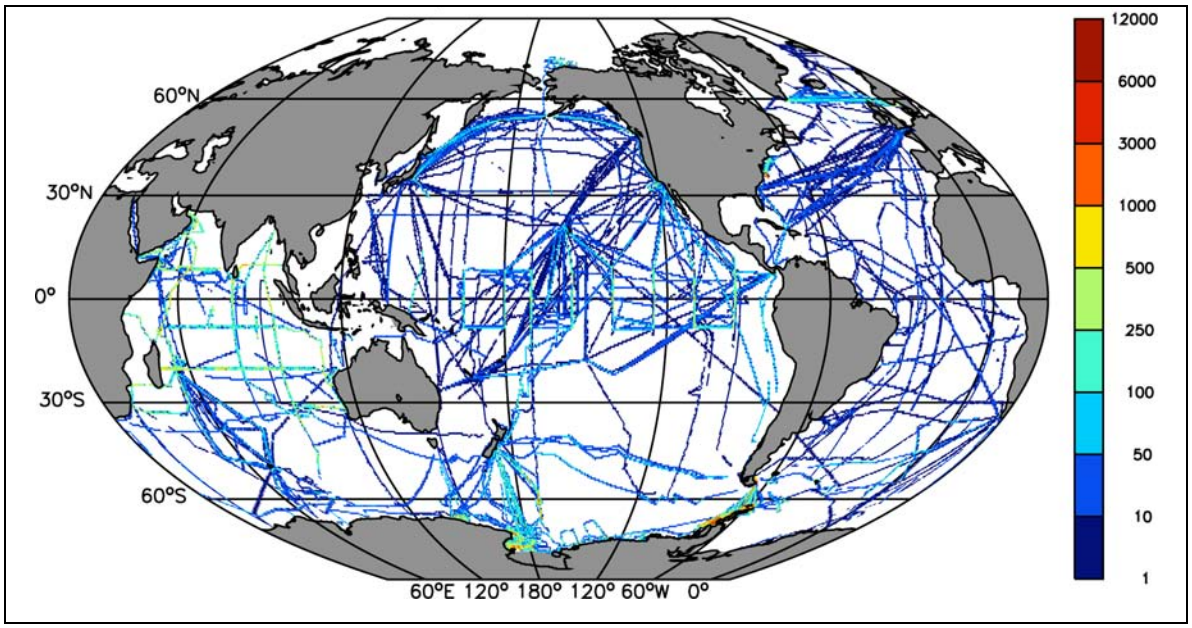

Fig. 2 – Spatial distribution of pCO_2 measurements in the global pCO_2 database. Number of measurements in each 0.5°x0.5° grid.

Ocean Regions	Ocean Area (10^6 km^2)	Average ΔfCO2 (μatm)	Annual Flux (PgC/yr)	ΔfCO2 per 0.1 PgC/yr uptake
Polar North Atlantic	7.05	-45.2	-0.26	17.1
Temperate North Atlantic	23.71	-19.0	-0.36	5.3
Equatorial Atlantic	17.13	11.2	0.09	12.4
Temperate South Atlantic	24.38	-8.4	-0.32	2.6
Polar South Atlantic	9.89	-5.9	-0.07	8.9
Polar North Pacific	5.26	-15.3	0.02	-75.4
Temperate North Pacific	42.01	-19.5	-0.67	2.9
Equatorial Pacific	50.67	17.6	0.40	4.4
Temperate South Pacific	36.50	-15.2	-0.49	3.1
Polar South Pacific	16.53	-12.6	-0.19	6.8
Temperate North Indian	4.15	35.3	0.17	21.4
Equatorial Indian	18.61	13.0	0.14	9.0
Temperate South Indian	26.94	-25.9	-0.70	3.7
Polar South Indian	7.27	-9.3	-0.09	10.9
Global Oceans	290.09	-6.9	-2.32	0.3

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.

Table 1 shows that estimation of a regional CO_2 flux to within ± 0.1 PgC/yr for the major oceanic regions requires that the sea-air fCO_2 difference be determined to within 3 to 12 μatm. Small oceanic regions such as the Polar North Pacific and Temperate North Indian

Oceans (area < 7 x10^6 km^2) fall outside this range since the net flux for these areas are much smaller than 0.1 PgC/yr. The Polar North Atlantic with its high fCO_2 difference and relatively small area also falls outside this range.

FY 2006 PROGRESS

Of the three integrated components of the optimal network design, we have

1.) **Expanded** global pCO_2 database to include new cruises conducted during 2005 and 2006. We have also added much of the as yet unpublished data collected aboard the R/V Nuka Arctica in the North Atlantic (provided by Are Olsen). The data base now contains approximately 2 million measurements
2.) **Completed** the large-scale regional analysis of pCO_2 variability within the global pCO_2 database (Table 1), and have begun the finer-scale temporal and spatial analyses focusing on seasonality and the relative importance of boundary current versus open ocean measurements.
3.) **Continued** analysis of seasonality, length and time scale of pCO_2 variability with the GFDL Earth System Model.

08. Arctic Ocean Obs System:

a. The Arctic Research Program, Fiscal 2006

The Arctic Research Program, Fiscal 2006

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Program Description

The Arctic Research Program is a component of the NOAA Climate Observations and Analysis Program and focuses on climate-related observations of the broad Arctic region. The observations include both physical and ecosystem indicators of climate change in the Arctic and as such the program provides information to all the NOAA goal teams: ecosystem (changing ecosystems under conditions of reduced sea ice cover, Arctic climate change and global responses, Arctic climate change and its effect on North American weather and Arctic Climate Change, sea ice change and commerce in the Arctic region.

The program follows the advice of the Science Steering Committee and the implementation plan developed by the Interagency Study of Environmental Arctic Change SEARCH: plans for Implementation during the IPY and Beyond. Observations focus on atmospheric variables such as clouds, radiation and aerosols that influence Arctic climate; on sea ice thickness and motion; on ocean climate such as water column temperature and salinity structure and currents, primarily in the ocean gateways to the Arctic (including the Bering Strait, Chuckhi Sea region, and the passages from the Arctic to the Atlantic Ocean). and changing ocean chemistry and biology in these regions to detect the impacts of physical climate change on the Arctic ecosystems and the globe as a whole. Additionally, activities are undertaken to analyze and integrate observations of the program and historical data from diverse sources. The program conducts web-based outreach activities, is involve in museum Arctic Exhibit development (e.g The Museum of Natural History) and supports a State of the Arctic report. The program is active in international coordination of Arctic observation activities, working with the Arctic Council, the International Arctic Science Committee and on a bilateral basis with Canada, Norway, Russia, China and others.

Major Program Elements

1. Climate Observatory Network

The Arctic Research Program has undertaken an agency leadership role in the Implementation of the International Arctic System for Observing the Atmosphere (IASOA)**-** As part of the SEARCH implementation plan, the Arctic Research Program will support with international partners 3-5 Observatories around the rim of the Arctic Ocean. Barrow, Alaska (Already supported by NOAA ESRL and the DOE Atmospheric Radiation Monitoring program). The second observatory in the network is at Eureka, Canada on Ellesmere Island. The third link in the planned network will be located at Tiksi in Siberia, Russia and preparatory work began there in 2006 with the completion of the first building for the observatory. NOAA will coordinate with an already established atmospheric observation program in Ny-Alesund, Norway and the Greenland, Summit Station to complete the circumpolar network. The goal of the observatory network is to provide long time-series data on clouds and cloud properties, aerosols, radiation, and trace gases. The data will support research on atmospheric climate processes, provide calibration/validation data for current and planned satellite sensors, and provide data to develop and test global and regional climate models with an end goal of answering questions of attribution.

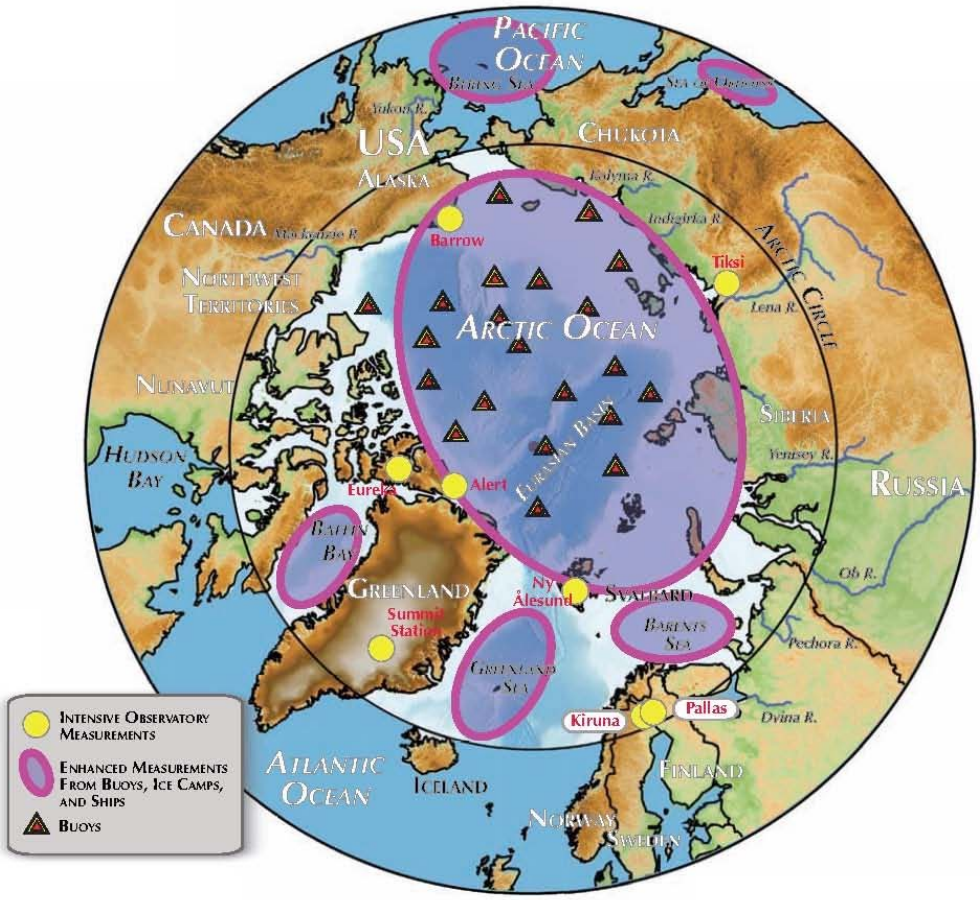


Figure 1. Priority areas for atmospheric observation activities. *A SEARCH atmospheric observing program should include coordinated intensive observatory measurements (yellow dots) in Barrow, Alaska; Alert and Eureka, Canada; Ny-Ålesund, Norway; Tiksi, Russia; the Greenland Summit Station; Pallas, Finland; and Kiruna, Sweden, as well as the inclusion of upper air measurements within existing ocean data collection activities (pink circles), including those from potential buoy deployment areas (see Figure 2). Weather station networks, unmanned aerial vehicles (UAV), and satellite data represent additional sources of atmospheric observations (not shown). Coordination of efforts between atmospheric observatory programs, integration with other interdisciplinary activities, and international support to reinstate, enhance, and establish new atmospheric observations throughout Siberia north of the Arctic Circle will significantly enhance the potential for understanding regional differences of atmospheric changes in the Arctic.*

2. Ocean and Sea Ice Observations

The NOAA Arctic Program is working with partners to implement the **Arctic Observing Network (AON).** The NOAA portion of the AON will be a subcomponent of the NOAA Integrated Ocean Observing System and is represented in the SEARCH implementation plan figure 2. There are 3 NOAA-supported elements to the AON: 1) ***oceanographic moorings*** along the shelf and slope, in the deep basin of the Arctic Ocean (NABOS) and across the Pacific Gateway to the Arctic, the Bering Strait; 2) ***ship- based*** observations focused on ecosystem-physical interrelated indicators of climate change in the Northern Bering Sea and the Chukchi Sea. NOAA conducted its first Arctic Ocean research cruise with the Russian Academy of Sciences in summer 2004 through what has become known as the RUSsian-American Long-term Census of the Arctic (RUSALCA) project. One objective of RUSALCA is to document the changes in the physical state of the northern Bering Sea and Chukchi Sea, regions that have experienced significant change over the past few decades and that models predict will experience even greater change in the decades ahead. General ocean and atmospheric warming and loss of sea ice should be accompanied by changes in water column structure, and possible changes in circulation and flux through the Bering Strait, which may have implications for the entire Arctic and Atlantic Ocean beyond. A second objective of RUSALCA is to observe changes in ecosystem structure and productivity that result from the physical changes, and to identify a set of ecosystem indicators that might be applied throughout the Arctic marine region. Marine ecosystem alterations will affect Native subsistence harvests and possibly commercial fisheries and protected mammals and birdsPlanning is underway for a major international research and observations expedition during the International Polar Year in 2008. The current strategy is to conduct a multidisciplinary cruise every 4 years with mooring and physical oceanographic based expeditions conducted annually. Additional RUSALCA goals are to, map and monitor fresh water and nutrient fluxes and pathways across the Pacific Gateway and into the Arctic Ocean, promote U.S. - Russian Federation and international cooperation in ocean and polar regions studies, and facilitate exploration and information gathering of this poorly mapped region of the climate system.

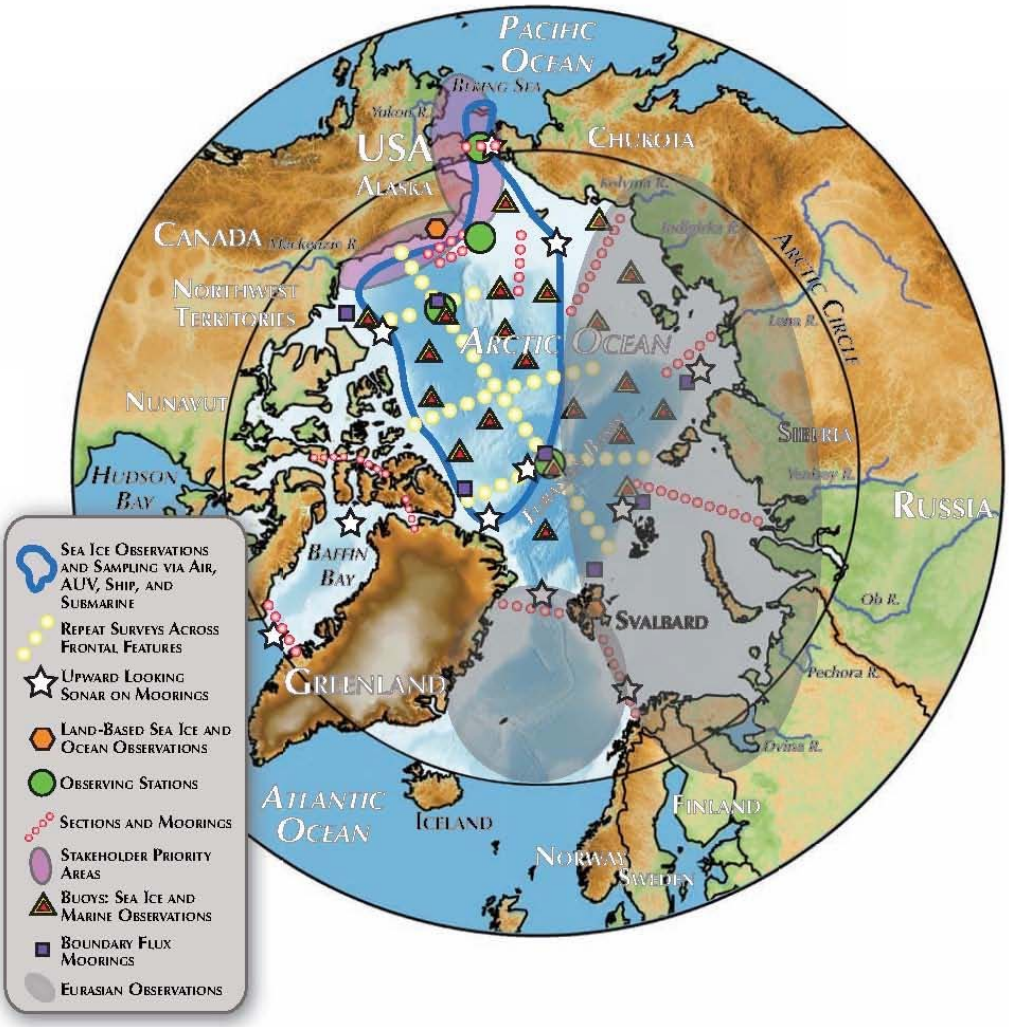
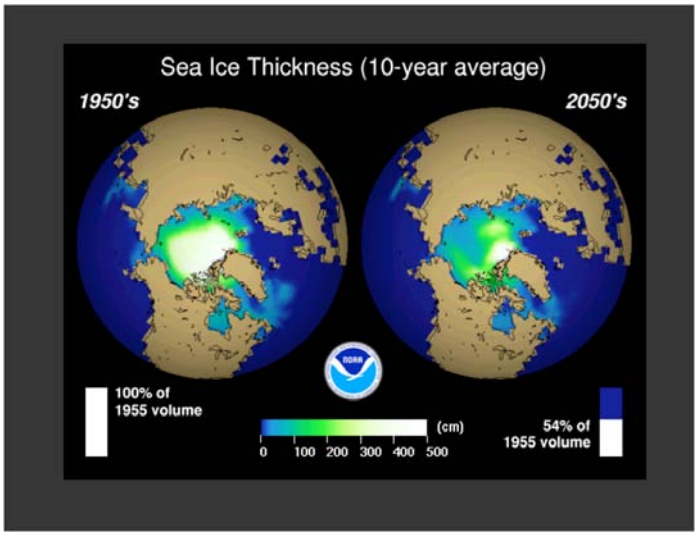


Figure 2. SEARCH priority areas for distributed ocean and sea ice observations. *The highest priority for SEARCH is long-term and large-scale observations of environmental change. Observation requirements include those related to physical/chemical ocean, geophysical sea ice, biological/chemical, and stakeholder-relevant variables; sensors and measurements should be co-located to the extent possible. Key regions include: Beaufort Gyre, North Pole, Bering Strait, Canadian Archipelago, and Eurasian Basin slopes and shelves; Alaska near-shore observations in the Bering, Chukchi and Beaufort Seas (stakeholder priority areas, purple shading); and the Chukchi/Beaufort shelf-slope area. Priority observation activities include: repeat hydrographic/ tracer surveys across frontal features (yellow dotted lines) and sea ice and ocean sampling along transects (blue line) via ship, aircraft, AUVs, and submarine; boundary flux sections (red dotted lines, additional boundary flux moorings denoted by purple squares); drifting buoys for marine and sea ice measurements (yellow/red triangles); sea ice and ocean observations via land-based platforms (orange polygons) and upward-looking sonar (ULS) on moorings (white stars); and long-term observing stations (green dots). Eurasian observations (gray shaded areas) will focus on Arctic/ Atlantic linkages, with some explicit U.S. collaborations assumed. The locations of all SEARCH sections, buoys, and moorings in this figure are meant only as general suggestions of deployment schemes.*

3) ***ice-tethered buoys*** in the perennial Arctic sea ice to measure sea ice drift, thickness and melt processes and basic meteorology; Monitoring changes in the volume or mass of the Arctic sea ice cover is crucial for developing our understanding of climate change processes and their impacts. Changes in the volume of the ice cover can result from changes in the ice extent (area) or ice thickness. The extent of the Arctic sea ice is effectively monitored by aircraft and from satellites. Monitoring the ice thickness is more challenging. Current satellites cannot measure ice thickness, therefore data sources are limited to on-ice mass balance measurements and submarine or seafloor-mounted upward looking sonars. Developing a coordinated network to monitor changes in the ice thickness of the ice cover is the focus of one aspect of the NOAA SEARCH initiative. A key objective of this study will be to establish international partnerships and to build upon existing programs such at the North Pole Environmental Observatory (NPEO) and the International Arctic Buoy Program (IAPB).Ocean



3. Data Analysis and Dissemination

The NOAA Arctic Program supports the **Arctic Climate Change Detection Protocol**. Historical and current data from diverse sources is assembled to evaluate variability and change in Arctic climate. The Arctic System Reanalysis is envisioned as a framework for organizing historical atmospheric, sea ice and ocean data into a data set that will be assimilated into coupled models to produce a reanalysis data set to support seasonal to interannual climate projections.

In addition, the Program contributes to preparation of a **State of the Arctic (SOA) Report**. Experts from several countries are preparing a report summarizing the current physical state of the Arctic. This is an update to the Arctic Climate Impact Assessment to include newer information not included in the ACIA.

For public education, the Program maintains the **NOAA Arctic Theme Page** (www.arctic.noaa.gov) as a mechanism for describing NOAA's Arctic programs and for providing a scientific resource to the public.

Partnerships

The Arctic Research Program is highly leveraged. All of the IAOOS activities described above and the IASOA site at Tiksi involve collaboration with the Russian Federation. NOAA Arctic Research has played a critical leadership role in developing and formalizing functional scientific linkages with Russian agencies and scientists. A Memorandum of Understanding between NOAA and the Russian Academy of Sciences on World Oceans and Polar Region studies was signed in December 2003, and this has proved to be a critical document for obtaining Russian support of our activities. This MOU under the U.S. – Russian Federation Science Technology Agreement is also an umbrella for NSF funded collaboration with Russia . Over the past few years, many meetings, teleconferences and e:mail exchanges were conducted with Russian officials and scientists to plan the joint activities, obtain the necessary formal "permissions" from involved Russian agencies and to arrange for visits by US scientists to Moscow, St. Petersburg, Tiksi, Petropavlosk and Vladivostok. The maintenance of good working relationships with Russia requires constant attention.
In addition to Russia, many other countries will be involved in establishment of Arctic Observing systems and the Arctic Research Program tries to collaborate with these countries. In particular, collaborative efforts with Canada, Finland and Norway are underdevelopment. China, Korea and Japan also have expressed interest in working with NOAA during the International Polar Year.

The Arctic Research Program has purposely designed observation programs to be interdisciplinary in scope to identify interactions between physical, chemical and biological processes that affect climate variability. The Arctic Research Program helps to facilitate interactions between modelers and observationalists to improve the ability to forecast weather and climate in the Arctic and the global environment.

To carry out its goals, the NOAA Arctic Research Program, COA,works with other NOAA groups, (NMFS, PMEL, ESRL), other U.S. agencies, such as NSF, and DOI, cooperative institutes at Woods Hole, University of Washington, University of Colorado, and the University of Alaska, Fairbanks. Numerous investigators have been funded to carry out the climate objectives of the Arctic Research Program (from the University of Alaska, the University of Washington, the University of Tennessee, the Smithsonian Institution, Woods Hole Oceanographic Institution and Pt. Stephens Research). Both the Bering Strait mooring nettwork an d the Tiksi Observatory are co-funded by the National Science Foundation

Arctic: A Friend Acting Strangely is an exhibit funded in part by the Arctic Research Program of NOAA. The exhibit opened in April 2006 and will run until the end of November, 2006. http://www.mnh.si.edu/exhibits/arctic/

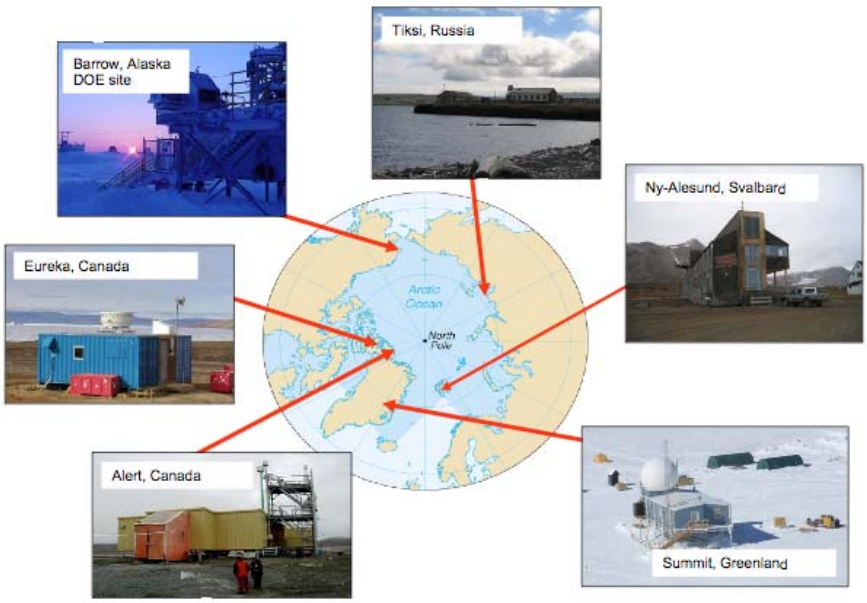
2006 Achievements

1. Grand Opening of SEARCH Observatory in Eureka, Canada

The NOAA Earth System Research Laboratory (ESRL), in conjunction with the Canadian Network for Detection of Arctic Change (CANDAC) program, and the

Meteorological Service of Canada, co-hosted a grand opening of a research site located in Eureka, Nunavut on Ellesmere Island; one of the most northerly research stations in Canada. On July 24, 2006 scientists, government representatives, and media from Canada and the U.S. attended official activities and had the opportunity to visit an observatory established through the NOAA Atmospheric Observatory Program, funded through the Arctic Research Program, Canada's Polar Environment Atmospheric Research Laboratory (PEARL), the newly rebuilt meteorological Services Canada weather station, and experience the surroundings and wildlife of this remote region of Canada.

The NOAA observatory is operated in Canada's High Arctic by the NOAA Arctic Research Program through ESRL as a contribution to the U.S. Studies of Environmental Arctic Change (SEARCH) program. The observatory was established in August 2005 by the ESRL Physical Sciences Division and ESRL Global Monitoring Division in collaboration with the University of Wisconsin, the University of Idaho, and the CANDAC program.

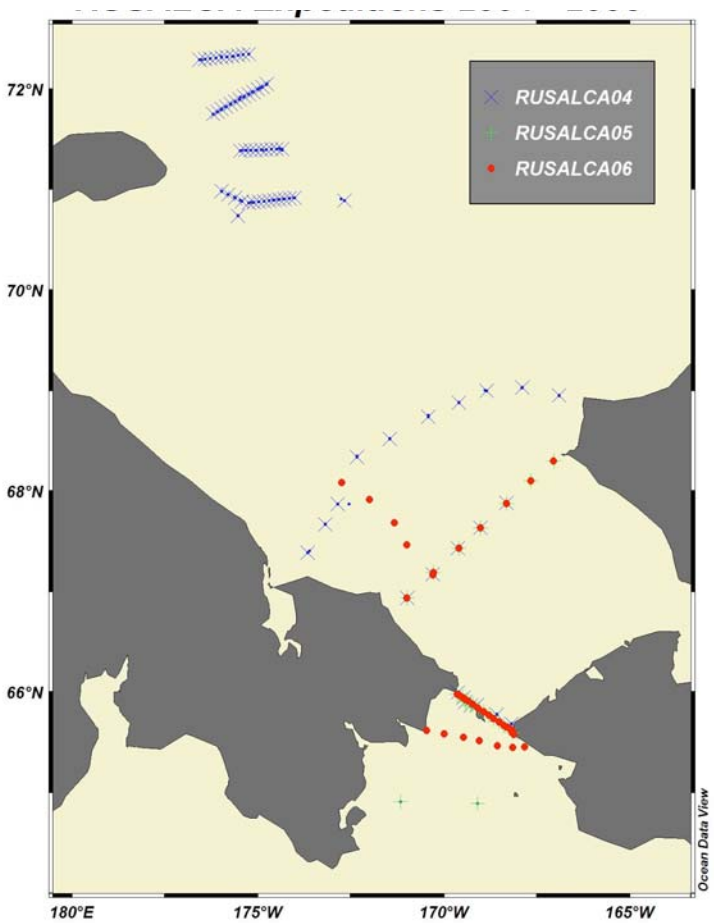


It was designed to make long-term climate measurements of Arctic clouds and aerosols. A collection of state-of-the-art scientific measurement equipment has been assembled at the site, including cloud radar, high spectral resolution lidar and spectral and narrow-band radiometers.

NOAA-SEARCH seeks to establish a number of intensive measurements that can be compared between Arctic regions. The emphasis of these activities will be on

determining attribution and developing databases and information that can be used for mitigation and adaptation strategies not only in the Arctic, but throughout the global climate system which is inextricably linked to Arctic changes. International cooperation and collaboration, as in this case with Canada, is a crucial component in successful and comprehensive global climate research. These activities support NOAA's mission goal of understanding climate variability and change to enhance society's ability to plan and respond.

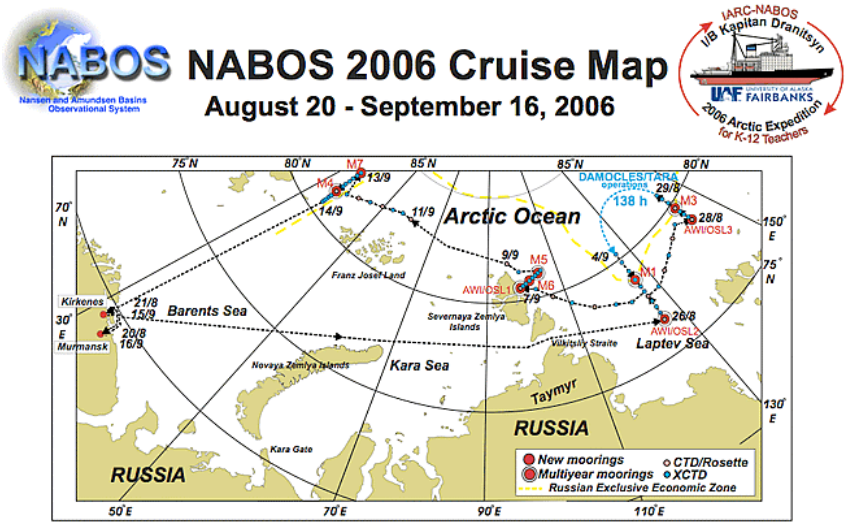
Implementation plans are developing for a state of the art climate observatory in Tiksi, Russia. The Program of Activities includes cooperation within the framework of the IPY,. This station has a long, although interrupted, history of earth science measurements, some of which date back to 1935, one of the longest in the Arctic. It will be a significant node in the GEOSS system, as it will become an interdisciplinary observation site for atmospheric, coastal, oceanographic, hydrological, terrestrial and biological observations. NSF, NOAA and Roshydromet are one year into the planning and creation of this Observatory. NOAA (Arctic Research Program) has made plans to begin operational measurements, which will support of the Climate Reference Network (CRN), WMO Global Atmospheric Watch (GAW), WMO Baseline Surface Radiation Network (BSRN), carbon cycle gases, and ozone. Finland and Norway are also partnering with the U.S. and Russia to support this Observatory.
Contact: Taneil Uttal, ESRL

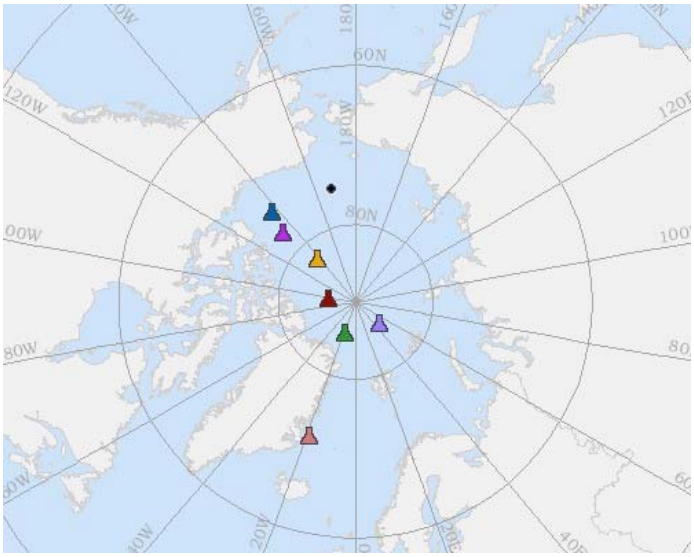


2. The ***RUSALCA*** program continued to reap benefits from the Russian-American collaboration in monitoring the fluxes through the Pacific Gateway into the Arctic Ocean Three moorings were deployed during the summer of 2005 and recovered during the summer of 2006 using the Russian hydrological vessel, SEVER. This is the first data of this type collected in the Russian waters of the Bering Strait since the 1990's. The U.S. section of the Bering Strait mooring line is also facilitated by the National Science Foundation. The combined mooring data provide a first time look at

the critical fluxes and changes occurring across and through the Bering Strait.

3. The Arctic Research Program also managed an earmark to the International Arctic Research Center for the NABOS program. Moorings launched via the NABOS program are included in the ARP's overall contribution to the U.S. 100 % Arctic Ocean Observing System (Arctic Observation Network). Five moorings along the Russian continental shelf were both recovered and redeployed during the 2006 NABOS expedition on the Russian icebreaker Kapitan Dranitsyn. With partners from Russia, Norway, Germany, Sweden, USA, and Canada the analysis of mooring-based records and oceanographic surveys have provided evidence that the Arctic Ocean had entered a new warm state, with potential implications for the melting of arctic ice. NABOS is co-funded by NOAA and NSF in the United States.





4. A three year summary of ***ice mass balance buoys*** data is being prepared. Current ice mass balance buoy and mooring positions as of September 17, 2006 are illustrated below.

5. ***Program data and information*** were made available through the Arctic Theme Page, Change Detection Website, publications, presentations at conferences and through an exhibition developed with NOAA funding and guidance at the Smithsonian Institution's Museum of Natural History "Arctic: A Friend Acting Strangely". http://www.mnh.si.edu/exhibits/arctic/

The exhibit ran at the museum until the end of November, 2006. Plans are developing for a traveling exhibit to other science centers across the country. The Arctic: A Friend Acting Strangely exhibit is part of the Forces of Change Program at the National Museum

of Natural History. The exhibit explored changes that have been observed in the Arctic, the Earth's northernmost region, and how they are monitored by scientists and polar residents. Native peoples of the Arctic have always lived with year-to-year fluctuations in weather and ice conditions. In recent decades, they have witnessed that the climate has become unpredictable, the land and sea unfamiliar. An elder in Arctic Canada recently described the weather as uggianaqtuq—an Inuit word that can suggest strange, unexpected behavior, sometimes described as that of "a friend acting strangely."

The Arctic: A Friend Acting Strangely exhibit was made possible by a grant from the National Oceanic and Atmospheric Administration (NOAA)'s Arctic Research Office. Additional support and funding were provided by the Department of Energy, the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF). Dr. John A. Calder and Dr. Kathleen Crane, NOAA Arctic Program Managers, Dr. Richard W. Spinrad, Assistant Administrator, NOAA Research, and scientists Drs. Richard Rosen, James Overland and Mark Serezze reviewed the script.

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09. Product Delivery, Analysis/Reanalysis:

a. A Web Site for NCEP's Global Ocean Data Assimilation System: Data Link, Model Validation and Ocean Monitoring Products
b. In Situ and Satellite Sea Surface Temperature (SST) Analyses
c. Investigating some practical implications of uncertainty in observed SSTs
d. Development of Global Heat and Freshwater Anomaly Analyses
e. Preparation of Ocean Heat and Freshwater Content Variability Estimates
f. Evaluating the Ocean Observing System: Performance Measurement for Heat Storage
g. A fifty-year analysis of global ocean surface heat flux to improve the understanding of the role of the ocean in climate
h. Climate Variability in Ocean Surface Turbulent Fluxes
i. Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses
j. Evaluating the Ocean Observing System: Surface Currents
k. Quarterly reports on the state of the ocean: Meridional heat transport variability in the Atlantic Ocean
l. National Water Level Program Support Towards Building a Sustained Ocean Observing System for Climate.
m. Satellite Altimetry
n. Reconstruction of Past Sea Level Change from a Combination ofSatellite Altimeter and Tide Gauge Measurements
o. Global Carbon Data Management and Synthesis Project
p. Determination of the information content in long-occupied Voluntary Observing Ship (VOS) Expendable Bathythermograph (XBT) transects
q. Arctic Ice Thickness: State of the Arctic Report
r. Observing System Research Studies
s. Simulation of the ARGO Observing System

A Web Site for NCEP's Global Ocean Data Assimilation System: Data Link, Model Validation and Ocean Monitoring Products

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Project Summary:

The project is to build a web site for the Global Ocean Data Assimilation System (GODAS) developed by the National Centers for Environmental Prediction (NCEP). The project is aimed to fill in the gap in the delivery of ocean analyses as an end product of ocean observation systems. The Environmental Modeling Center of NCEP produced a global ocean reanalysis for 1979-present using GODAS, and made it available to the general public. The Climate Prediction Center of NCEP is in charge of building a web site for GODAS products that serves user communities. The content of the web site is expected to grow in order to satisfy the needs of user communities. Currently, the web site includes data link, model validation and ocean monitoring products.

Background:

One of the main objectives of the in situ network managed by the NOAA's Office of Climate Observation (OCO) is to provide ocean observations to increase our understanding of the dynamics of the seasonal to interannual (SI) variability, and to improve its forecast skill. This has been largely done through a delivery of ocean analysis as an end product of ocean observations. Since 1995, the National Centers for Environmental Prediction (NCEP) has been producing ocean reanalysis for the Pacific Ocean by assimilating observations into an ocean model forced by atmospheric fluxes (Ji et al. 1995). The assimilated observations include temperature profiles from XBT, profiling floats and TAO moorings. The Pacific Ocean reanalysis (referred as RA6 hereafter) has been used to initialize the oceanic component of the NCEP's coupled atmosphere-ocean general circulation model, and has been shown to improve the forecast skill of the SI variability (Behringer et al. 1998). In 2003, a Global Ocean Data Assimilation System (GODAS) was developed that uses the Geophysical Fluid Dynamics Laboratory's (GFDL) Modular Ocean Model version 3 forced with the atmospheric fluxes from the NCEP's Reanalysis 2, and assimilates not only temperature but also synthetic salinity constructed with local temperature-salinity climatology (Behringer and Xue 2004; Behringer and Xue 2007). A retrospective global ocean reanalysis for 1979-2005 has been used to initialize the oceanic component of the new NCEP's Climate Forecast System, which has competitive seasonal forecast skills for ENSO and U.S. temperature and precipitation (Saha et a. 2006). The GODAS produces both pentad and monthly oceanic fields in real time, and is a unique dataset to serve research, application, and operational communities.

To gain a broader dissemination of GODAS data products, and to increase research community's involvement in the assessment of GODAS and the effectiveness of the NOAA's ocean observing systems, OCO sponsors the CPC to construct a comprehensive web site to display the rich information in GODAS. The web site contains numerous images that describe not only the SI variability but also the subseasonal variability. Since the goal of the web site is to serve a broad user community that includes operational

forecast centers, scientific research groups, and the general public, we solicit feedbacks from all users, answer their questions in a timely manner, and improve the web site according to the needs of user communities.

Website: http://www.cpc.ncep.noaa.gov/products/GODAS/

Parternership:

This project has been coordinated with the generation of the GODAS data sets by the Environmental Modeling Center of NCEP. We also work with the expert team of OCO to validate model fields against in situ observations.

Accomplishments:

1. Correcting the warm biases in GODAS prior to 1990

We pointed out in our last year report that there was a warm bias in GODAS prior to 1990. It turned out that the warm biases before 1990 were due to a bug in the program that processes the XBT data for the years prior to 1990. After correcting the error, a new GODAS data set was produced in early 2006. The impacts of the corrections are summarized below:

- Most of the changes are in 1979-1989 due to corrections of XBT profiles in that period.
- Average reductions of temperature in 1979-1989 are about 0.5-0.6 degree, distributed approximately evenly in depth.
- Average reductions of sea level are 1-2 cm in tropical Indian and Pacific, and 3-4 cm in western tropical Atlantic.
- Average reductions in depth of 20°C isotherm are as large as 18 meter in midlatitude, but only 1-2 meter in the tropics.
- Correlation with tide gauge observations is improved, and it is about 0.7-0.9 in tropical Pacific, equivalent or better than that of RA6, and 0.4-0.7 in tropical Indian and Atlantic Oceans (see Fig. 1).
- Although the discontinuity in 1989/1990 is largely removed, there are remaining downward trends in 1979-1990, probably due to the warm biases in the forward model (see Fig. 2).

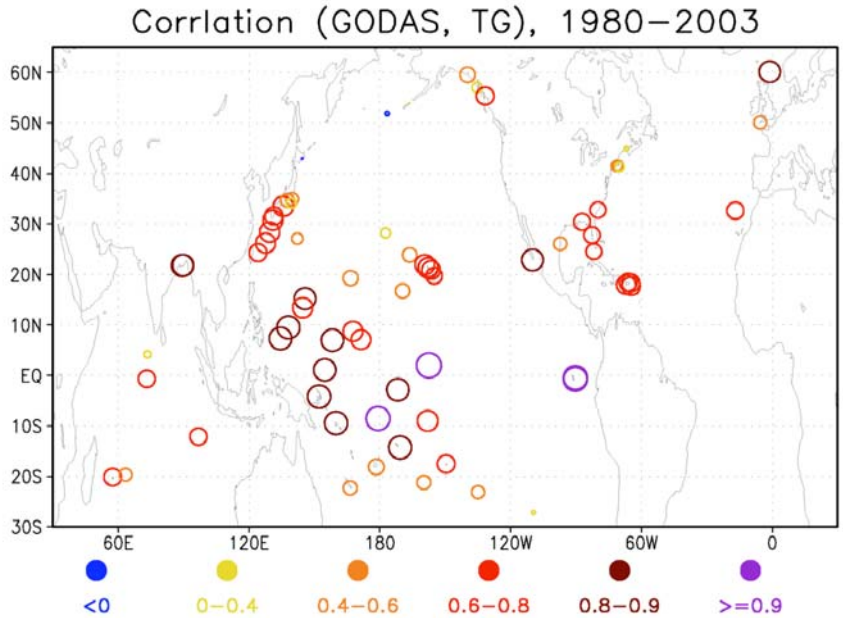

Fig. 1 Correlations between sea level deviations of GODAS and those of tide gauge observations are presented by circles, the sizes of which are proportional to the amplitudes of correlations. The number of years with valid data within 1980-2003 is required to be at least 15 years.

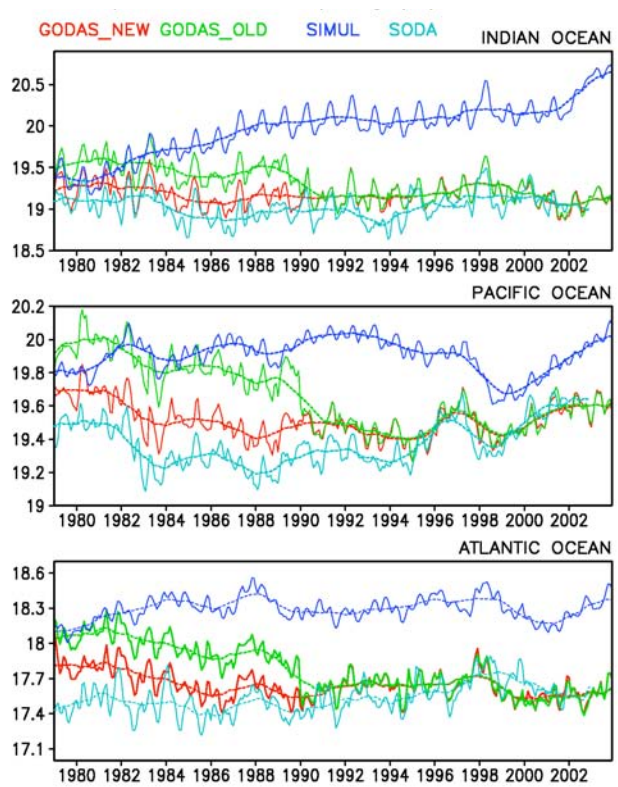

Fig. 2 Upper 300 meter temperature average in 5°S-5°N in the Indian Ocean (upper

panel), the Pacific Ocean (middle panel) and the Atlantic Ocean (lower panel). Monthly value (solid) and 25 month running mean (dash) of the new GODAS (red), the old GODAS (green), the Simple Ocean Data Assimilation System by University of Maryland (Cyan) and the simulation run in which no observations are assimilated (blue) are shown. Note that warm biases in the simulation run are large in all ocean basins. Although the warm biases of the old GODAS prior to 1990 are significant reduced, the new GODAS still has warm biases, relative to SODA, in 1980s and has a downward trend in 1979-1990.

2. Improved GODAS home page for ocean monitoring in real time

The GODAS home page has been modified significantly to best serve the user communities concerning real time monitoring and forecasting of climate variabilities such as ENSO and hurricane. This is done through an informative home page that contains cursor activated animations and plots documenting the current conditions of the ocean state (Fig. 3). The home page contains animations of pentad means for the past three months as well as plots of monthly means for the past 30 days. Because of the easy access to many plots and animations about the current conditions of the ocean state from the GODAS home page, the monthly visits to GODAS web increased from 133 in June 2006 to 582 in July, and slowly increase afterward. As October 2006, the total visits are 743, the total hits are 56077, and total downloaded data are 3.2 Gbytes (Fig. 4).

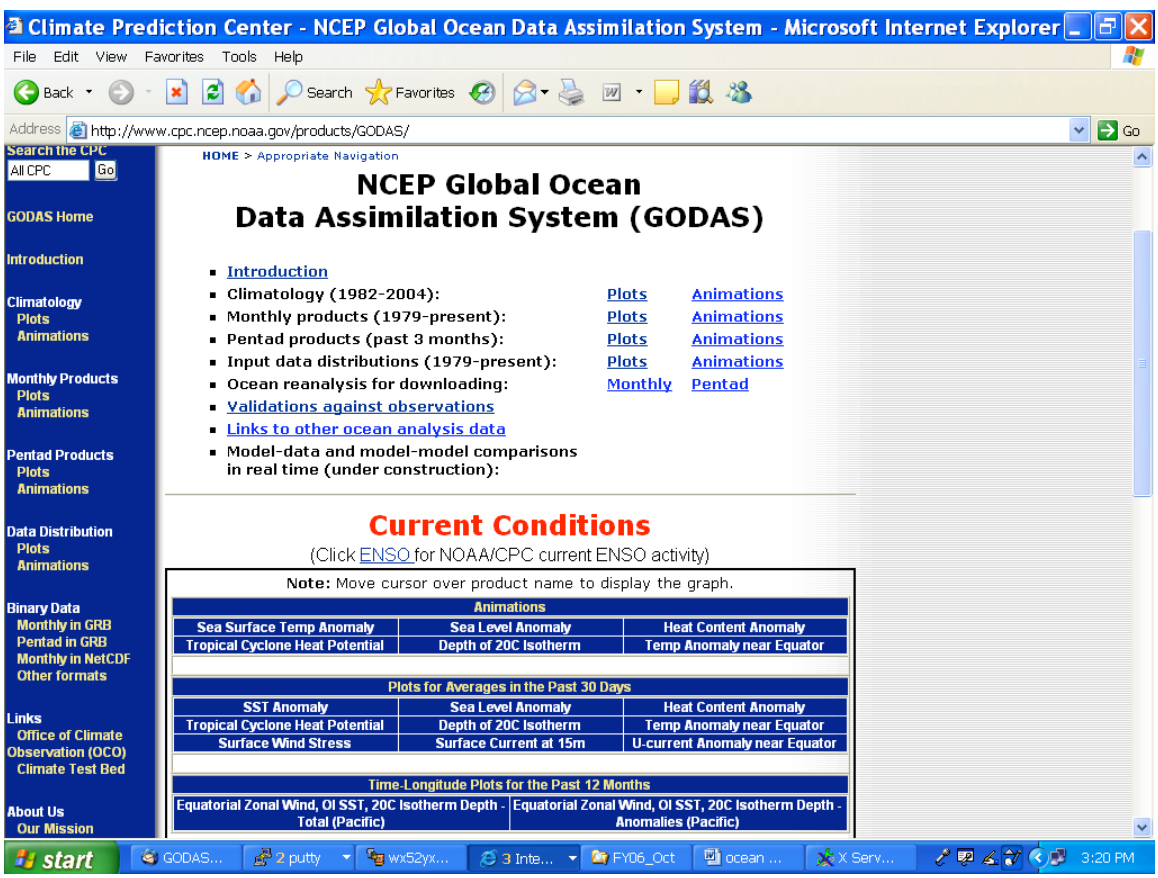

Fig. 3 The home page of the GODAS web site.

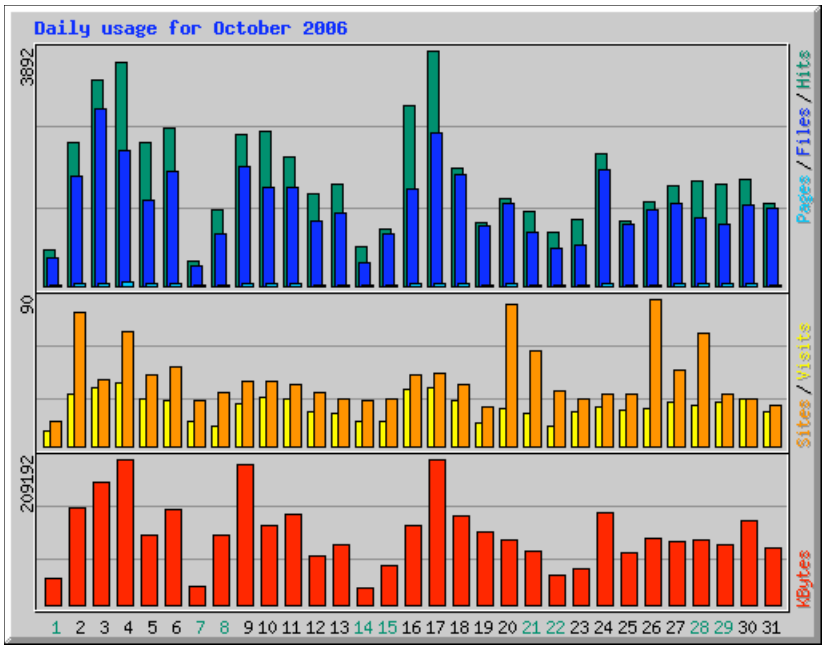

Fig. 4 Daily statistics for the GODAS web site.

3. Adding a subsection on model validation against observations

The quality of the GODAS ocean reanalysis has been evaluated against various independent data sets such as ocean currents from TAO moorings and drifter velocity program, CTD and ADCP data from cruises, tide gauges and altimetry sea level. It is found that the temperature field in GODAS is closer to observations than that in RA6. Although this version of GODAS does not assimilate satellite sea level as RA6 does, GODAS does as well as or better than RA6 in comparisons with altimetry and tide gauge sea level records. Despite of the improvement in the climatological salinity, GODAS seriously underestimates salinity variability. Similar to RA6, the equatorial currents contain large errors, which are suspected to be related to the errors in salinity. Those validation results are critical information for user communities to access the quality of the GODAS data set, but they are not well covered by our limited publications. So the validation results are presented through the web site (Fig. 5). It is worth noting that significant progresses have being made to overcome the defects in the operational GODAS by assimilating altimetry seal level and Argo salinity, and applying a multivariate constraint on geostrophic velocity since the operational GODAS was produced (Behringer, 2007). Those incremental improvements in GODAS will contribute to the future operational GODAS scheduled to be implemented in 2009.

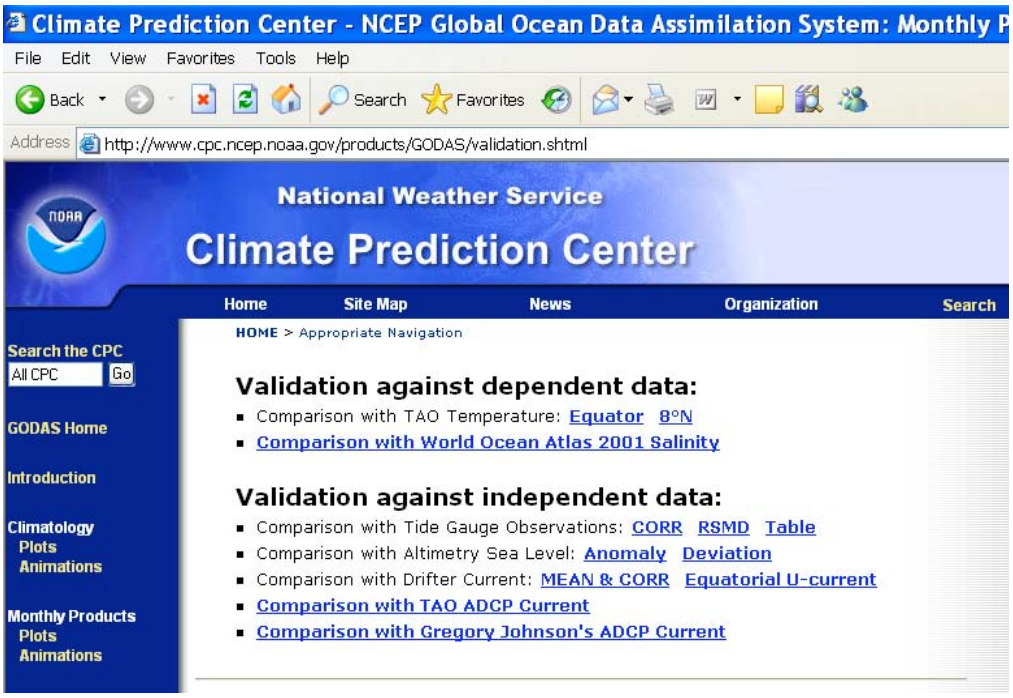

Fig. 5 The web page for model validation against observations.

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In Situ and Satellite Sea Surface Temperature (SST) Analyses

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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 as described by Reynolds et al. (2002) and Smith and Reynolds (2004). This effort is designed to support the development of an ocean climate observing system. The major effort has focused on the optimum interpolation (OI) analysis which includes a separate step to correct any large scale satellite biases relative to in situ (ship and buoy) data. A new version has been developed (Reynolds, et al., 2006), henceforth called the daily OI, which has improved the spatial grid resolution from 1° to 1/4° and the temporal resolution from weekly to daily. The daily OI was designed use multiple satellite data sets as well as in situ data. At present there are two version of the daily OI. 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 began in January 1985 and the AMSR+AVHRR product began in June 2002 when AMSR data became available. Both products include a large-scale adjustment of satellite biases with respect to the in situ data. Two products are needed because there is an increase in signal variance when AMSR became available due to its near all-weather coverage.

Additional efforts have been carried out to improve the Extended Reconstruction SST (ERSST) analysis of Smith and Reynolds (2004). This analysis presently uses in situ data and begins in 1854. The reconstructions were produced from two analyses. First the low frequency, or decadal-scale component, of the anomaly was analyzed using averaging and filtering of the available anomalies. The analyzed low frequency signal was subtracted from the anomalies and the residual high-frequency signal was analyzed. The high frequency analysis was performed by fitting the observed high frequency anomalies to a set of large-scale spatial-covariance modes. The new version is tuned using climate general circulation model (CGCM) output, which reduces the low frequency analysis damping. The effects of several other problems will also be corrected.

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° 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 Ten Climate Monitoring Principles.

2. FY 2006 PROGRESS

2.1 The Daily OI Analyses

During FY2006, two new products have been developed: the AVHRR-only daily OI from January 1985 to present and the AMSR+AVHRR daily OI from June 2002 to present. As described in Reynolds et al. (2006) both analyses use in situ data and use a new satellite bias correction based on empirical orthogonal teleconnections (EOT) functions (van Den Dool et al. 2000). Both products are presently available via FTP: (ftp://eclipse.ncdc.noaa.gov/pub/OI-daily/), TDS: (http://nomads.ncdc.noaa.gov:8085/thredds/catalog.html) and LAS: (http://nomads.ncdc.noaa.gov:8085/las/servlets/dataset). A web server is under development.

To evaluate the new daily OI analyses, the input data and the analyses were compared with each other and with other analyses. For this comparison, the weekly OI of Reynolds et al. (2002), henceforth referred to as the OI version 2 (OI.v2) was used. As mentioned above the OI.v2 uses AVHRR satellite data and in situ data and is performed weekly on a 1° spatial grid from November 1981 to present. An additional analysis was obtained from the National Center for Environmental Prediction daily Real Time Global SST (RTG_SST) analysis (Thiébaux et al., 2003). The RTG_SST analysis uses the same data used in the OI.v2. However, the RTG_SST is run daily beginning on 30 January 2001 on a 1/2° grid and uses smaller spatial error correlation scales than those used in the OI.v2.

Chelton and Wentz (2005) compared these two analyses with AVHRR and AMSR data with particular focus on 6 regions with strong SST fronts, including the Gulf Stream. The Gulf Stream gradients are presented in Fig. 1 following Chelton and Wentz with the addition of the two new daily OI analyses. The figure shows the magnitude of the 3-day mean Gulf Stream SST gradients centered on 1 October 2003. The AVHRR data panel shows high resolution details in cloud-free regions, although the coverage for AVHRR data is less than half of the possible number of ocean grid points. The AMSR data panel shows smoother details because of the coarser footprint but with the expected better coverage. The analyses fill in the missing AMSR and AVHRR data gaps with different smoothing. In particular, note the region of missing AMSR data due to precipitation contamination between 35°N and 45°N along 60°W. The OI.v2 is heavily smoothed as reported by Chelton and Wentz. The RTG_SST and AVHRR OI are similar, showing much more detail. Here the RTG_SST slightly smoother than the AVHRR OI. The best analysis resolution is shown by the AMSR+AVHRR analysis, which is similar to the AMSR data in most of the offshore regions. All statistical parameters in the daily OI are the same for both products. Thus, the improvement in the AMSR+AVHRR analysis is due to the better AMSR coverage.

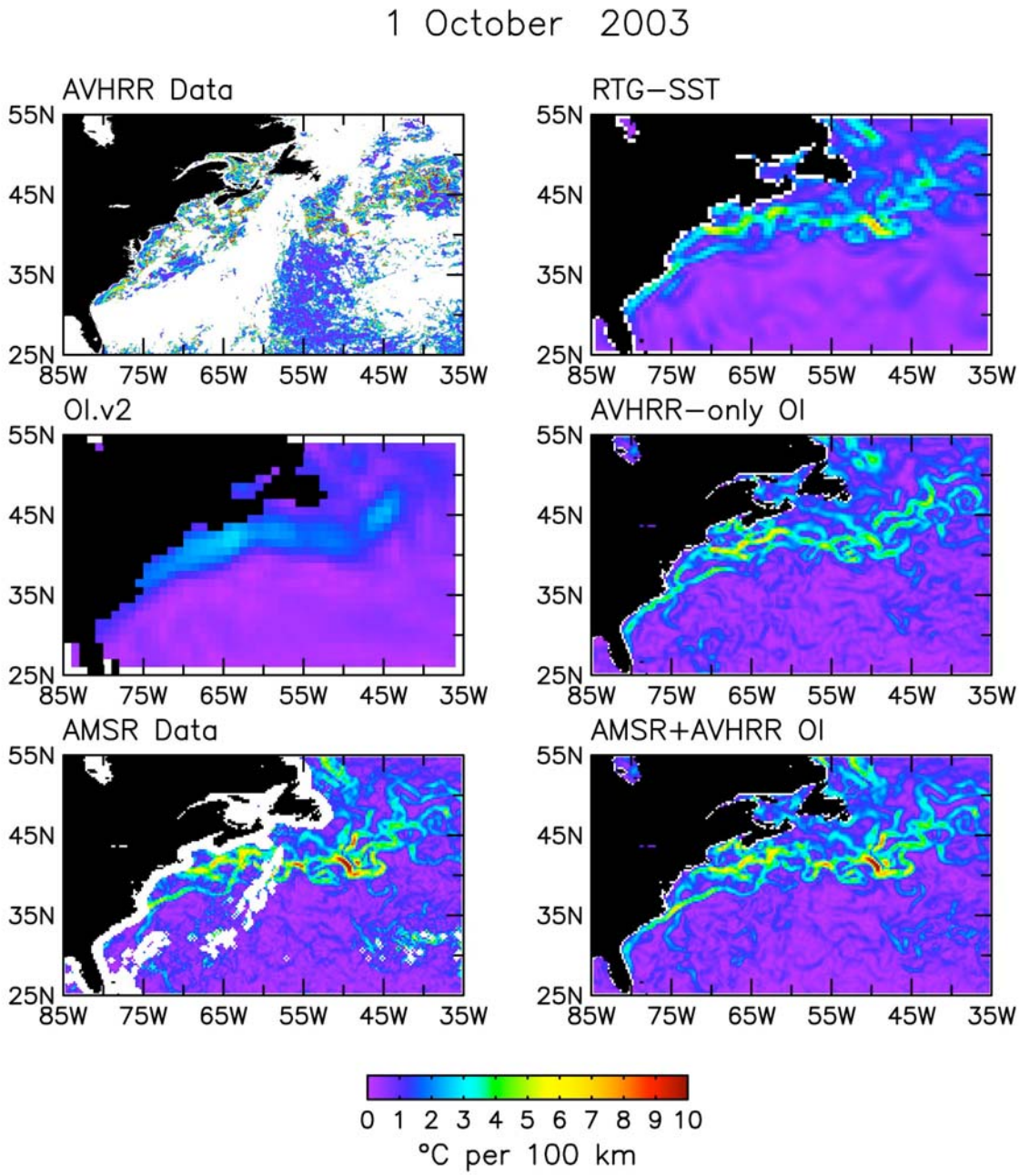

Figure 1. Three-day averages of SST gradient magnitudes for analyses and data centered on 1 October 2003 for the Gulf Stream region. The data products are AVHRR and AMSR. The analyses are: OI.v2, RTG_SST and the daily OI for AVHRR-only and AMSR+AVHRR.

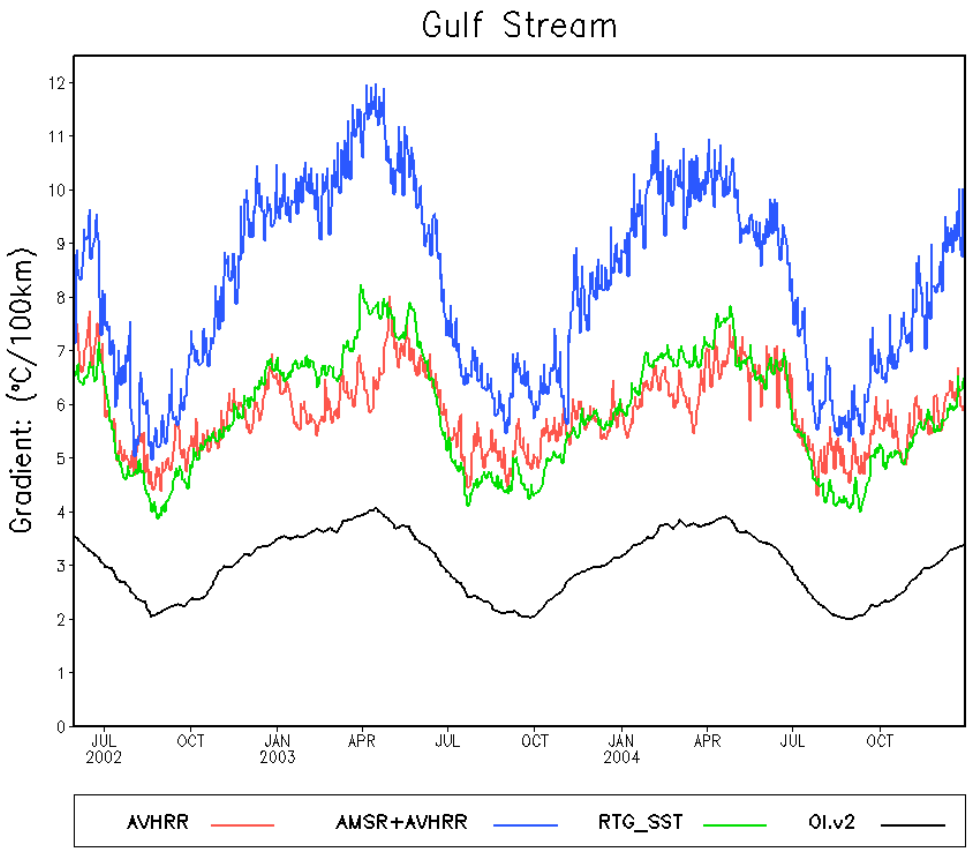

Figure 2. Analysis SST gradient index (see text) for the Gulf Stream region for 1 June 2002 - 31 December 2004. The analyses are the OI.v2, the RTG_SST and the daily OI using AVHRR-only and AMSR+AVHRR.

To better examine the gradients over time, gradient indices were computed. The index for the Gulf Stream was computed from the daily magnitude of the SST gradients from June 2002 through December 2004 for daily OI runs: AVHRR-only and AMSR+AVHRR and for the OI.v2 and RTG_SST analyses. For the Gulf Stream the maximum gradient value was determined along lines of longitudes from 70°W - 40°W between 35°N and 50°N ; these maximum values were then averaged over longitude. The daily index is shown for the Gulf Stream in Fig. 2. The results show that the OI.v2 index is much lower than the others as expected from Fig. 1. Also as expected, the AVHRR-only and the RTG_SST indices are generally quite similar. Perhaps the most interesting difference occurs between the AVHRR-only and AMSR+AVHRR gradient indices. These indices are similar in August and September with the AMSR+AVHRR gradient index only slightly stronger. The differences gradually increase from September to roughly March and then decrease again to the August minimums. In winter the AMSR+AVHRR gradient index is almost double the AVHRR-only index. The results show that the seasonal cycle of the index is under represented by AVHRR alone, because cloud cover tends to be more pervasive in winter. Indices for the Kuroshio region (not shown) show a similar seasonal cycle although both the average and seasonal amplitude are weaker. The Kuroshio index is again stronger for the AMSR+AVHRR product in winter because of reduced AVHRR coverage due to cloud cover.

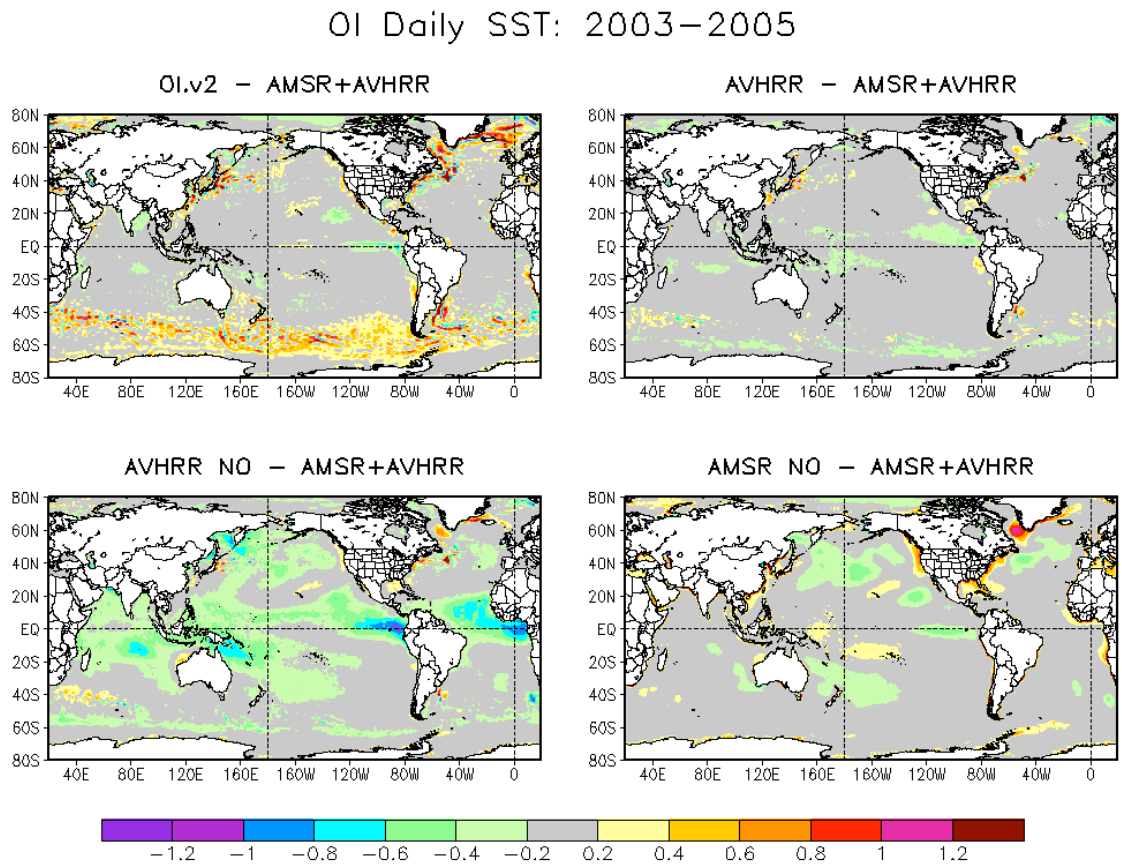

Figure 3. Average analysis differences for 2003-2005 with respect to the daily OI AMSR+AVHRR with bias correction. The analyses compared with bias correction are the AVHRR-only daily OI and the OI.v2 (top row). The analyses without bias correction are the AVHRR-only and the AMSR+AVHRR daily OI (bottom row). "No" in the title indicates no bias correction.

The large-scale biases for the January 2003 - December 2005 period are now examined where the AMSR+AVHRR daily OI analysis is used as a reference. Two special AVHRR-only and AMSR+AVHRR daily OI analyses were made without satellite bias correction. The average difference with respect to the AMSR+AVHRR was computed for this period for the OI.v2, the AVHRR-only daily OI (with and without bias correction) and the AMSR+AVHRR daily OI without bias correction. For this comparison the OI.v2 was linearly interpolated to the daily OI grid. The average difference is shown in Fig. 3 where "NO" indicates an analysis without bias correction. The OI.v2 (top left in Fig. 3) shows that the biggest difference with respect to the AMSR+AVHRR daily OI occurs between 60°S and 40°S, with largest values in the Pacific east of the dateline. This is the region with sparse in situ data and thus, the true bias is not well known. Many of the other differences in the western boundary current regions (e.g., in the Gulf Stream and Kuroshio) and the eastern Pacific equatorial region are due to the increased resolution of the daily OI. The AVHRR-only OI with bias correction (top right) shows some residual biases with respect to the AMSR+AVHRR daily OI primarily along the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone, SPCZ), a reminder that

residual biases can survive the bias correction step if the biases persist. The bottom row of Fig. 3 shows the biases in the OI analyses without satellite bias correction. The AVHRR-only OI analysis without bias correction (bottom left) shows the largest biases with respect to the AMSR+AVHRR analysis with bias correction. The biases are especially evident tropical oceans. Comparison with the AVHRR-only OI analysis with bias correction (top right) shows the necessity of the bias correction. The AMSR+AVHRR OI analysis without bias correction (bottom right) with respect to the AMSR+AVHRR analysis with bias correction shows smaller long-term biases although some biases remain.

2.2 The Historic ERSST Analysis

The monthly ERSST analysis initially used a low frequency analysis on a 15-year period to begin the analysis. The reconstructions were designed to analyze signals supported by the historical sampling, with damping of anomalies when sampling was insufficient to analyze the climate-scale signal. Deciding how much sampling was sufficient was based on the data themselves and on estimates of spatial and temporal scales of the low frequency components. In the Smith and Reynolds (2004) these decisions were conservative, to ensure that data noise would not contaminate the analysis in sparse-sampling periods. A disadvantage of such conservative decisions is that they may lead to overly damped analyzed anomalies early in the historical record.

To evaluate these decisions, simulated SST anomaly data from the Geophysical Fluid Dynamics Laboratory (GFDL) Climate Model 2.1 (CM2.1) were used. The low frequency analysis was tuned by use of different parameters. The test analyses were computed using the data with simulated random errors and data gaps determined from the observations. They were compared to a full analysis, computed using data with no random error and no data gaps. Tuning was done to minimize the mean-squared error of the test analyses relative to the full analysis.

The influence of changing these parameters is shown in the merged low frequency average between 60°S and 60°N in Fig. 4. In the figure, "Full" indicates the fully sampled data. After about 1930 there is little damping with respect to the "Full" analysis in any of the estimates computed using historical sampling. In the earlier period, most damping occurs using the default parameter settings, labeled “Old”. The damping is greatly reduced using the new tuned parameters, labeled “New”. With the improved tuning there is little damping after about 1875, but before that year there is still damping due to sparse sampling. In the next version of ERSST the “New” tuning parameters for the low frequency analysis will be used.

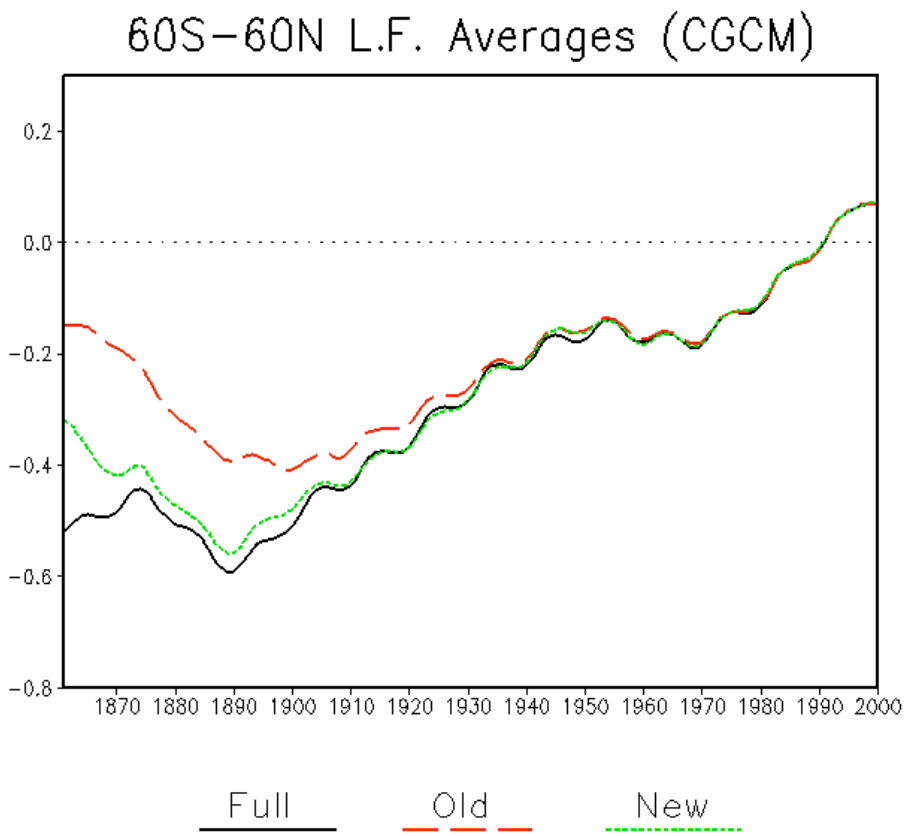

Figure 4. Low frequency analysis using the fully-sampled data (Full), and the historically sampled data using the operational parameter settings (Old), and the newly tuned settings (New). Random error is excluded from the Full data and included in the historically-sampled data used for the test Old and New analyses.

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°C as a worse case. Thus, the "potential satellite bias error" would be 2°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° 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. For more details see Zhang et al (2006).

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Copies of Zhang et al. (2006) and Reynolds et al. (2006) will be attached to this report.

Investigating some practical implications of uncertainty in observed SSTs

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Project Summary

The purpose of this task is to evaluate the impact of uncertainty in observed SSTs on seasonal-to-interannual prediction. One of the important goals of the Sustained Ocean Observing System for Climate is to improve the SST accuracy over the global ocean. The activities described here are intended to provide feedback to the climate observing community on the apparent impact of that improvement for seasonal climate simulations and predictions.

The activity under this task explores the implications of uncertain SSTs prescribed as boundary forcing in AGCM experiments: an AGCM is forced with 'scenarios' of observed SSTs for one El Niño, one La Niña and one neutral case during the JFM season. The scenarios differ from one another by the magnitude of imposed "error" over the global oceans. Additional integrations will consider only errors over Indian Ocean and Western Pacific region, where SST variability is believed to impact climate over the United States, in situ data is low, and remotely sensed data is more problematic. Changes in AGCM response are then examined, including magnitude, spatial structure and uncertainty, for near-surface climate and large-scale circulation.

FY 2006 Progress

Model integrations using global error fields have been completed. For each of the three ENSO states, two scenarios have been run: one in which the estimated sampling error field is added to the observed SSTs and one in which the error field is subtracted. The years chosen are: JFM 1983 (El Niño), 1986 (ENSO-neutral), and 1988 (La Niña).

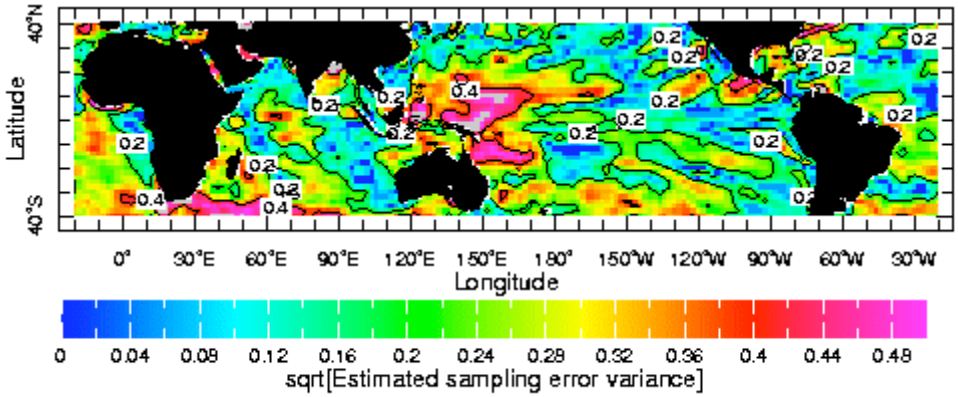
In all cases examined, the SST errors lead to a discernible modification of tropical precipitation anomalies (not shown), and often on extra-tropical anomalies also. The more noticeable impact is on global temperatures (not shown). In this first set of experiments, the error field is applied over the global ocean. Thus, it is difficult to discern how much of the temperature response is driven by errors in the tropics and how much due to fact that the global oceans are slightly cooler/warmer than "observed".

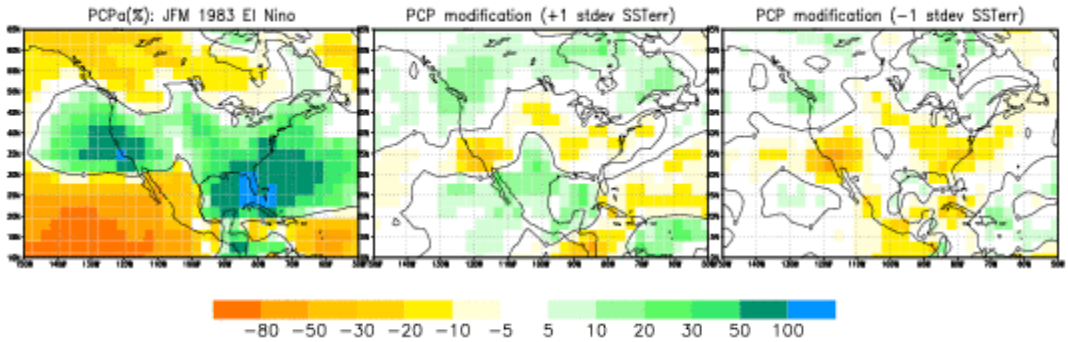
The attached figures focus on climate anomalies over the US, and indicate substantial modification of the simulated anomalies by the SST errors. In some cases, the temperature or precipitation modifications due to the 'error modified SST field' are of comparable magnitude to those forced by the 'true SST anomalies'. These differences due to uncertainties in the SSTs used to force the model have several implications for seasonal climate prediction. First, the added climate uncertainty confounds estimation of potential predictability of the climate. Second, if these SST uncertainties are not treated rigorously, the probabilistic calibration of models is

likely to be sub-optimal. Third, if the uncertainties are treated rigorously and the models calibrated accordingly the resulting seasonal probability distributions will be more diffuse than they would be with more precise estimates of the SST forcing. Finally, conclusions from diagnostic attribution exercises that estimate the causes regional climate variability will be somewhat degraded.

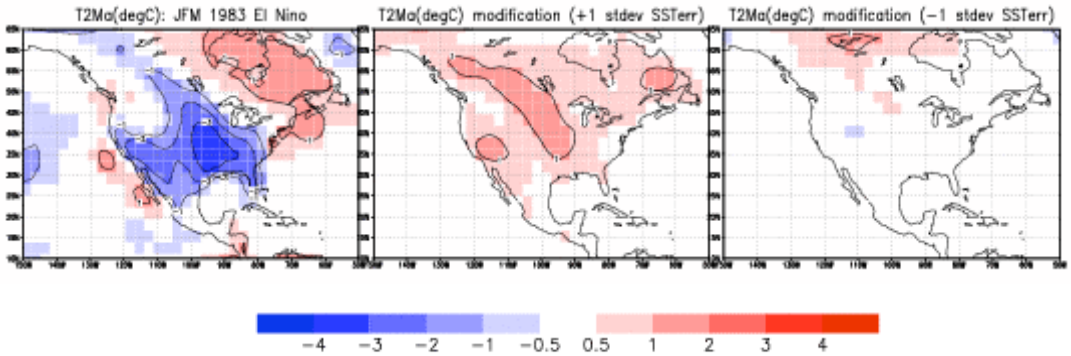
Additional model integrations isolating SST errors in the Western Pacific and Indian Oceans are currently underway. This will allow more explicit statements on the contribution of the observing array in those regions.

JFM 1983 (El Nino): Imposed SST error (i.e. positive)





Precipitation: % deviation from average

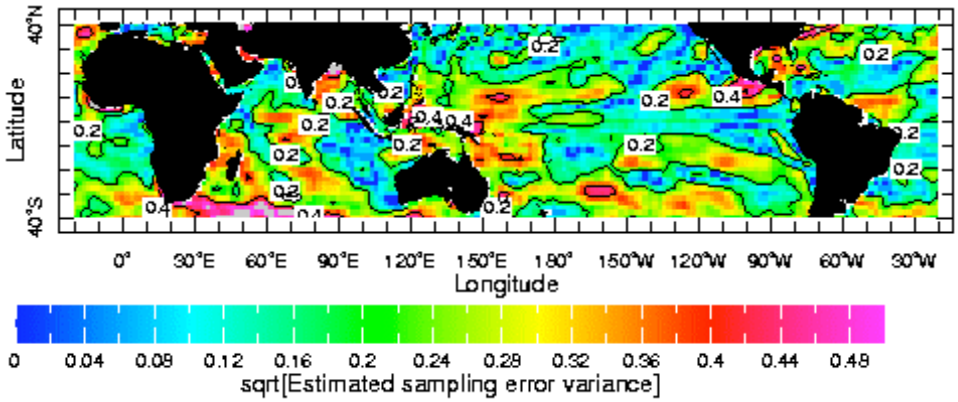


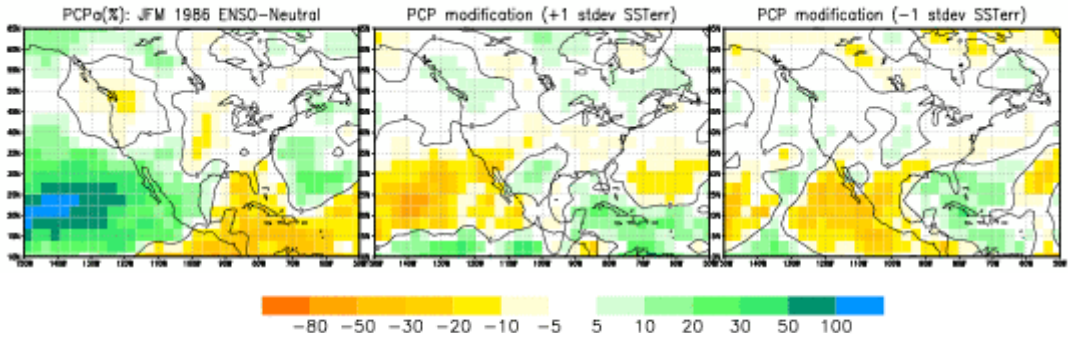
2m Temperature: Degrees C departure from average

Figure 1. Top panel: Square root of estimated sampling error variance in ERSSTv2 data for JFM 1983, during a strong El Niño. This field was added to/subtracted from the 'observed' monthly SST data and applied to the ECHAM4.5 AGCM.
Middle panel: Precipitation anomalies from control experiment, +1 error field experiment, and -1 error field experiment (going from left to right). Anomalies are plotted as % deviation from average, such that 0=average, 100%=2 x average, etc. The "modification panels" indicate additional anomaly, on top of that in left panel, due to imposed SST error.

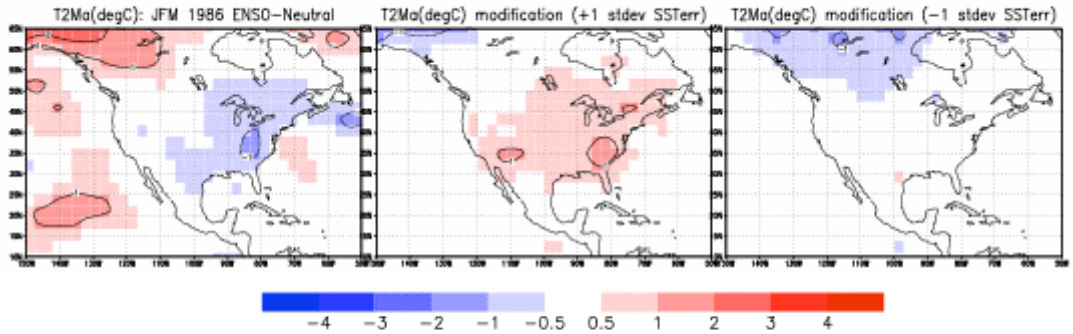
Bottom panel: Temperature anomalies (deg. C), panel layout similar to that for precipitation.

JFM 1986 (ENSO-Neutral): Imposed SST error (i.e. positive)





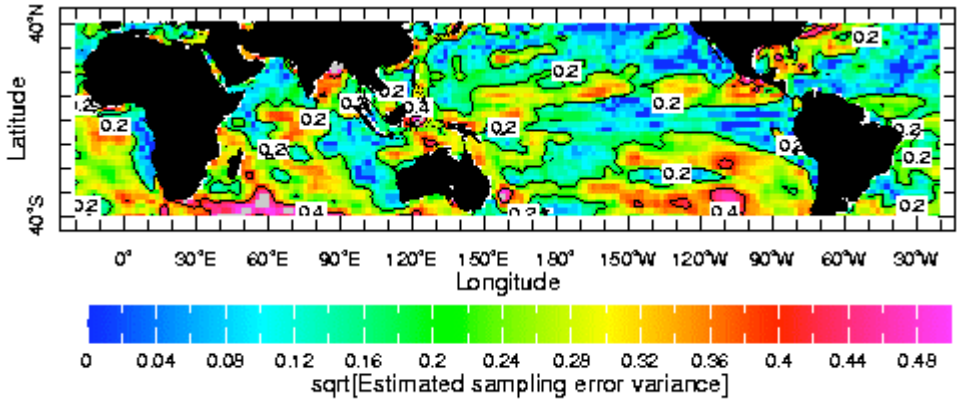
Precipitation: % deviation from average

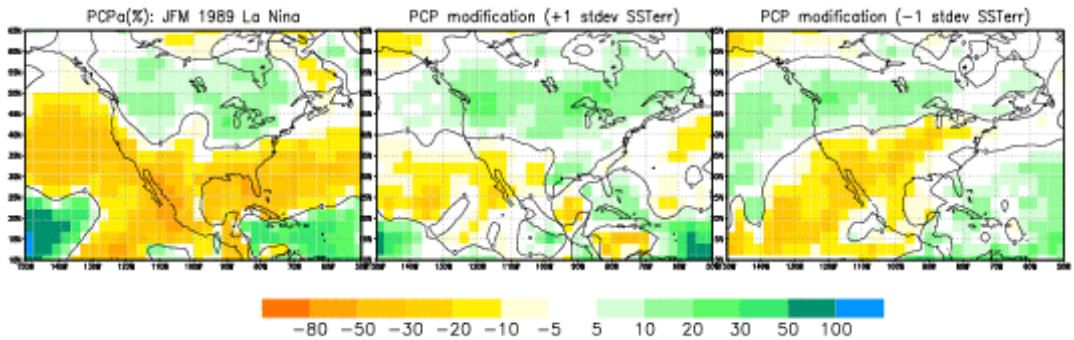


2m Temperature: Degrees C departure from average

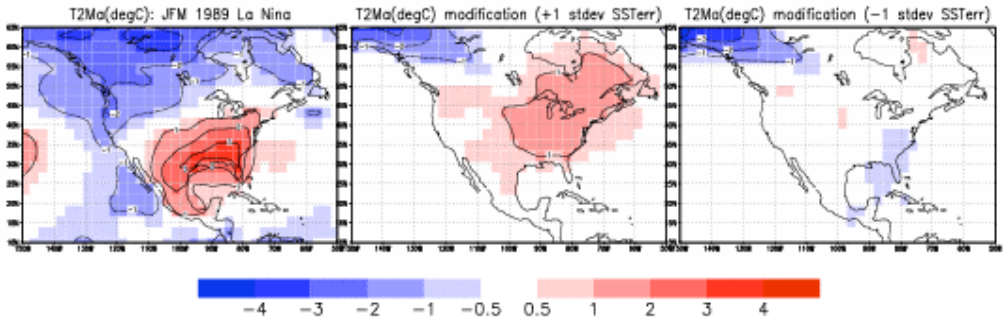
Figure 2. Similar to Figure 1, except for JFM 1986, during ENSO-neutral conditions.

JFM 1989 (La Nina): Imposed SST error (i.e. positive)





Precipitation: % deviation from average



2m Temperature: Degrees C departure from average

Figure 3. Similar to Figure 1, except for JFM 1989, during a strong La Niña.

Development of Global Heat and Freshwater Anomaly Analyses

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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 eXpendable Bathy Thermographs (XBTs), shipboard Conductivity-Temperature-Depth (CTD) measurements, CTD-equipped autonomous profiling floats (Argo), 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 can relatively sparse, especially before the advent of Argo. However, variations in ocean heat content are closely related to variations ocean 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 the 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, will help 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.

Project Accomplishments:

In FY2006 we have updated maps of annual upper (0-750 m) ocean heat content primarily for the ice-free portions of the globe from 1993 through 2005 in two manners. For one set of maps we used in situ temperature profile data alone the better to investigate large (basin) spatial scale and long (decadal) time-scale variability. For the other estimate we combined in-situ and satellite altimetric data (following Willis et al. 2004) to better resolve smaller (sub-gyre) scale spatial variability over shorter (year-to-year) time-scales.

Comparing the in situ data distribution for 2005 vs. 1994 (Figure 1 top panel) shows the effect of the growing Argo array, with over twice the number of data for 2005 compared with 1994, and a much more even geographical (and temporal) coverage in 2005 compared with 1994. Since the start of the Argo Program in 2000, the number of in situ observations has steadily ramped up (Figure 1 bottom panel). When the Argo array is at full strength, it alone should deliver about 100,000 temperature profiles per year.

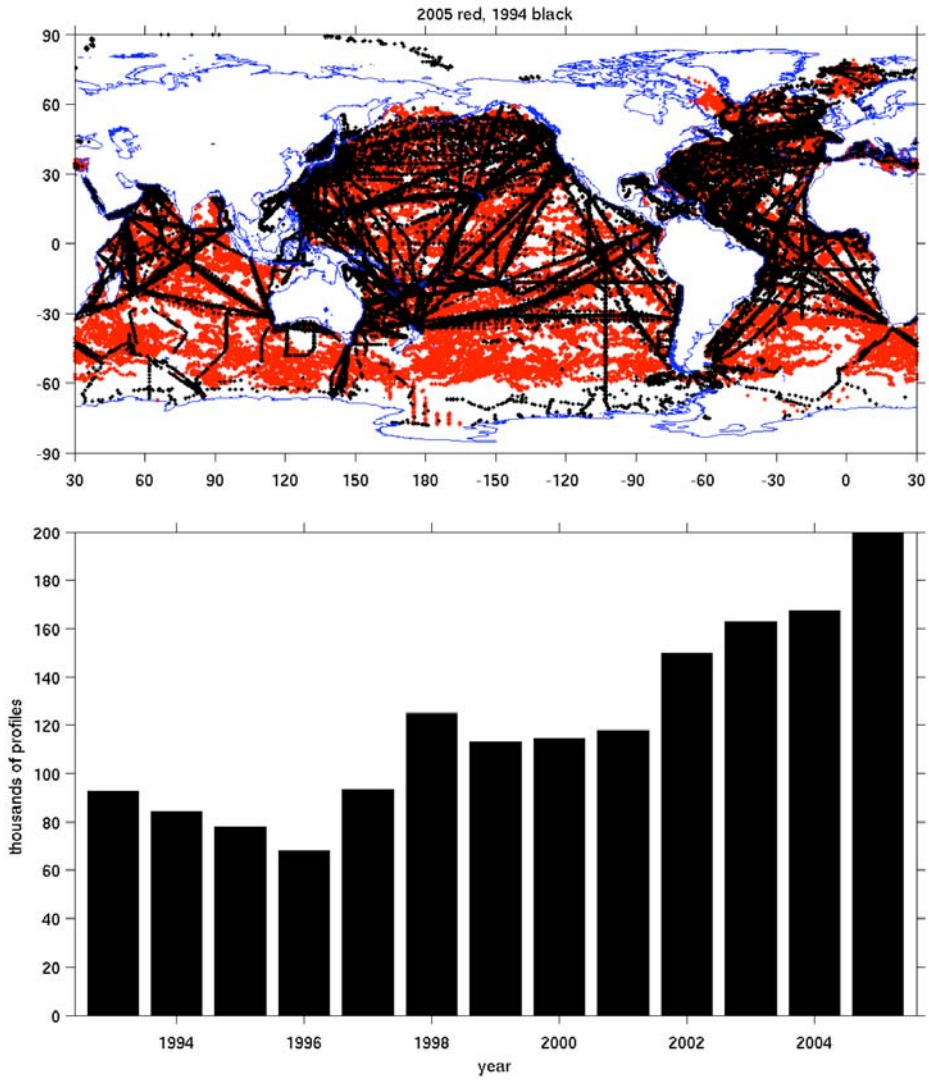

Figure 1. Location of in situ temperature profiles from 2005 (red dots) with 1994 profile locations (black dots) overlaid (top panel). Number of in situ temperature profiles per year (bottom panel).

The difference between 2004 and 2003 upper ocean heat storage (Figure 2, top panel) and that between 2005 and 2004 (Figure 2, bottom panel) demonstrate the large year-to-year variability in ocean heat storage, with changes reaching or exceeding the equivalent of a 80 W m^{-2} magnitude surface flux over a year in many places. Ocean

advection likely plays a large role in many of these changes. For instance, the increase in equatorial Pacific Ocean upper ocean heat content in 2004 compared to 2003, and then subsequent decrease in 2005 compared to 2004, is due to shifts in ocean currents (as well as air-sea heat flux changes) associated with El Niño. The large changes in both years associated with the western boundary currents and the Antarctic Circumpolar Current are likely partially due to advection as well.

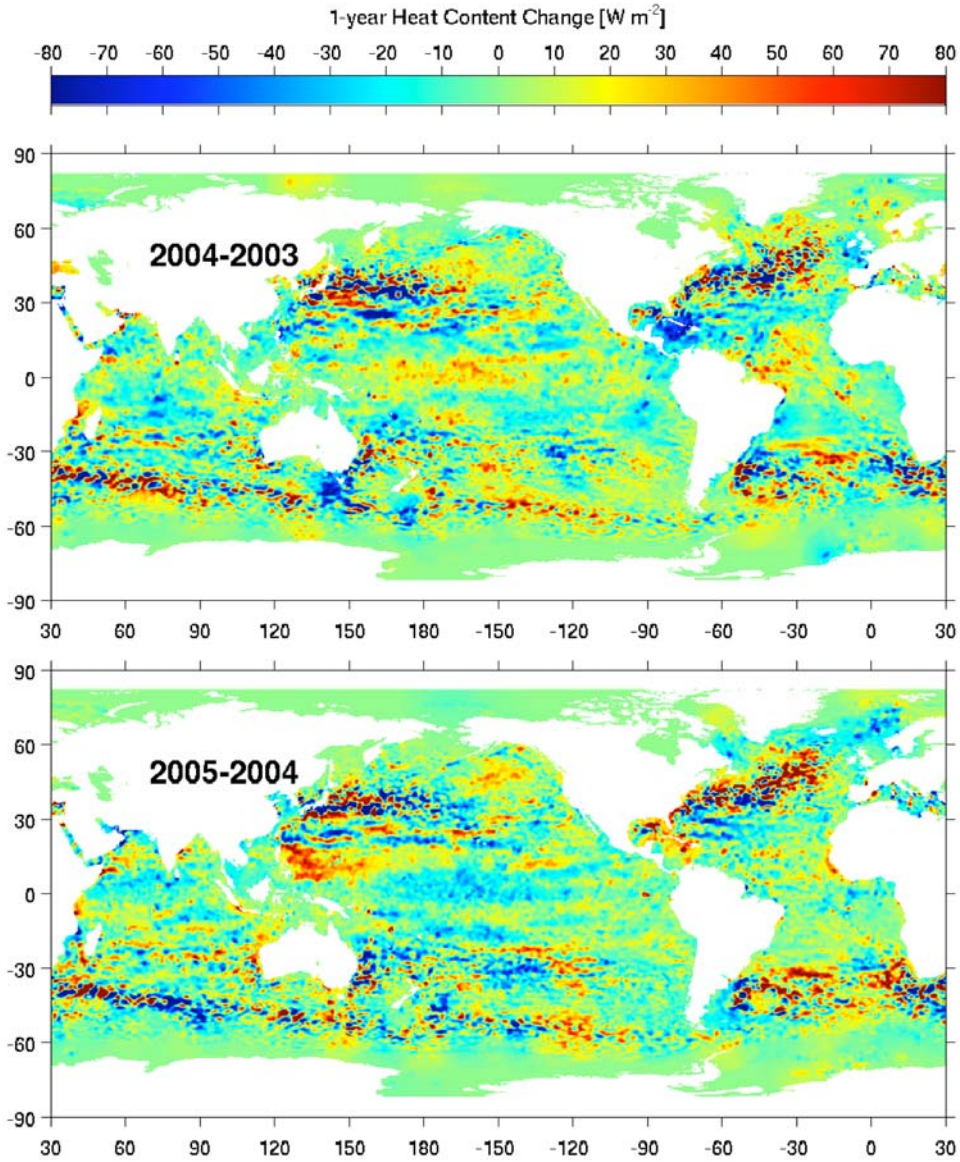

Figure 2. Upper (0 - 750 m) ocean heat content anomaly changes from the 1-year average for 2004 with that for 2003 subtracted (top panel) and from the 2005 average with that for 2004 subtracted (bottom panel) expressed as a surface flux [W m^{-2}] over the intervening years. Maps are made from the combination of in situ heat content anomalies and satellite altimeter data following Willis et al. (2004).

Local linear trends in upper ocean heat storage estimated over the entire 13-year period analyzed (Figure 3, top panel) generally have larger spatial scales but smaller amplitudes than the year-to-year changes. Examination of the ratio of the trend to the 95% uncertainty in the trend (Figure 3, bottom panel) shows that the trend is significant only in limited regions. The large positive values in the northern North Atlantic Ocean may be due in part to the mid 1990's shift in the North Atlantic Oscillation. The large negative values in the subpolar North Pacific may partly reflect changes in the Pacific Decadal Oscillation. The Southwest Pacific also contains significant positive values, including south of Australia, in the Tasman Sea, and east of New Zealand.

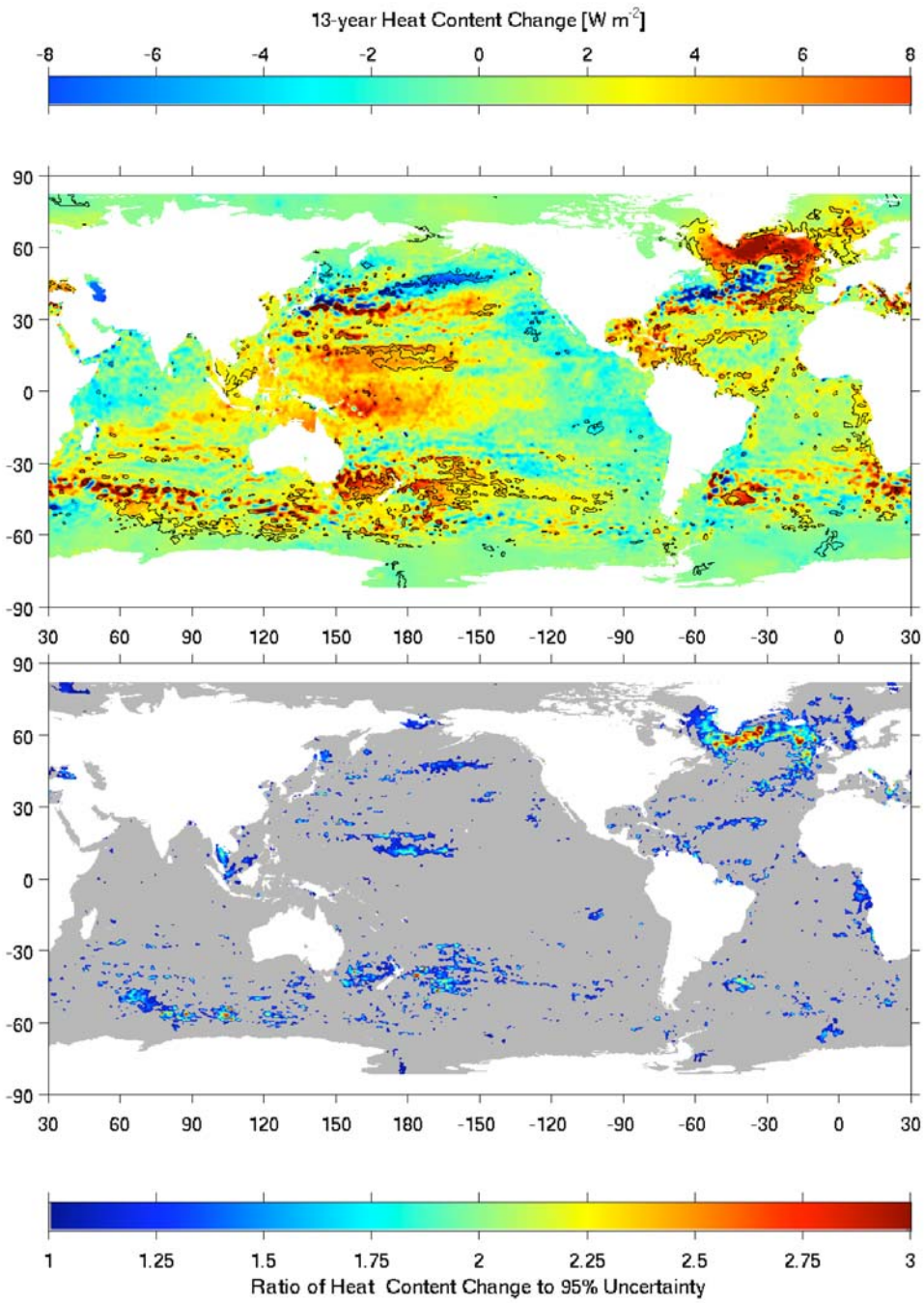

Figure 3. Linear estimates of upper (0 – 750 m) ocean heat content change from 1993 to 2005 (top panel) with areas of significant slope outlined in black as estimated by the ratio of these trends to their 95% uncertainty estimates (bottom panel, where colored regions are significantly different from zero but grey are not). Heat content estimates used here are based on a combination of in situ heat content anomalies and satellite altimeter data following Willis et al. (2004).

Globally integrated upper ocean annual heat content anomalies based on in situ data alone (Figure 4) yield an even smaller trend of 0.59 (±0.14) W m^{-2} (at the 95%

confidence level) over the analysis period. This number is expressed as a flux over the entire surface of the earth.

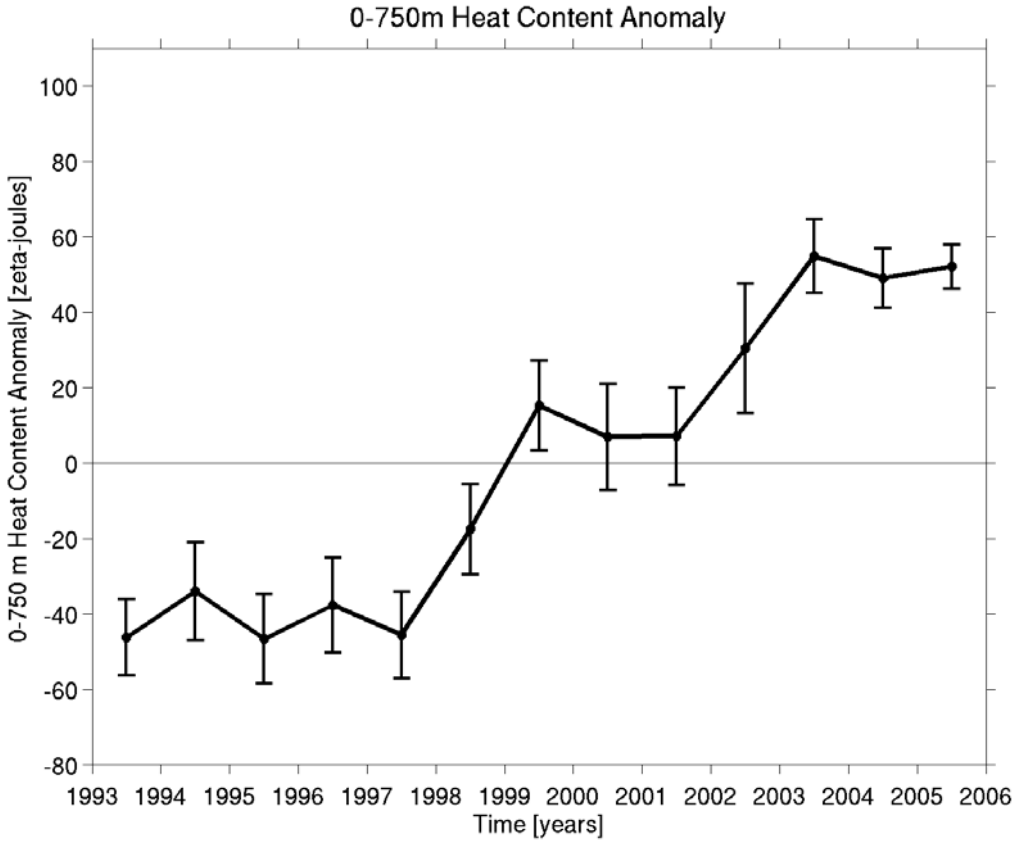

Figure 4. Globally averaged interannual heat content anomalies using maps from in situ data alone. Sampling standard errors are displayed (bars). Instrument biases could increase uncertainties over those shown here.

To quantify the effect of improved in situ ocean heat content measurements over time as the Argo array grows, we interpolated each year (from 1993 through 2005) of synthetic heat anomalies generated from the altimeter data following Willis et al., (2004) to the locations and time of year of in situ observation locations for a given year. We then used these interpolated values as fake "in situ" data to construct heat anomaly maps using the Willis et al. (2004) methodology from 1993 through 2005 and a given year's sampling pattern. For a given year's sampling pattern, we then compared each of the 13 mapped fields to the fully resolved synthetic fields. This yielded a variance from which an error estimate could be derived. We combined this error estimate with an appropriately scaled estimate of the RMS error in globally averaged sea level about a 1-year mean (0.2×10^{22} J) following Willis et al. (2004). We assume the two error sources are independent (Figure 5).

The sampling standard errors in Figure 4 vary significantly from year to year (Figure 5). Most notably, as the Argo array grew dramatically in from 2003 through 2005 with more widespread sampling than previous years (see. Figure 1), the sampling standard errors shrank significantly compared with the previous years (Figure 5). There may still be a lag of several years for in situ data to makes its way to the archives we are

using, in which case sampling standard errors for subsequent analyses that include additional in situ data will be further reduced.

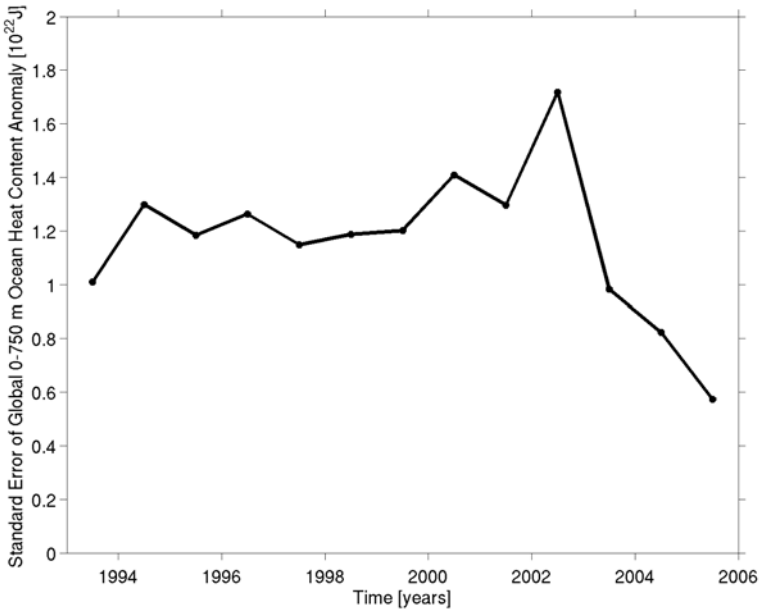

Figure 5. Sampling standard errors of global upper ocean heat content anomalies following Lyman et al. (2006).

Some of our analyses have been published in the Bulletin of the American Meteorological Society as part of the supplement "State of the Climate in 2005" report (Johnson et al., 2006). The global averaged in situ data based upper ocean heat content and error estimates were not ready for that report but were recently published elsewhere (Lyman et al. 2006). This paper generated significant scientific and media interest. In addition, we recently built project web page (http://oceans.pmel.noaa.gov/).

Revision Notes, 19 April 2007:

After this report was first submitted but before it went to press two instrument errors in the data used in ocean heat content estimates were discovered. These discoveries prompted revisions to Figures 2-4 and some of the text in this report. We have also just submitted a correction to Lyman et al. (2006) for publication as a result of these discoveries. One error is a large cold bias in a small fraction of Argo float data. Ascribing incorrect pressures to otherwise valid temperature and salinity data caused this error. The other error is a smaller but more prevalent warm bias in eXpendable BathyThermograph (XBT) data. This error may result from variations in fall rates and it may vary with time, manufacturer, and other variables. The erroneous Argo float data will eventually be corrected, but for now they have simply been removed from the analyses presented here. The XBT biases will require substantial investigation for optimal correction. For the results presented here a very preliminary ad-hoc time-independent reduction of the XBT depths by a factor of 0.985 after application of the

latest recommended fall rate corrections has been used to reduce temperature discrepancies between the XBT data and data from other sources (including floats).

FY2006 Publications and Reports:

Aagaard, K., T. J. Weingartner, S. L. Danielson, R. A. Woodgate, G. C. Johnson, and T. E. Whitledge. 2006. Some controls on flow and salinity in Bering Strait. *Geophysical Research Letters*, **33**, L19602, doi:10.1029/2006GL026612.

Johnson, G. C. 2006. Generation and initial evolution of a mode water θ-S anomaly. *Journal of Physical Oceanography*, **36**, 739-751.

Johnson, G. C., J. M. Lyman, and J. K. Willis, 2006: Global Oceans: Heat Content. *In* State of the Climate in 2005, K.A. Shein, Ed., *Bulletin of the American Meteorological Society*, **87**, *6*, S23-S24.

Johnson, G. C., J. M. Toole, and N. G. Larson, 2006. Sensor corrections for Sea-Bird SBE-41CP and SBE-41 CTDs. *Journal of Atmospheric and Oceanic Technology*, accepted.

Lyman, J. M., G. C. Johnson, and W. S. Kessler. 2006. Distinct 17-day and 33-day tropical instability waves in subsurface observations. *Journal of Physical Oceanography*, in press.

Lyman, J. M., J. K. Willis, and G. C. Johnson. 2006. Recent cooling of the upper ocean. *Geophysical Research Letters*, **33**, L18604, doi:10.1029/2006GL027033.

Preparation of Ocean Heat and Freshwater Content Variability Estimates

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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 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 ocean heat content has attracted considerable attention from the scientific community, Congress, and the media.

Our work has been used in published IPCC Assessments and will be used in the IPCC 2007 Assessment. Our work has also been used in an NRC Report to President Bush.

ACCOMPLISHMENTS FY2006

During FY05 the P.I. and his colleagues authored or co-authored several peer-reviewed papers that dealt with the climatological and interannual variability of heat content and salinity of the world ocean. In FY06 we have published *World Ocean Database 2005* and we are updating our ocean heat content estimates through the third quarter of 2006. Several publications are being worked on that will further document the temporal variability of the heat content of the world ocean and the variability of Salinity and freshwater. Figure 1 is an example of our most recent work and shows the time series of ocean content for the 0-700 m layer the world ocean through the end of the third quarter of 2006. After reaching a relative maximum in heat content during 2003, the world ocean cooled for two years and then begin warming through the third quarter of 2006.

Much scientific, media, and Congressional interest has been generated by studies claiming an increase in the intensity of hurricanes during recent decades consistent with an increase in sea surface temperature (SST). While SST is an important parameter of air-sea interaction it is actually upper ocean heat content that is physically meaningful. Figure 2 shows the time series of the globally, zonally-integrated heat content in the 0-100 m layer for the world ocean. Clearly there has been a long-term warming trend that encompasses the entire world ocean. Also apparent in this figure is the change in temperature structure of the Pacific Ocean during El Nino and La Nina phenomena and possibly during the reversal in polarity of the Pacific Decadal Oscillation.

We have continued the work of Boyer et al. (2005) who documented large-scale variability of salinity of the world ocean by computing the Equivalent Freshwater Fluxes associated with the salinity changes of the N. Atlantic Ocean during 12955-2002. We will be publishing work during the next year on this subject. Figure 3 shows this quantity for various sub-basins of the NZ. Atlantic and clearly shows the freshening that occurred in the subarctic and Nordic seas basins during 1969-1993 and the subsequent salinification since 1993 of this basin. Concurrent with these changes the rest of the N. Atlantic has become more saline during 1955-2002. This work documents the variability of earth's hydrological cycle.

The P.I. is also a Lead Author of the upcoming 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.

PUBLICATIONS AND REPORTS

Boyer, T.P., J. I. Antonov, S. Levitus, R. Locarnini, 2005: Linear trends of salinity for the world ocean, 1955-1998. Geophys. Res. Lett., 32, L01604, doi:1029/2004GL021791.

Levitus, S., J. I. Antonov, T. P. Boyer, 2005: Warming of the World Ocean, 1955-2003. Geophys. Res. Lett., L02604, doi:10.1029/2004GL021592.

Boyer, T. P., J. I. Antonov, H. Garcia, D. R. Johnson, R. A. Locarnini, A. V. Mishonov, M. T. Pitcher, O. K. Baranova, and I. Smolyar, 2006: World Ocean Database 2005, Chapter 1: Introduction, NOAA Atlas NESDIS 60, Ed. S. Levitus, U.S. Gov. Printing Office, Wash., D.C. , 182 pp., DVD.

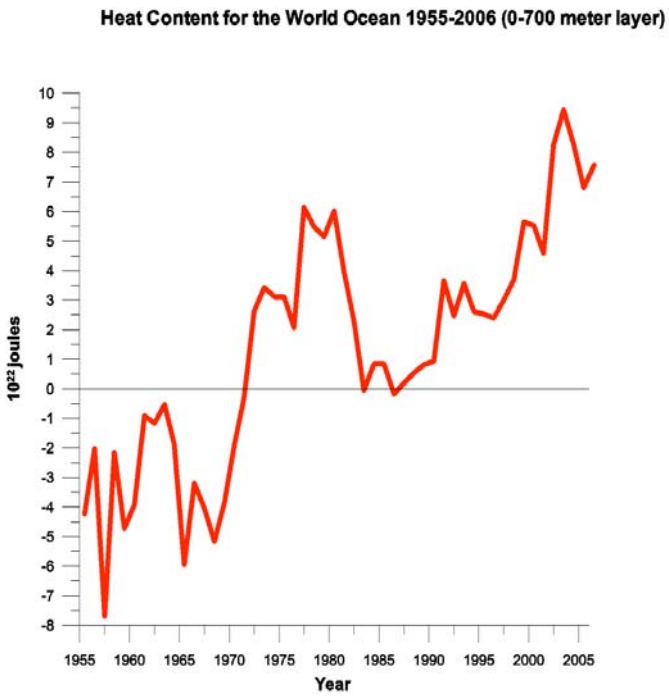

Figure 1. Time series (1955-2006 (as of the end of the 3d quarter)) of yearly ocean heat content (10^{22}J) for the upper 700 m of the world ocean.

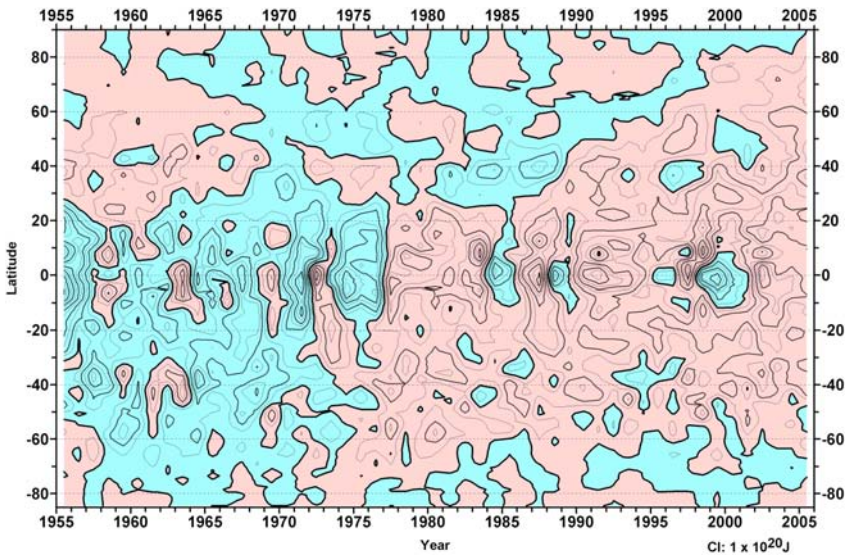

Figure 2. Global, zonally-integrated upper ocean (0-100 m) heat content (10^{20} J).

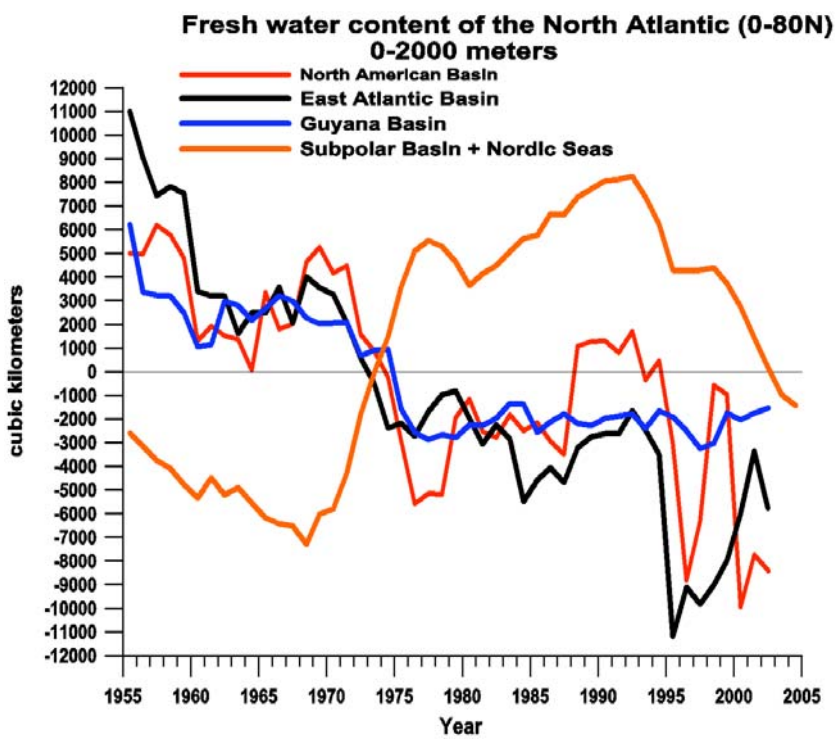

Figure 3. Variability of the Equivalent Freshwater Content of the North Atlantic Ocean and different subregions within the N. Atlantic Ocean.

Evaluating the Ocean Observing System: Performance Measurement for Heat Storage

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NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

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° 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, we are conducting comparisons between altimetry- and hydrographic-derived estimates of upper ocean heat storage, which will 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 Nino.

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.

Accomplishments:

Quarterly Reports.

We continued creating the Quarterly Status Report for the heat storage of the mixed layer from in situ observations on a quarterly basis. 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. It is anticipated that the quality of the heat storage estimates from satellite altimetry will depend on the region. This could 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.

A web site that reports on various key variables describing the state of the ocean (AOML/SOTO) has been created. This site gives an outline of the approach to the estimation of the errors of the heat storage, 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/

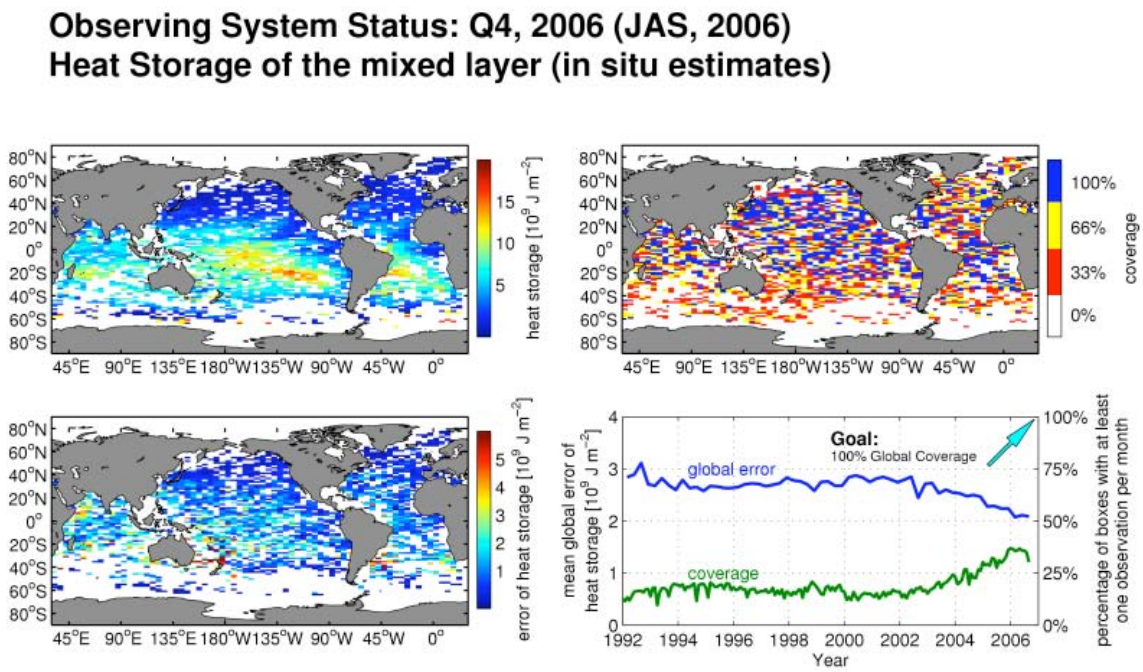

Figure 1: Example of Quarterly System Status Report for heat storage of the mixed layer, covering the time period July through September 2006. The goal of this additional task is to generate quarterly reports for the upper ocean heat storage of the global ocean.

The correlation coefficient between the sea height anomaly and the oceanic heat storage derived from the hydrographic profiles is computed for different layers (Fig. 2). 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 800m, 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 increase to above 0.7 for layer depths reaching 100m or more (Fig. 3).

The mean error in the estimates of the heat storage is estimated by comparing the altimeter estimates against the observed values of heat storage. The errors are in general smaller than the annual amplitude of heat storage over most regions and depths (fig. 4).

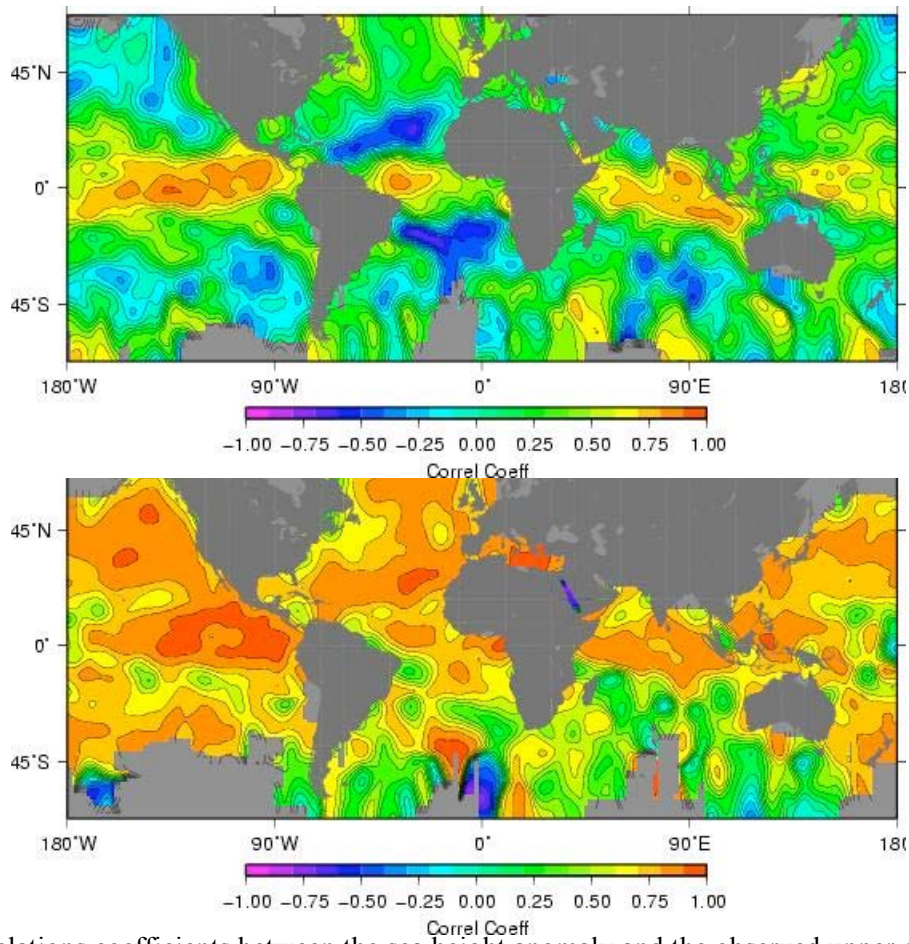

Figure 2: Correlations coefficients between the sea height anomaly and the observed upper ocean heat storage for the mixed layer (top) and for the upper 100m (bottom).

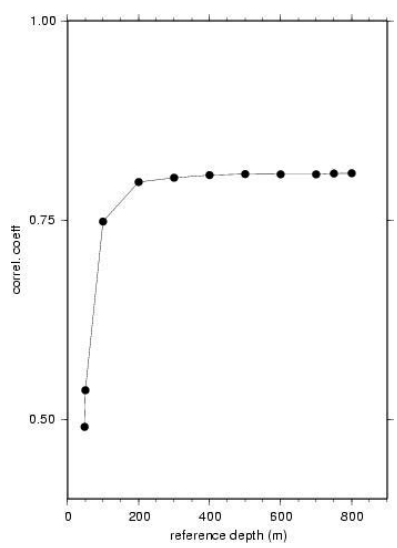

Figure 3: Global mean correlation coefficient between altimetry-derived heat storage and in-situ observations for selected depths, starting with the mixed layer depth.

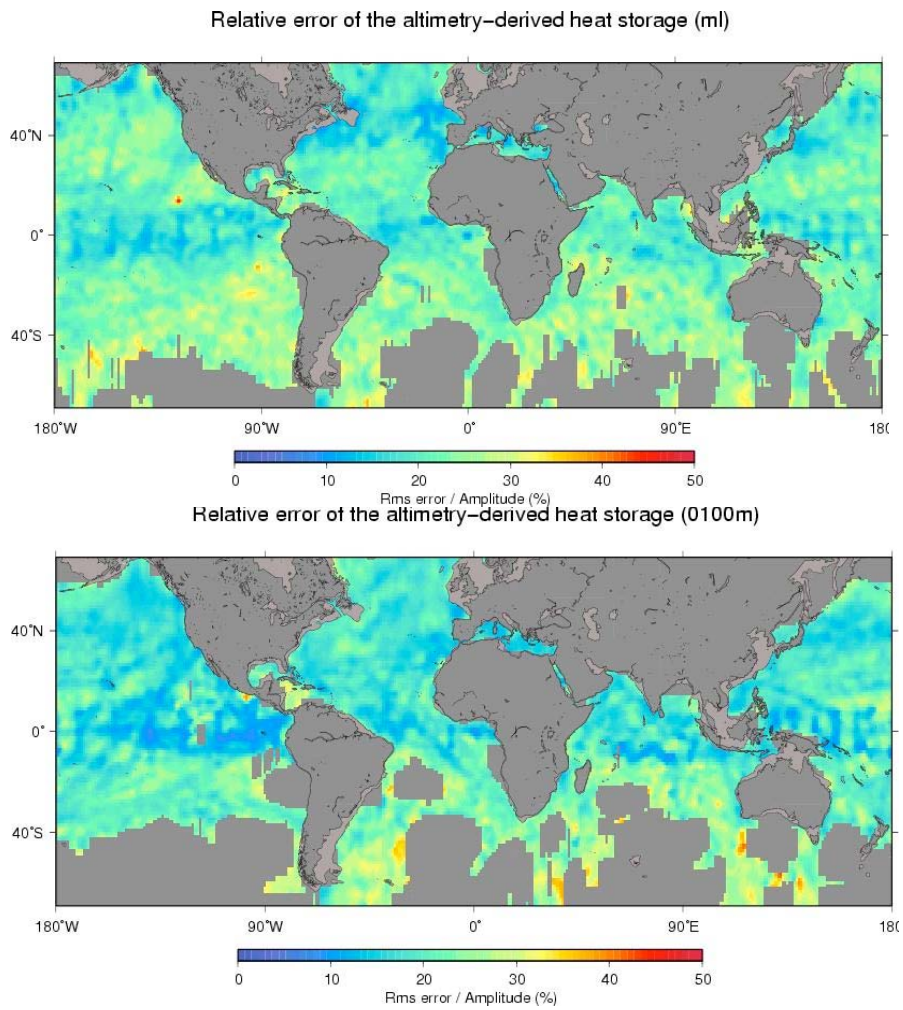

Figure 4: Average relative error of the altimeter estimates of heat storage for the mixed layer (top) and the upper 100m (bottom).

Research Highlights.

- Develop software to produce global quarterly fields of the heat storage from in-situ observations.
- Develop method and software to derive the error of the global heat storage from in-situ observations.
- Develop software to produce global quarterly fields of the heat storage from satellite altimetry.
- Comparison of the two independent estimates of the heat storage
- Produce status reports (Figure 1)
- Identification of regions where altimetric sea height anomalies are correlated to in-situ observations of heat storage (Figure 2).
- Quantification of the error of the altimetry-derived heat storage.

Publications:

Schmid, C. (2005): The impact of combining temperature profiles from different instruments on an analysis of mixed layer properties. *Journal of Oceanic and Atmospheric Technology*. 22(10), 1571-1587.

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.

Meetings:

Schmid:
"15 years of progress in radar altimetry" and "2nd Argo science workshop", Venice, Italy, March 13-18, 2006.
AMMA US workshop, Silver Spring, MD, May 4-5, 2006
Office of Climate Observations Review Workshop, Silver Spring, MD, May 10-12, 2006.

Goni:
"15 years of progress in radar altimetry" and "2nd Argo science workshop", Venice, Italy, March 13-18, 2006.
Office of Climate Observations Review Workshop, Silver Spring, MD, May 10-12, 2006.

Community Service:

C. Schmid: Argo Data Management Team, Executive Committee.
G. Goni: Ocean Surface Topography Science Working Team

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 includes 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. Synthesis denotes the process of using an advanced objective analysis approach to combine several kinds of individual data sources with different characteristics. Such a process reduces the errors in data and produces an estimate that has the minimum error variance at the solution. This type of approach has been applied successfully to generate gridded products surface vector wind, SST, and precipitation. This project, which is termed "Objectively Analyzed air-sea heat Fluxes (OAFlux)", is to develop an equivalent global synthesis product for surface heat fluxes by utilizing the methodology developed and experience learnt 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 is to be achieved by an appropriate combination of COADS data, NWP reanalysis outputs, and satellite retrievals using advanced objective analysis. The target resolution is 1° longitude by 1° latitude and monthly. Daily flux fields will be 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 1950s and to provide physical insights into the dataset.

The end product, multi-decade, gridded global fields of surface latent, sensible, fluxes with monthly and/or daily resolutions is freely available to the community via the project website (http://oaflux.whoi.edu). The proposed study contributes to 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

Two major tasks, with one on the product development and the other on the analysis study of climate variability of global heat fluxes, have been undertaken in response to the two main objectives stated in the project summary.

(i) Task 1: Product development

The data development efforts in FY2006 have been placed on the production of the 50-year time series of global latent and sensible heat fluxes from the mid 1950s to present. This is achieved by applying a synthesis approach to each of the flux-related variables (i.e., wind speed, air and sea surface temperatures, and specific air humidity) and then computing the estimates of latent and sensible heat fluxes using the state-of-the-art bulk flux algorithm version 3.0, which was developed from the Coupled Ocean Atmosphere Response Experiment (COARE) (Fairall et al. 2003). The input data for the synthesis include satellite observations and NCEP and ECMWF model reanalyses and operational analyses. However, no satellite observations were available before 1981. A two-phase development process is, therefore, carried out and discussed below.

The first development phase is for the satellite era from 1981 onward. For this period, most flux-related variables (e.g., wind speed, sea surface temperature (SST), humidity) can be derived from passive and active satellite sensors such as the Advanced Very High Resolution Radiometer (AVHRR), Advanced Microwave Scanning Radiometer (AMSR), NSCAT and Quikscat scatterometers, TRMM Microwave Imager (TMI), and the Special Sensor Miscrowave Imager (SSM/I). Nevertheless, not all flux-related variables are satellite retrievable. To fill the data gap, the surface meteorology outputs from ECMWF operational forecast, ECMWF ReAnalysis-40 (ERA40), and NCEP-1 and NCEP-2 reanalyses are incorporated. COADS ship observations are not a direct input data source; but they, together with in situ buoy measurements, serve as the base data to provide the estimates for error properties of each input dataset and to validate flux estimates at the buoy sites. The analysis of daily global latent and sensible heat flux fields on a 1-degree grid from 1981 to 2002 has been made online since December 2005 via the project website http://oaflux.whoi.edu/.

The second phase is for the pre-satellite era from the mid 1950s to 1980, the period that there are only limited ship reports of surface meteorology. In absence of sufficient observations, NWP reanalyses play a major role in the development. Extensive efforts are made to compare NWP surface meteorology against available COAD in situ observations, from which error statistics are computed and included as weighting information during synthesis to control the actual contribution of each dataset. That is, data with poor quality are given a small weight so that their impact on the solution is minimized. To date, we have completed the analysis and validation of the dataset, and are in preparation for the release of the entire dataset in the coming months. Only monthly-mean data fields are to be distributed for this period, as the dataset may

not be sufficient to resolve the spatial and temporal evolution of synoptic variability due to the lack of observations.

(ii) Task II: Analysis study

A series of the analysis study has been conducted to utilize the newly developed flux dataset to investigate climate variations of global heat flux fields, their relation to SST, and their implications for regional and global climate change. As a result, six papers have been submitted/accepted/published in peer-review journals during FY2006. The major findings are highlighted and discussed below.

(1) The manuscript on "Objectively Analyzed air-sea heat Fluxes (OAFlux) for the global ice-free oceans" (Yu and Weller, 2006) introduced the newly developed 25-year (1981-2005) time series of daily latent and sensible heat fluxes and also presented variability of the global ocean heat flux fields on seasonal, interannual, decadal and longer timescales suggested by the new dataset. The paper showed that among all the climate signals in study the most striking is a long-term increase in latent heat flux that dominates the 25-year data record. Positive linear trends occur on a global scale, being most significant over the tropical Indian and western Pacific warm pool and the boundary current regions. The increase in latent heat flux is found to be in concert with the rise of sea surface temperature (SST), suggesting a response of the atmosphere to oceanic forcing (Figures 1a-b).

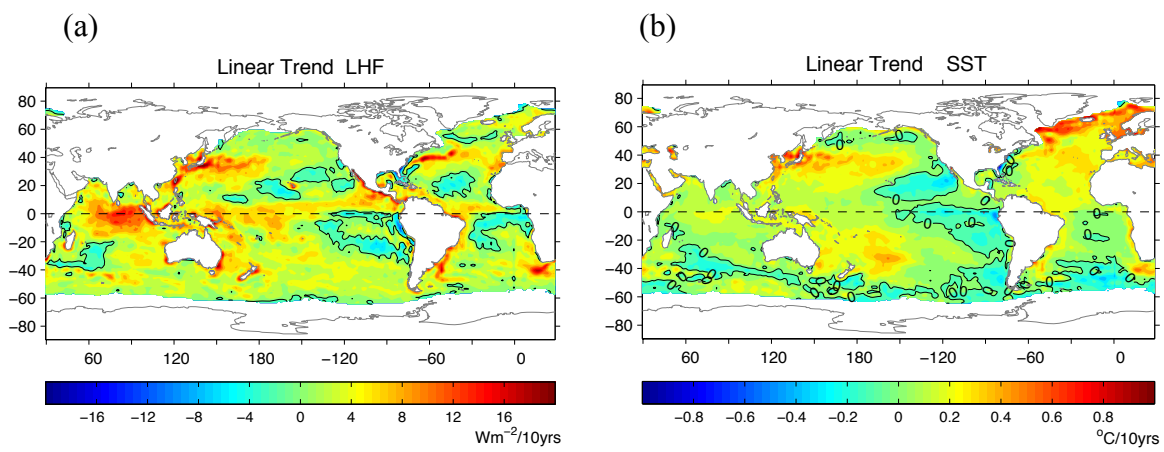

Figure 1 Linear trends in yearly-mean (a) latent heat flux (LHF) and (b) SST derived from the period from 1981 to 2005. Zero contours are highlighted.

(2) The ocean, being the source of 86% of the global evaporation and the receiver of 78% of global precipitation, is a key component of the global water cycle. A good understanding of the change of oceanic evaporation can lead to improved understanding of the climate behavior of the water cycle in the context of global climate change. Evaporation (*Evp*) is related to latent heat flux (LHF) by $Evp = LHF/\rho_w L_e$. Hence, time series of global evaporation fields is derived as a by-product of the OAFlux project (Figure 2a). The manuscript on "Global variations in oceanic evaporation (1958-2005)" (Yu, 2006) showed that the decadal change of the global oceanic evaporation (*Evp*) is marked by a distinct transition from a downward trend to an upward trend around 1977-78. Since the transition the global oceanic *Evp* has been up about 12 cm yr^{-1}

(~11%), from a low at 115 cm yr^{-1} in 1977 to a peak at 127 cm yr^{-1} in 2002 (Figure 2b). The increase in *Evp* is most significant during the decade of the 1990s. The analysis of the cause of the *Evp* change suggested a dominant role of the wind forcing. It is hypothesized that wind impacts *Evp* by two ways. The first way is direct: the greater wind speed induces more evaporation by carrying water vapor away from the evaporating surface to allow the sea-air humidity gradients to be reestablished at a faster pace. The second way is indirect: the enhanced surface wind strengthens the wind-driven subtropical gyre, which in turn drives a greater heat transport by the western boundary currents, warms up SST along the paths of the currents and extensions, and causes more evaporation by enlarging the sea-air humidity gradients. Although the trend in *Evp* can be traced directly to changes in surface wind forcing and its effects on sea-air humidities, the long-term trend in SST is, nevertheless, the ultimate cause of the change.

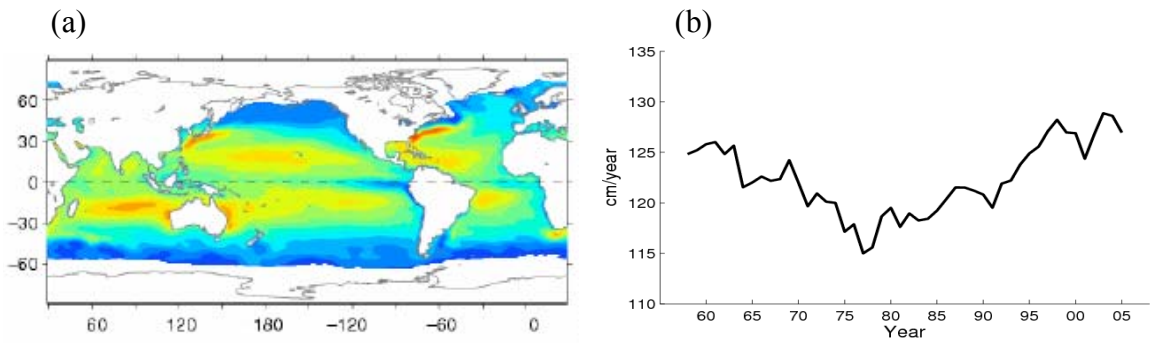

Figure 2 (a) Mean global evaporation pattern averaged over the 1958-2005 period. (b) Time series of the yearly-mean evaporation averaged over the global ice-free regions.

(3) In situ flux measurements made by buoys and ships provide benchmark time series for evaluation the accuracy of various heat flux products. The manuscript on "Annual, Seasonal, and interannual variability of air-sea heat fluxes in the Indian Ocean" (Yu et al. 2006a) presented an evaluation study for six net heat flux products, including the latent and sensible fluxes from OAFlux plus net shortwave and longwave radiation from the International Satellite Cloud Climatology Project (ISCCP), the heat flux analysis from Southampton Oceanography Centre (SOC), NCEP1, and NCEP2, ECMWF operational (ECMWF-OP) and ERA40. The study showed that the net heat flux into the northern Indian Ocean is considerably underestimated by the four NWP model flux products; sometimes, even the sign is wrong. At the two in situ measurements sites, NCEP1 net heat flux is 52 – 69 Wm^{-2} lower, and ERA40 is about 26 Wm^{-2} lower – the magnitude of the bias is larger than the mean itself. On the other hand, the OAFlux+ISCCP has the best comparison at both measurement sites, differing from buoy/ship flux measurements by about 5% on average.

(4) The manuscript on "Role of net surface heat flux in the seasonal evolution of sea surface temperature in the Atlantic Ocean" provided an example that the better fluxes can lead to a better understanding of SST variability (Yu et al. 2006b). Ocean observations indicate that the seasonal SST increase in the tropical Atlantic Ocean is associated with a shallow thermocline, suggesting that the major contributor to the surface mixed layer heat budget is the net surface heat flux through the air-sea interface. By combining the OA latent and sensible heat fluxes with

ISCCP surface radiation, the role of surface heat fluxes was clearly depicted. In consistent with ocean subsurface observations, surface heat fluxes are the forcing for the seasonal SST cycle over most of the tropical Atlantic basin except for the equatorial cold tongue and the region under the Intertropical Convergence Zone (ITCZ) (Figure 3a). Such depiction cannot be established using NWP flux products from NCEP and ERA40. The seasonal evolution of *dSST* can be well simulated by the OAFlux+ISCCP heat fluxes outside of the two zonal belts (Figure 3b).

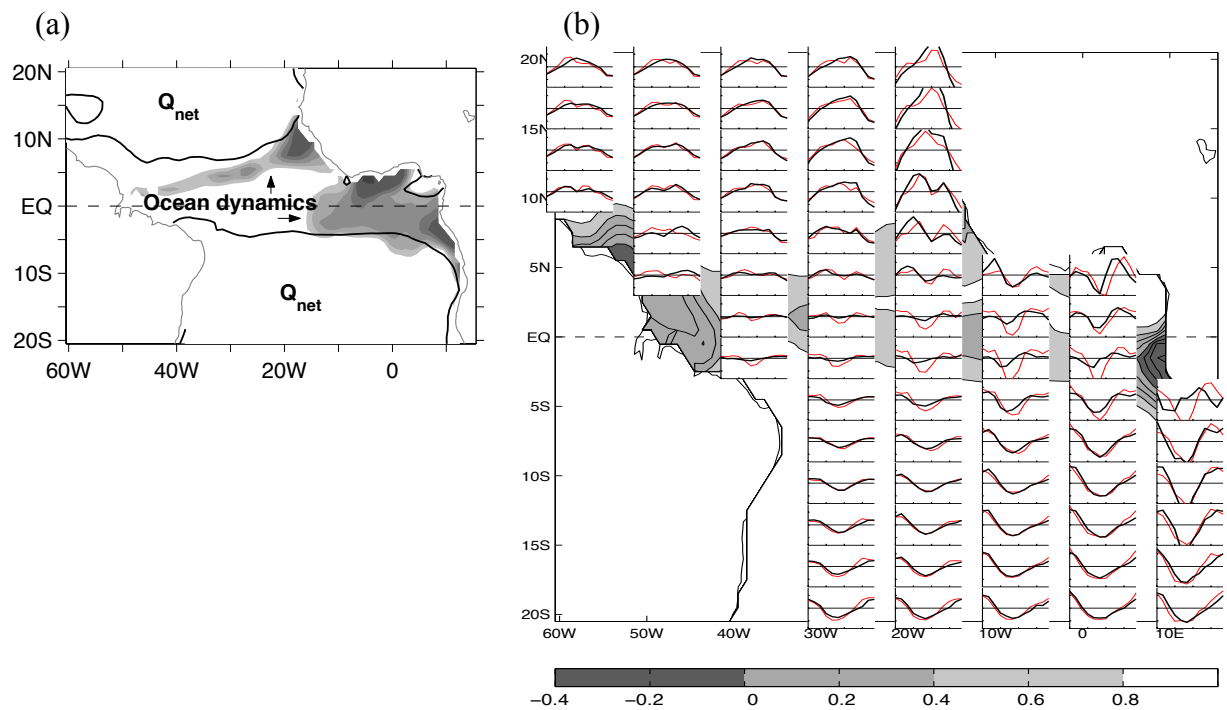

Figure 3 (a) Schematic diagram of the dominant influence of net heat flux (Q_{net}) and ocean dynamic processes in seasonal variations of SST of the tropical Atlantic Ocean. The pattern is based on the 0.9 correlation coefficient of <Q_{net}, *dSST*> derived from the OAFlux product. *dSST* denotes the monthly increment in SST. The role of oceanic process is deemed important in the two zonal belts (gray color shaded). (b) Model predicted (black) versus observed (red) *dSST*. The individual plots are drawn at every 10° in longitude and every 3° in latitude starting from the grid location (60.5°W, 18.5°S). The x-axis is Month and the y-axis ranges between -1.6 to 1.6°C.

(5) In addition to heat flux products, the OAFlux project also delivers daily/monthly estimates of the flux-related variables including SST, wind speed, sea/air temperatures and humidities since the mid 1950s. The study on "Dependence of hurricane formation on sea surface temperature anomaly fields in the Atlantic Ocean" (Saotome and Yu, 2006) provided one example of the use of the supplemental OAFlux datasets in climate studies. In this study, the daily SST dataset from the OAFlux product was taken to analyze the relationship between SST and hurricane formation locations using singular value decomposition. The study yielded two interesting results. The first is that between the positive SST anomaly pattern to the East of Florida in the first mode and the positive SST anomaly pattern in the Gulf of Mexico, Gulf Stream, and MDR in the second mode, almost all the hurricane formation locations from 1981-

2005 can be accounted for. The second is that the principle component time series shows an increasing trend in the second mode and a decreasing trend in the first mode since 1995, which coincides with the time point at which hurricane activity in the North Atlantic has dramatically increased. These two results strongly suggest that SST anomaly patterns and hurricane formation locations are linked.

3. Publications and reports

Yu, L., R. A. Weller, 2006: Objectively Analyzed air-sea heat Fluxes (OAFlux) for the global ice-free oceans. *Bull. Amer. Meteor. Soc*. Accepted.

Yu, L., 2006: Global variations in oceanic evaporation (1958-2005). *J. Climate*. Accepted.

Yu, L., X. Jin, and R. A. Weller, 2006a: Annual, Seasonal, and interannual variability of air-sea heat fluxes in the Indian Ocean. *J. Climate*. In press.

Yu, L., X. Jin, and R. A. Weller, 2006a: Role of net surface heat flux in the seasonal evolution of sea surface temperature in the Atlantic Ocean. *J. Climate*, **19**, 6153–6169.

Saotome, R., and L. Yu, 2006: Dependence of hurricane formation on sea surface temperature anomaly fields in the Atlantic Ocean. *J. Climate*. Submitted.

Schein, K.A. et al, 2006: The state of the climate 2005. *Bull. Am. Meteorol. Soc., 87,* S1-S102.

Yu, L., 2006: Objectively analyzed air-sea fluxes (OAFlux) for the global oceans. Proceeding of the 86th American Meteorological Society Annual Meeting. Atlanta, Georgia. January, 2006.

Helber, B., F. Bonjean, R. H. Weisberg, E. S. Johnson, and L. Yu, 2006: Heat transport analyses of the tropical Atlantic Ocean mixed layer. Proceeding of the 86th American Meteorological Society Annual Meeting. Atlanta, Georgia. January, 2006.

Yu, L., Xiangze Jin, and R. A. Weller, 2006: Objectively analyzed air-sea fluxes (OAFlux) for the Indian Ocean climate studies. Proceeding of the 13th AGU Ocean Sciences meeting. Honolulu, Hawaii.

Jin, X., L. Yu, and R. A. Weller, 2006: Global daily air-sea heat fluxes from the WHOI OAFlux Project. Proceeding of the 13th AGU Ocean Sciences meeting. Honolulu, Hawaii.

Helber, B., F. Bonjean, R. H. Weisberg, E. S. Johnson, and L. Yu, 2006: Heat transport analyses of the tropical Atlantic Ocean mixed layer. Proceeding of the 13th AGU Ocean Sciences meeting. Honolulu, Hawaii.

Climate Variability in Ocean Surface Turbulent Fluxes

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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 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 (Enfield et al. 2001), East Coast storm intensity (Hurrell and Dickson 2004), and storm tracks (Hurrell and Dickson 2004). 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 Nino/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 its 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 (Adams et al., 1995). 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 (Solow et al., 1998). 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 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 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/.

Accomplishments

Our focus over the past year was the expansion of our research-quality, in-situ monthly Atlantic and Indian Ocean products to include the turbulent fluxes. Through this process several data problems were identified and corrected. These products have been compared to a select set of flux and satellite products. In summer 2006, we began developing a the FSU3 flux product for the Pacific Ocean. We also continued our operational production of monthly quick-look wind fields for the tropical Pacific and Indian Oceans. All products are available on a new web site which also includes methods for tracking data users.

Global and Regional satellite stress products have continued to improve through more effective use of rain-flagged (suspect) observations. Preliminary validation of our in situ wind products in comparison to satellite wind products indicate excellent similarity. Formal analysis of uncertainty was delayed when we discovered biases in the NCDC TD-1129 data set lead to biases in our flux products. These biases were corrected through use of the ICOADS data set. We have been working on bias correction of NWP temperature and moisture data, which will be used in our satellite/NWP flux products. We have also improved blending of satellite and a NOAA tropical cyclone analysis product (H*WIND), which was used in a study identifying the cause of a storm surge far greater than the NOAA prediction (Morey et al. 2006). That study lead to a change in NOAA prediction of storm surges, which should prevent this type of error in future forecasts.

Deliverables for FY 2006 included:

1. Complete 1978-present research-quality 1˚ in situ wind and flux analyses for Atlantic, Indian, and Pacific Oceans (north of 30˚S)
    - Subtask 1: Reduce regional and temporal biases in the in situ FSU winds and Fluxes, and improve estimates of random error.

    - Subtask 2: Reprocess 1998-2004 fields based on expected release of new ICOADS data set
    - Subtask 3: Reduce regional biases in the tropics
2. Continue operational production of quick-look winds for tropical Pacific and Indian oceans
3. Complete variability analysis of 1978-present 1˚ analyses for tropical Pacific, Indian, and Atlantic Oceans
4. Evaluate methods for extending tropical Pacific and Indian Ocean fields prior to 1978
5. Extend development of uncertainty fields to cover fluxes
6. Calculate wind uncertainty fields for completed ocean basins
7. Continue comparisons of FSU winds and fluxes to available products
8. Produce global (over water) satellite fields scalar winds and fluxes
9. Develop an objective technique for assessing periods for temporal averaging of satellite data.
10. Produce and distribute products containing surface turbulent and radiative fluxes

Production of research quality 1˚ in-situ fluxes [Deliverable 1]

Over the past year we completed the 1978-2004 1˚ wind and flux products for the Atlantic Ocean (north of 34˚S) and the Indian Ocean (north of 30˚S). Examples of these monthly products, known as the FSU3 (version 3.0 of the Bourassa objective method; Hughes et al. 2006), are provided in Figures 1 and 2. During this process, we discovered that using the NCDC TD-1129 marine observations for 1998-2004 resulted in a discontinuity in the wind and flux products, as well as an error that increased with time. The reasons for this are beyond the scope of our investigations. In Fall 2005, the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) project released version 2.2 of their product. The product included a full update of the 1998-2004 period, so we decided to replace the NCDC data with the ICOADS and reprocessed the FSU winds and fluxes. This required additional man hours to be allocated to the Indian and Atlantic products. The resulting ICOADS based products did not exhibit the same discontinuity that appeared in the version using the NCDC data, and the winds were and excellent match to satellite observations (which are an excellent comparison data set). The ICOADS-based products are now being distributed to the community (see below).

The downside of reprocessing the 1998-2004 period for the Atlantic and Indian oceans it that it delayed our work on a 1˚ product for the Pacific Ocean and our formal error analysis. Analysis of the tropical and North Pacific began in summer 2006 and is 40% complete for the period 1978-2004.

Production of in-situ quick-look products [Deliverable 2]

An older version (the FSU2) of the Bourassa et al. (2005) objective method continues to be applied to create two-degree tropical Pacific Ocean wind (pseudo-stress) fields based on in-situ data. Quick-look two-degree 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. (1989). 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 Bourassa 3.0 method. This switch was delayed by the problems discovered with the NCDC data. We anticipate the switch to occur once the 1˚

FSU3 product is completed for the Pacific. 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.

Complete variability analysis of 1978-present 1˚ analyses for tropical Pacific, Indian, and Atlantic Oceans [Deliverable 3]

Atlantic Ocean fluxes have been completed; Indian Ocean fluxes have been completed for 1978 through October 2006; and Pacific Ocean fluxes are still being processed (40% complete for the 'modern period'). We have completed a preliminary analysis of variability in the Atlantic (Hughes 2006) and Indian (Banks 2005) Oceans for the available periods.

Evaluate methods for extending tropical Pacific and Indian Ocean fields prior to 1978 [Deliverable 4]

This deliverable was dependent on developments from NASA supported activities, for which funding has been delayed for more than a year.

Extend development of uncertainty fields to cover fluxes [Deliverable 5]

The conceptual framework on uncertainties has been extended to fluxes. The mathematical formulas have been determined, and some of the coding has been completed.

Calculate wind uncertainty fields for completed ocean basins [Deliverable 6]

This task appears to be nearly completed. It was delayed due to the man-hours lost in resolving the issues associated with the subtle flaws in the NCDC TD-1129 data set. We have compared satellite and in situ winds for the QSCAT observational period. The satellite observations are an excellent standard of comparison; therefore, this study resulted in good estimates of uncertainty and biases for that period. These results will be ideal for evaluating the technique we are developing to estimate uncertainty directly from in situ observations.

Continue comparisons of FSU winds and fluxes to available products [Deliverable 7]

We found large difference in winds and particularly surface turbulent fluxes among the products that we compared: FSU3, NOC, WHOI, and NCEPR2. Due to the problems with the NCDC TD-1129 data set, we focused much of our attention to comparisons between the above products and satellite winds (which have less observational uncertainty and much better sampling). The FSU3 and NOC products were very good matches to satellite winds (winds are not included in the WHOI product). Nevertheless, there were large differences in NOC and FSU3 energy fluxes. These differences could be due to either flux algorithms or biases in temperatures and humidities.

Produce global (over water) satellite fields scalar winds and fluxes [Deliverable 8]

This product is dependent on completion of bias corrections in NWP temperatures and humidities. That evaluation was delayed due to the man-hours lost in resolving the issues associated with the subtle flaws in the NCDC TD-1129 data set. We have acquired the data sets to be used in this comparison.

Develop an objective technique for assessing periods for temporal averaging of satellite data [Deliverable 9]

This objective is dependent on the completion of the objective determination of uncertainties (deliverable 6), which was delayed due to the man-hours lost in resolving the issues associated with the subtle flaws in the NCDC TD-1129 data set.

Completion of FSU Flux web page [Deliverable 10]

A new distribution web site for the FSU Fluxes is now available (http://www.coaps.fsu.edu/RVSMDC/FSUFluxes/). The web site provides an overview of the FSU Flux project and User Notes allow the community to make an informed choice about which FSU products (in-situ or satellite/NWP) would best serve their research needs. Access is provided for all scatterometer products, the FSU3, and all older versions of the FSU fluxes and winds. Links to publications resulting from the FSU winds and flux project and technical documentation are provided. New to flux pages is an extensive catalog of "Related Products". This page includes links to available in-situ, satellite, and blended flux products, NWP products, high latitude fields, ocean analyses and wave products, and in-situ flux validation data. The products catalog was produced in response to a need put forward by the World Climate Research Program Working Group on Surface Fluxes.

New to the FSU Flux page is a user tracking tool. When a user first accesses the "In-Situ Fluxes" link on the page, they are asked to enter some basic user contact information (the system is modeled on one used by the National Center for Atmospheric Research Data Support Section). The user's email address is collected and is used as their password for future access to the data site. There are no restrictions on who can access the data, the information collected simply allows us to track our user community. The information is stored in a database and allows the data center to contact users with updates and information related to the FSU Flux products. As of 1 November 2006, we have 24 registered users from 7 countries (Brazil, China, France, Germany, India, U.S., and the UK).

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Figures

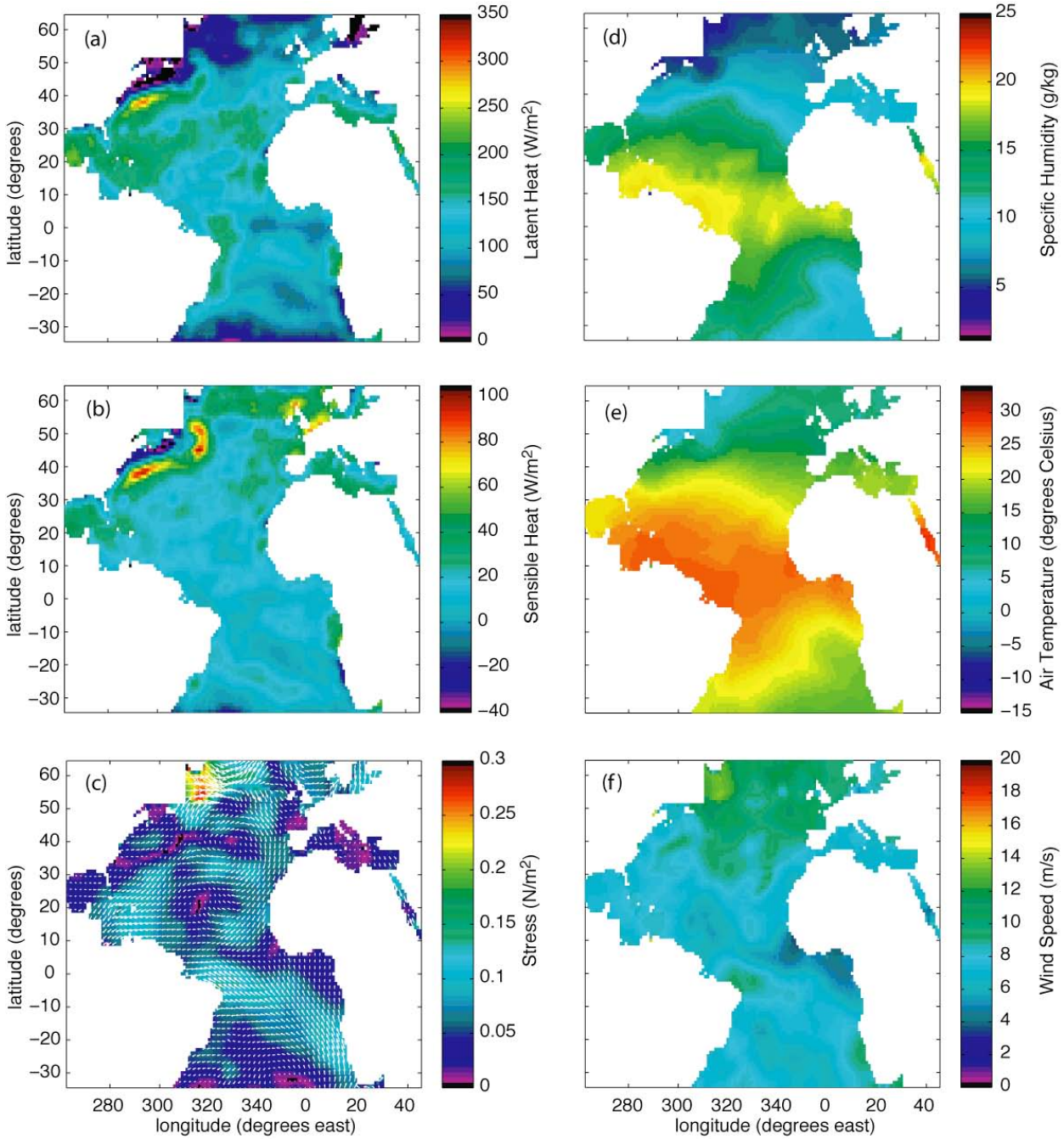

Figure 1. Atlantic Ocean FSU3 flux products for November 2005: (a) latent and (b) sensible heat flux, (c) momentum flux (wind stress), (d) 10 m specific humidity, (e) 10 m air temperature, and (f) 10 m wind speed. Scales and units are noted in the color bars.

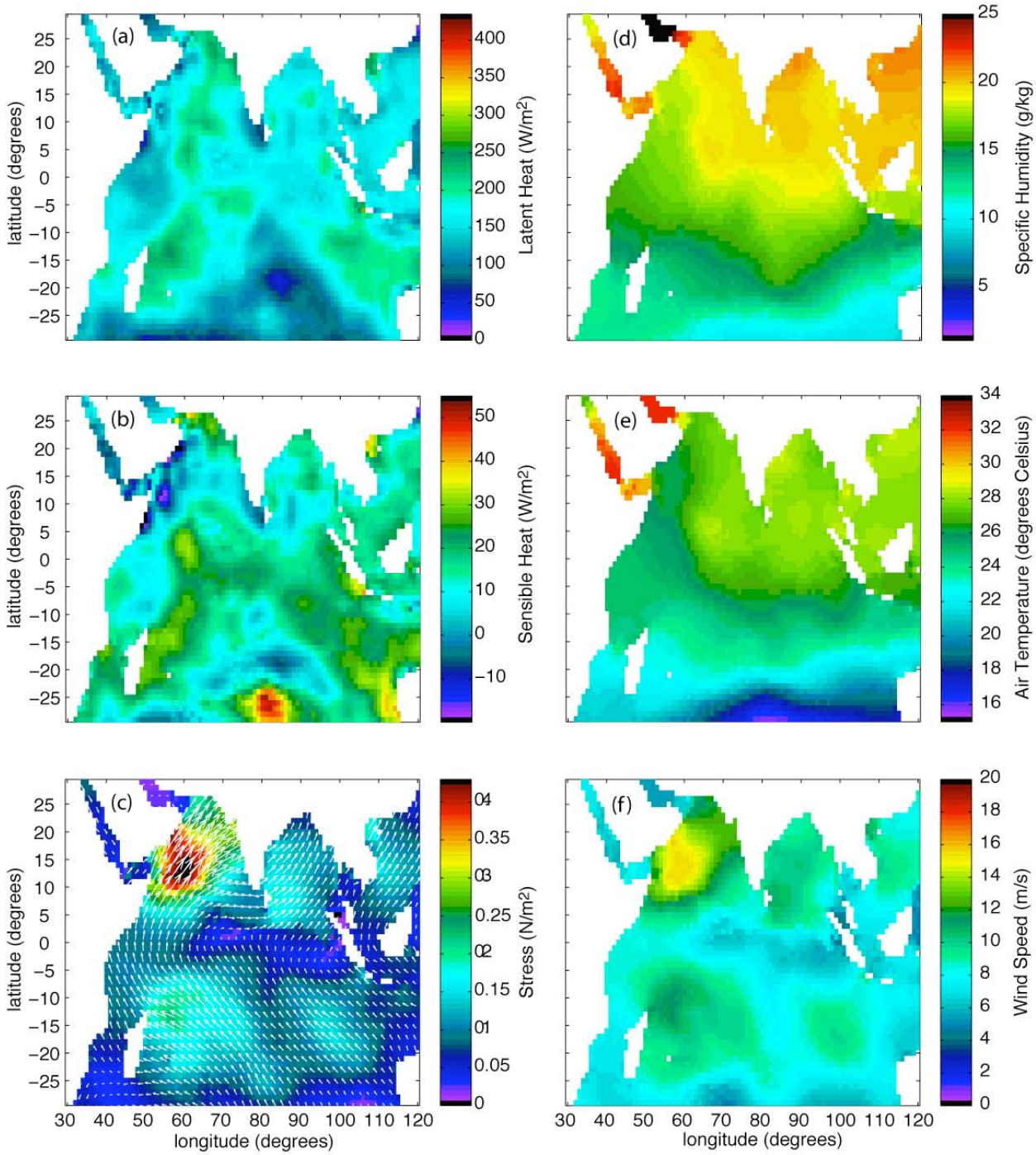

Figure 2. Indian Ocean FSU3 flux products for July 2006: (a) latent and (b) sensible heat flux, (c) momentum flux (wind stress), (d) 10 m specific humidity, (e) 10 m air temperature, and (f) 10 m wind speed. Scales and units are noted in the color bars.

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 Climate Prediction center (CPC) and 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 27-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 'move' the precipitation systems observed by the more-physically-based but less frequently sampled microwave observations in the time-space domain to get the analyzed fields of precipitation at the targeted times. The CMOPRH precipitation analysis is produced on an 8kmx8km grid over the globe from 60°S to 60°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 several 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 (GDAS). 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. FY 2006 ACCOMPLISHMENTS

2.1 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 precipitation analysis and observation-based data sets of evaporation; and 2) improvements of the current CMAP for better quantitative applications over ocean. In FY2006, we have examined the seasonal and interannual variations of the oceanic fresh water flux using observation-based data sets of CMAP monthly precipitation analysis and the Goddard Satellite-based Surface Turbulent Fluxes (GSSFC, Chou et al. 2003 and compared them with those used in the NCEP Reanalysis 2 for a 13-year period from 1988 to 2000. Fresh water flux generated by the NCEP Reanalysis 2 is used to drive the NCEP GODAS.

Global annual mean precipitation distribution (fig.1,top) is characterized by bands of strong precipitation associated with the Inter-Tropical Convection Zone (ITCZ) and South Pacific Convection Zone (SPCZ) over tropics and the storm tracks over extra-tropics. Maximum annual mean precipitation exceeding 10 mm /day is observed over western Pacific, while minimum amount of rainfall presents over oceanic dry zones over SE Pacific, SE Atlantic and oceanic regions west of Mexico and North Africa. NCEP Reanalysis 2 (fig.1, middle) reproduced the overall large-scale patterns of precipitation very well. Regional biases, however, are observed, with the Reanalysis 2 over- estimate precipitation over most of the oceanic regions except over coastal regions near maritime continent and northeast Asia and several other regions (fig.1, bottom).

Global distribution of annual mean evaporation (fig.2, top) has maxima at latitudes south and north of the ITCZ, respectively. Maximum annual mean evaporation of more than 6 mm/day appears over tropical central Pacific and Indian Ocean, while evaporation of limited quantity is observed over high latitude oceans and over coastal oceans near maritime continent. In general, the NCEP Reanalysis 2 captured the overall structure of the global evaporation depicted in the satellite-based GSSTF data set (fig.2, middle). The Reanalysis 2, however, tends to generate too much (too less) evaporation over western Pacific and Indian Ocean (eastern Pacific, South Oceans) (fig.2, bottom).

Combined, the NCEP reanalysis produces too much (less) fresh water flux (E-P) over central Pacific (Western Pacific and eastern Indian Ocean), providing the NCEP GODAS with a biased forcing field (fig.3). Correlation between the monthly anomaly of observed fresh water flux (E-P) and that in the Reanalysis 2 is low over tropics where exchange of fresh water components between ocean and atmosphere is most active (fig.4). These results suggest that fresh water flux used to force the current version of the NCEP / GODAS contains substantial errors and need to be improved in the future.

Part of the differences between the E-P in the observation and the Reanalysis 2 are attributable to the uncertainties in the observed precipitation (CMAP) and evaporation (GSSTF). To quantify the uncertainties, we have started to intercomparison various in-situ and satellite-based precipitation estimates, and, based on the intercomparison results, to refine the CMAP precipitation analysis. In FY06, we have

- Collected and processed precipitation estimates from several satellite and merged products. The data collection/processing activities are extremely time consuming and part of it is carried out jointly with the second part of this project on the improvements of CMORPH analysis;
- Performed brief comparisons of these satellite precipitation estimates to get insight into the overall structure of uncertainties in the observed precipitation with an emphasis on the systematic error; and
- Started examinations of evaporation data sets in several observed and modeled data sets (e.g. WHOI, NCEP Reanalysis 1); and
- Started development of the objective analysis technique used to generate the new CMAP analysis. The technique is based on the Optimal Interpolation (OI) technique of Gandin (1965) and combines information from multiple input sources based on their error structure.

2.2 CMORPH Global Precipitation Analyses

In this section, we address progress for each work item that was listed in the FY05 report.

- Development and integration of a decision model to determine when it is optimal to propagate precipitation using model winds rather than IR

We have developed three distinct ways to produce estimates of precipitation for each 30-minute period between overpasses by passive microwave sensors at a given location. One is to morph by using successive IR imagery to determine the motion of the precipitation field that has been identified and quantified by passive microwave data. The second method is to use NWP model winds instead of IR to morph the data. The third is to estimate precipitation directly from IR data. The issues are that morphing usually produced more accurate estimates of precipitation than estimates made from IR data, except when the time between microwave sensor overpasses is sufficiently long (about four hours). In addition, over the Tropics the use of mid-level model wind information to propagate the precipitation is often superior to using IR imagery to determine the motion of the precipitation field. Therefore, during FY06 we developed a decision model to determine which of these three estimates to use at any given location and time. This model was developed by withholding from the morphing process precipitation estimates that were derived from passive microwave data and using those data to validate morphed or IR-derived estimates at each 30-minute period between microwave overpasses.

- Development and implementation of an AMSU-B oceanic rainfall calibration method that increases detection frequency resulting in a better rain rate distribution.

The detection of oceanic rainfall is a problem for AMSU-B because the high frequency channels on that sensor have difficulty in detecting rainfall that is not associated with deep convection. Since "warm cloud" precipitation is not detectible by AMSU-B, overall the rainfall frequency of TMI is 2-3 times greater compared to the rainfall frequency derived by AMSU-B over oceanic areas (figure 5, top and middle panels respectively). Previously, since the CMORPH frequency matching calibration method conserves total rainfall relative to TMI, precipitation estimates derived from sensors or algorithms that suffer from rainfall detection deficiencies are adjusted upwards in regions where rainfall is detectable in order to match the larger rainfall area and hence total volume of the TMI-derived rainfall. Therefore, previously in oceanic regions where precipitation is detectable by the AMSU-B instrument, (convective regions primarily), the AMSU-B precipitation magnitude was adjusted heavier than TMI so that the rainfall volume per unit matches the TMI-derived estimates (not shown).

A new calibration method utilizes previously indeterminate AMSU-B retrievals to increase rainfall frequency of the AMSU-B instrument that nearly matches TMI. The oceanic AMSU-B rainfall detection in "warm rain" regions is improved (figure 5, bottom panel) by assigning the lightest rainfall rates possible to AMSU-B retrievals that are flagged because the ice water path (IWP) and effective diameter (De) do not "converge" (in the 0.05 - 3.0 Kg m-3 and 0.3 -3.5 mm respective ranges). An instantaneous case study depiction reveals the current NESDIS algorithm estimates higher rainfall in smaller regions relative to the TMI (figure 6, top and middle panels respectively). By assigning indeterminate retrievals the lightest remaining rainfall (figure 6, bottom panel), the new calibration procedure now produces a realistic characterization of rainfall in previously detected regions and while conserving total sensor estimated rainfall to the TMI

calibration standard. The scan angle dependent frequency matching calibration method will then be applied to this "expanded" AMSU-B rainfall.

- Determine the bias characteristics by comparing the CMORPH estimates with available in situ precipitation observations which will also assist in the development of error estimates (Figure 7).

As a first step, CMORPH estimates were used in conjunction with hourly rain gauge data from a dense network in southeastern China, to develop a bias reduction procedure. The procedure first interpolates the gauge data to match the CMORPH grid. Then, for each grid box that contains a rain gauge observation, we compute the ratio between the CMORPH and rain gauge estimates at each location over the previous 30 days (Gauge/CMORPH). Those ratios are then interpolated via the optimum interpolation (OI) method to obtain a spatially complete field of ratios. Then, at each grid box, the CMORPH value is multiplied by the appropriate ratio. The second step uses OI to integrate the rain gauge and bias corrected CMORPH data. Although this work is not directly relevant to oceanic precipitation, the methodology that was developed may be useful for CMORPH bias adjustment over the oceans by using coastal radars and buoy measurements of precipitation.

- Reprocess the entire CMORPH period of record using a frozen system in which all recent improvements have been incorporated

This task has been deferred to the next year, mainly because of the level of effort to derive the AMSU-B scan angle adjustment procedure, which we felt was necessary to have in place before beginning a reprocessing effort.

- Extend the CMORPH period of record back through January 2002 – perhaps further, depending upon the availability of inputs

In order to perform this task, it is necessary to retrieve precipitation estimates derived from passive microwave sensors (SSMI, AMSU-B, TMI, AMSR) in the form of "orbit by orbit" files. This is a substantial effort and considerable "data mining" was accomplished during FY06. To date, we have retrieved approximately 80-90% of the necessary passive microwave data from all available sources back to 1998.

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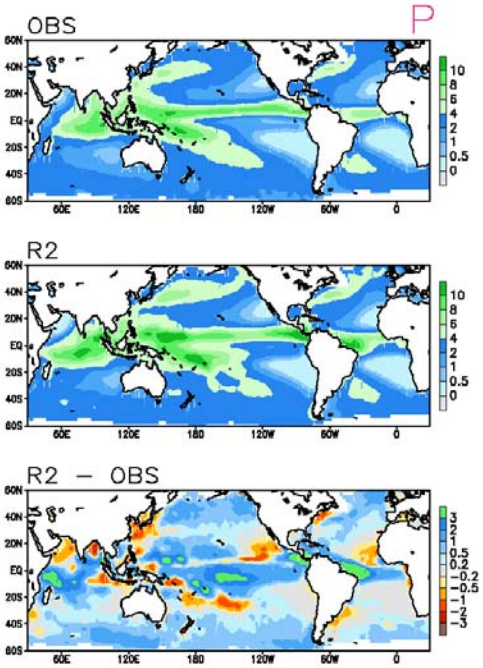

Fig. 1

Annual mean precipitation (mm/day) averaged over a 13-year period from 1988-2000, from the CMAP global precipitation analysis (OBS,top), the NCEP Reanalysis 2 (R2, middle), and the differences between them (bottom).

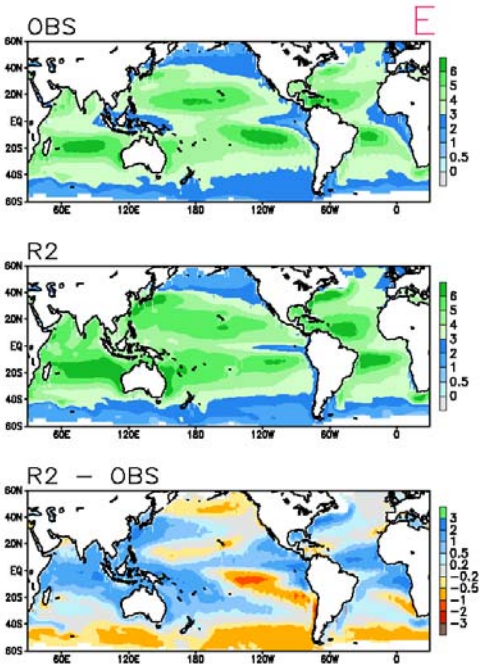

Fig. 2

Annual mean evaporation (mm/day) averaged over a 13-year period from 1988-2000, from the observation-based Goddard Satellite-based Surface Turbulent Fluxes (GSSTF, Chu et el. 2003, top), the NCEP Reanalysis 2 (middle), and the differences between them (bottom).

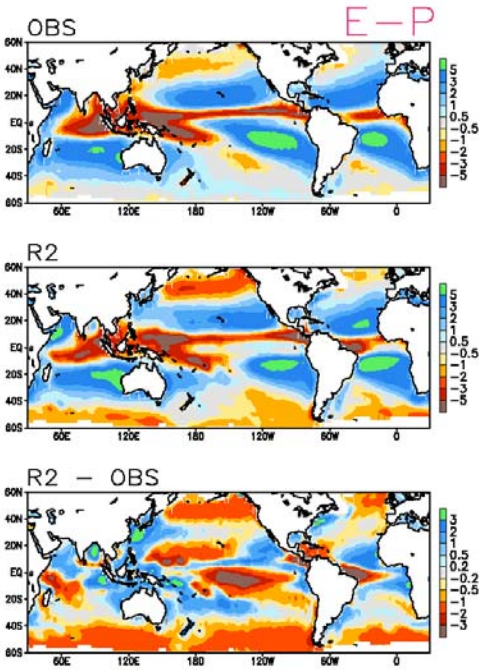

Fig. 3

Annual mean fresh water flux (E-P, mm/day) averaged over a 13-year period from 1988-2000, from the observation (OBS, top), the NCEP Reanalysis 2 (R2, middle), and the differences between them (bottom).

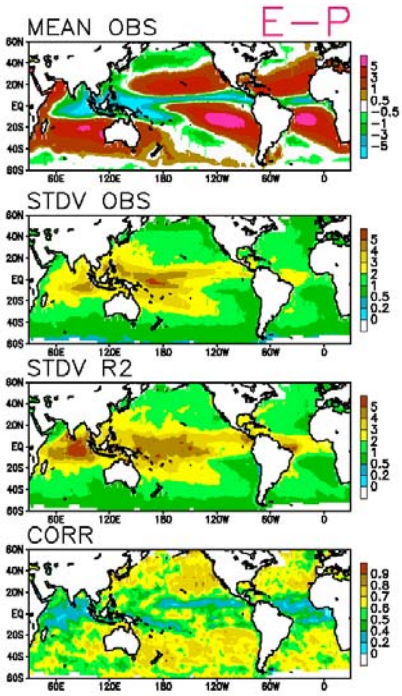

Fig. 4

Spatial distribution of mean E-P in the observation (top), standard deviation of E-P in the observation (2nd from top), standard deviation of E-P in the NCEP Reanalysis 2 (3rd from top), and correlation between monthly E-P anomaly in the observation and that in the Reanalysis 2 (bottom). Statistics are

calculated over a 13-year period from 1988 to 2000.

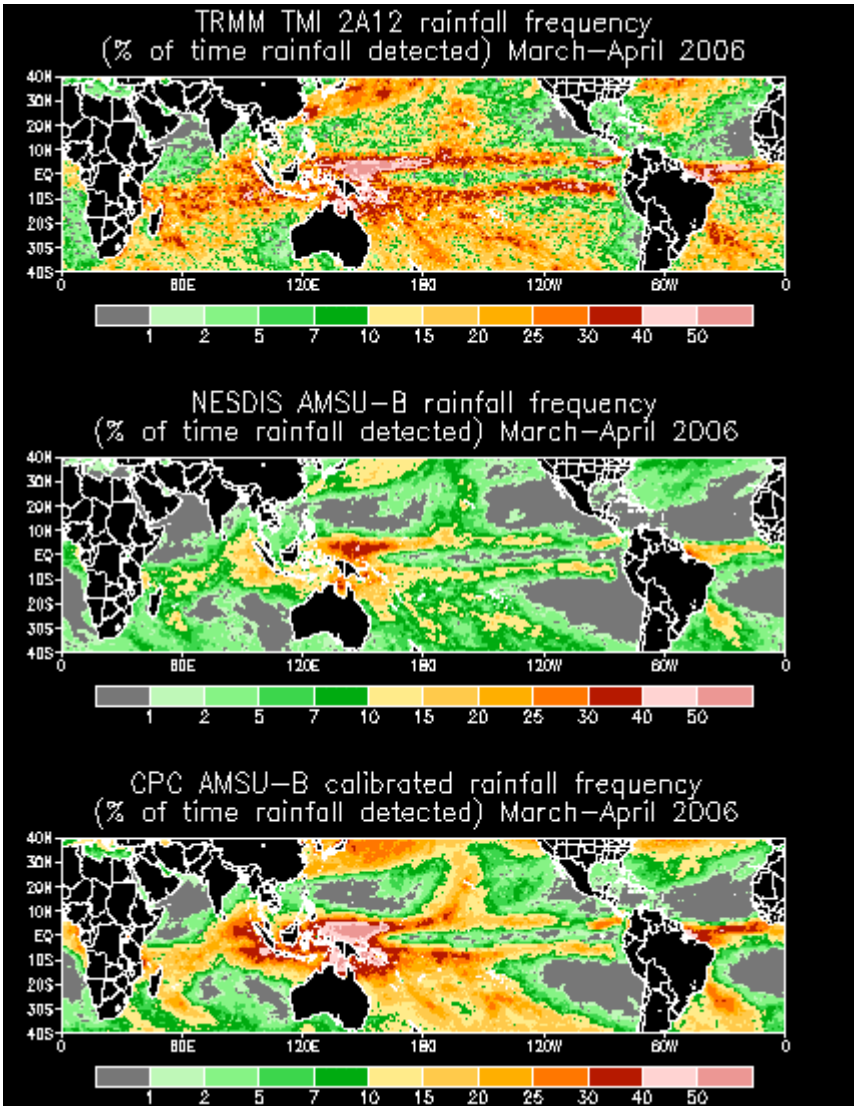

Figure 5. Comparison of precipitation frequency from the TRMM TMI 2A12 (top), unadjusted AMSU-B algorithm (middle), and the adjusted AMSU-B (bottom) for March – April 2006.

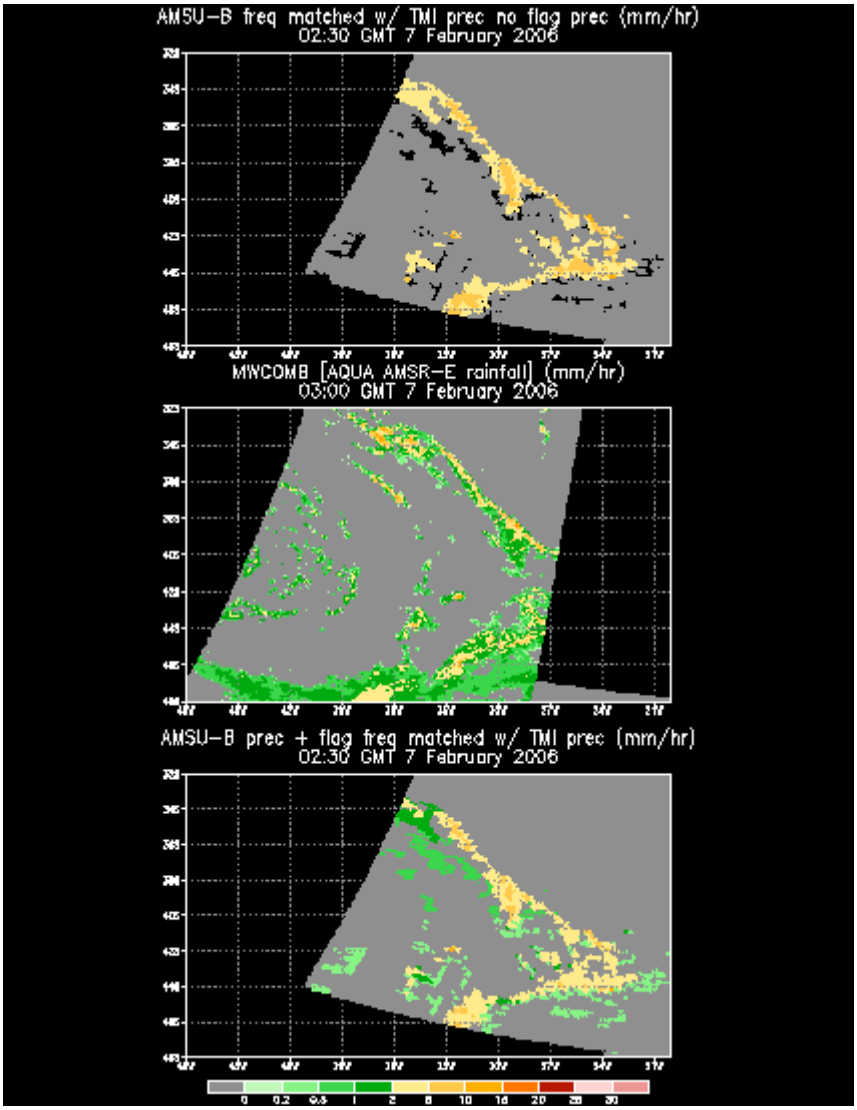

Figure 6. Comparison of instantaneous precipitation from the unadjusted AMSU-B NESDIS algorithm (top), TRMM TMI sensor (middle), and the calibrated AMSU-B algorithm (bottom).

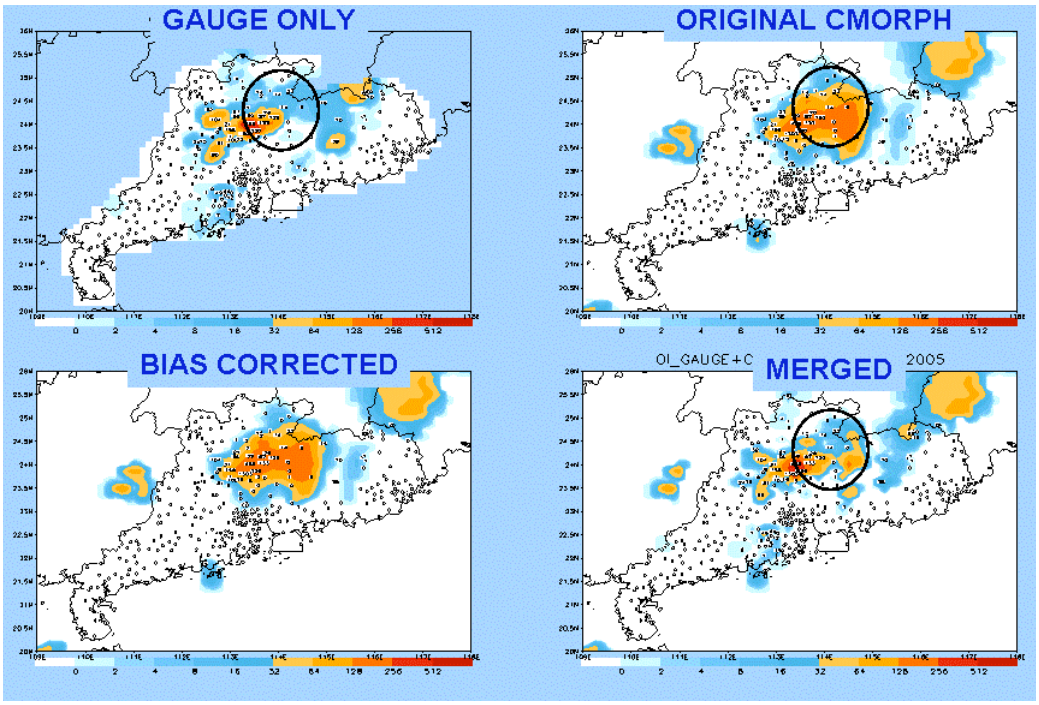

Figure 7. Example result of bias-adjustment procedure applied to CMORPH precipitation estimates. Rain gauge locates are denoted by dots. Note the circled areas in three of the panels, where CMORPH (upper-right) is high compared to the gauge analysis (upper-left) but that rain gauges are sparse in the region. The CMORPH/rain gauge merged analysis (lower-right) gives more weight to CMORPH (after bias adjustment) in gauge-sparse locations.

Evaluating the Ocean Observing System: Surface Currents

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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 NESDIS quarterly report. 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. The goal of this project is to maintain a quarterly "Observing System Status Report for Surface Currents", which evaluates how well the IOOS satisfied these requirements. 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. As a part of this report, we will quantify the global mean bias in satellite-based estimates of surface currents, analogous to the evaluation done for SST measurements.

For many years, spatio-temporally dense satellite observations of SST have been calibrated with the sparser but direct set of in-situ observations to produce operational SST products. The potential biases in these data have been carefully quantified (Zhang et al., 2004) and the observing system's performance is measured in these terms by NESDIS. Many researchers routinely calculate surface currents from satellite observations of wind and altimetry; geostrophic currents derived from blended satellite altimetry fields are already being estimated at AOML and posted daily in near-real time at http://www.aoml.noaa.gov/phod/trinanes/java.html. 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). No one has yet performed this

comparison globally using non-interpolated altimetry, and the observing system is not evaluated in this context.

In this project, we have begun generating a product that evaluates the success of the observing system in satisfying GOOS/GCOS requirements for surface current observations, on a quarterly basis. Surface current measurements are collected by drogued drifting buoys and by moorings with a near-surface point acoustic current meter. As seen in the FY06 quarterly report (Fig. 1), we present the spatial coverage of these 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).

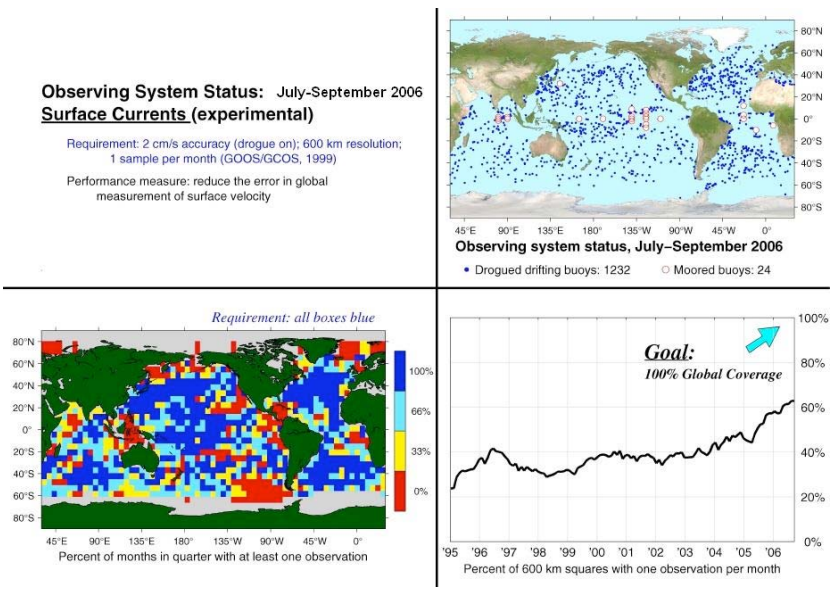


Fig. 1: FY06 Q4 report evaluating the IOOS's performance for near surface current measurements.

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 META

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 measurements. We thus merge these two data sets to eliminate drogue-off drifters from our analysis.

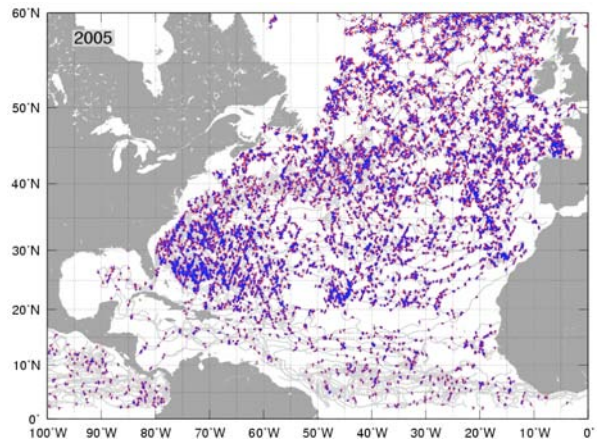
Moored current measurements are collected by near-surface point acoustic meters on the Tropical Atmosphere-Ocean (TAO) array in the Pacific, the Pilot Research Array in the Tropical Atlantic (PIRATA), the sustained array of ATLAS moorings in the tropical Indian Ocean, and the Kuroshio Extension Observatory (KEO) mooring at 32.3ºN, 144.5ºE. Currents at daily resolution are downloaded from the TAO Project Office each quarter to quantify the number of observations at each site, and the TAO office separately provides their record of days of observations per site. Each quarter, these independent measures are compared to ensure accuracy.

Each quarter, we crate an integrated data set of surface current observations by merging the drifting and moored buoy data; we then analyze these data in 600km squares to evaluate the IOOS for surface current measurements according to the GOOS/GCOS requirements.

Since the project was initiated at the beginning of FY06, quarterly reports have been produced within two weeks of each quarter's end. These reports are e-mailed to the Office of Climate Observations for their web site at:
http://www.oco.noaa.gov/index.jsp?show_page=page_status_reports.jsp&nav=observing, and are separately archived on the AOML "State of the Ocean" site at:
http://www.aoml.noaa.gov/phod/soto/gsc/index.php. We have also created backdated reports starting from January—March 2005.

To derive the bias in satellite-based estimates of surface currents, we are comparing altimetry-derived geostrophic velocity anomalies to coincident cross-track drifter speeds, with the Ekman component (using the Ralph and Niiler 1999 parameterization) removed. By doing this comparison with cross-track speeds from individual altimetric passes, rather than using a gridded altimetric product, we will be able to assess the accuracy of a satellite-based product independent

of mapping errors in a gridded product. In short, a comparison of gridded altimetry vs. drifters does not tell us how the errors are distributed for cross-track vs. along-track speeds, and they do not tell us how the global bias may change if a different number of altimeters are flying. Our analysis will permit the global bias to be characterized by the current IOOS coverage for 100% altimetric coverage, for the actual present altimetric coverage, and could be used to quantify the impact on surface current estimates if an altimeter were to fail or be added.



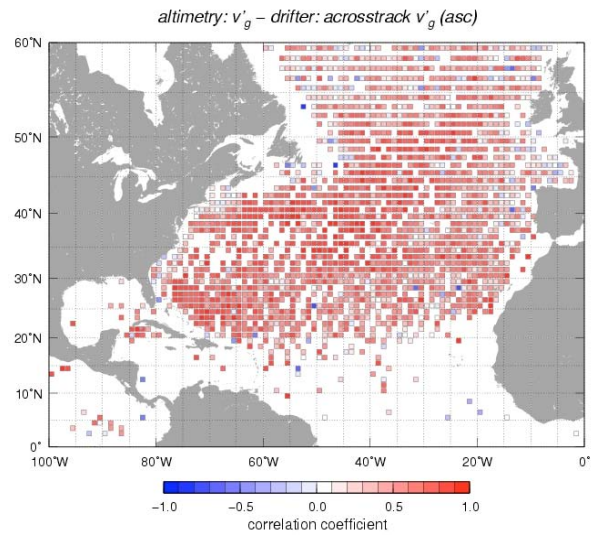


Fig. 2: Left: Locations of all coincident measurements where across-track altimetry-derived geostrophic velocity anomalies (red) are match with the drifter geostrophic velocity anomalies (blue) during 2005. The drifter values were computed by removing the Ekman component, which was estimated from NCEP winds. Right: mean correlation between drifter and altimetry geostrophic velocity anomalies, averaged in 1° bins, for the time period October 1992—March 2006. Correlations are computed when the number of observations in the bins is larger than 15.

Preliminary results (Fig. 2) have focused on the North Atlantic, with FY07 plans to expand the results globally. These results, in particular the high correlation between drifter- and altimetry-derived geostrophic currents in the subtropical North Atlantic, demonstrate the ability to explain a majority of the surface current variance from altimetry with high skill. However, the correlation tends to decrease at subpolar latitudes, where sustained drifter observations are needed to eliminate biases or errors in the satellite-based estimates. At low latitudes (0-20°N) and in the Gulf of Mexico, there are currently an insufficient number of observations to compute robust correlations at 1° resolution. In these two regions more drifter observations are needed to be able to produce more matches between altimetry and drifter observations at 1° resolution. Maps of the bias between total drifter velocity and the altimetric geostrophic velocity anomaly (not shown) clearly show the time-mean currents, while the bias between drifter-derived and altimetric-derived geostrophic velocity

anomaly reveal unexpected patterns that appear to be associated with Gulf Stream meanders or rings, but must be explored more carefully.

Publications and Reports:

- Lumpkin, R. and G. J. Goni, 2006: Global oceans: Surface currents. In *State of the Climate in 2005*, K.A. Shein, A.M. Waple, H.J. Diamond, and J.M. Levy (eds.). Bulletin of the American Meteorological Society, **87**(6), S25-S26.

- Lumpkin, R. and G. J. Goni, 2006: Surface currents. In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 61-67.

Quarterly reports on the state of the ocean: Meridional heat transport variability in the Atlantic Ocean.

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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

$$M = \iint \rho v \, dxdz \qquad V = \iint v \, dxdz \qquad H = \iint \rho c_p \theta v \, dxdz$$

$$[\mathrm{Kg/s}] \qquad [Sv = 10^6 m^3/s] \qquad [PW = 10^{15} Watts]$$

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.

Preliminary 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}.

Accomplishments

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 energy produced by about one million nuclear power plants.

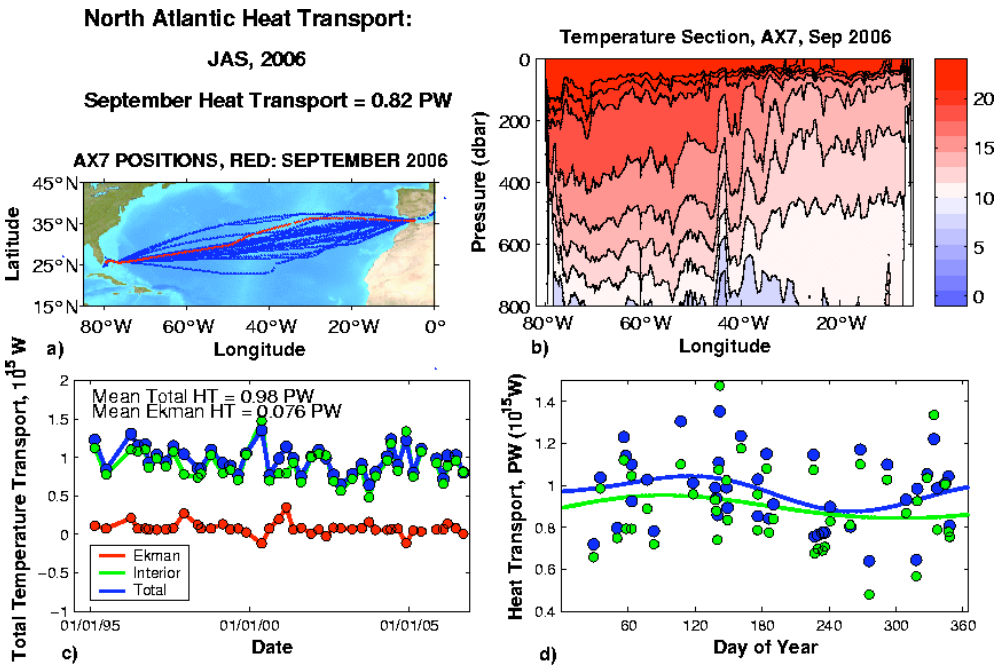

Figure 1: Report for the July-August-September quarter of 2006 for North Atlantic Meridional Heat transport along the AX7 high density XBT line. Transport results based on September 2006 XBT section (positions shown in top left, temperature section shown in top right). Heat transport estimates were decomposed into the geostrophic (interior) and Ekman components and their total (lower left). Heat transports demonstrate a small seasonal signal (lower right) with spring sections having a higher heat transport than fall sections. The heat transport during this quarter was significantly lower than the mean heat transport.

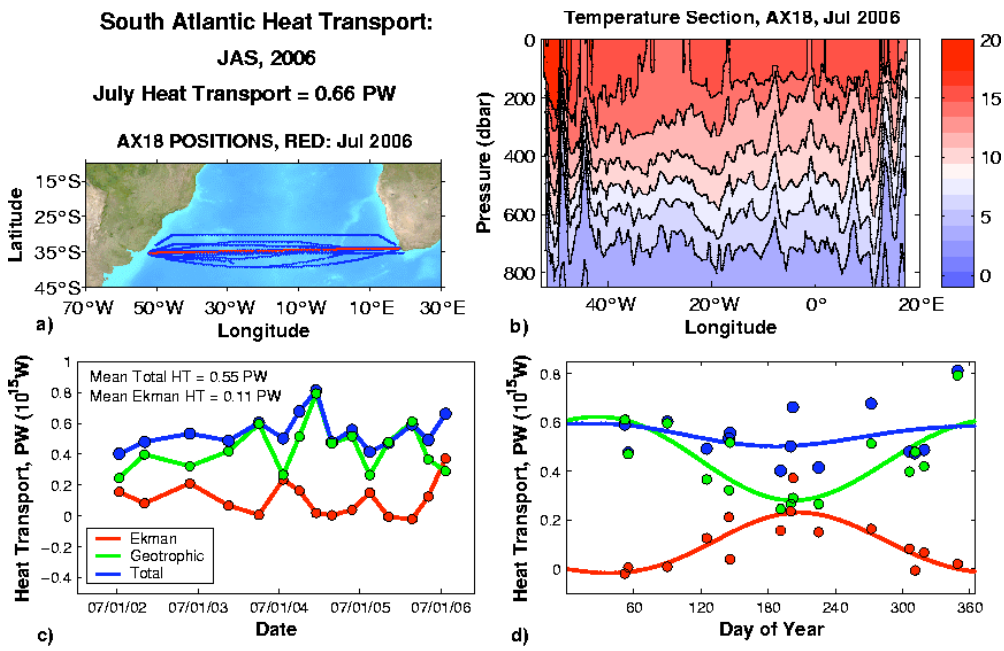

Figure 2: Report for the July-August-September quarter of 2006 for South Atlantic Meridional Heat transport along the AX18 high density XBT line. Transport results based on July 2006 AX18 XBT section (positions shown in top left, temperature section shown in top right). Heat transports were estimated using a shallow (green squares) and deep (red diamonds) reference level (lower left). Total heat transports demonstrate no significant seasonal signal (lower right). The July heat transport was significantly higher than the mean transport.

Scientific Findings:

This year, Thacker (2006a, 2006b) completed two studies of how to estimate Salinity for each XBT by using available Argo and CTD profiles. Results from this work allow us to improve the estimation of salinity by using a spatially dependent function where salinity depends on the Temperature and Depth of the XBT observation.

In the North Atlantic, the heat transport was found to vary on inter-annual time scales from 0.8 ± 0.2 PW at present to 1.2 ± 0.2 PW in 1996 with instantaneous estimates ranging from 0.6 to 1.6 PW (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[2]). At low frequencies, North Atlantic heat transport variations were found to correlate with the Atlantic Multidecadal Oscillation (AMO) as shown in Figure 3.

Improvements to these estimates should include (i) time varying Florida Current transports and wind fields, (ii) improved salinity estimates and extrapolations to the bottom, and (iii) improved error estimates that reflect the effect of the initial reference level, the wind field variability, the importance of barotropic flows, and the uncertainties of the salinity estimates and the extrapolations.

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

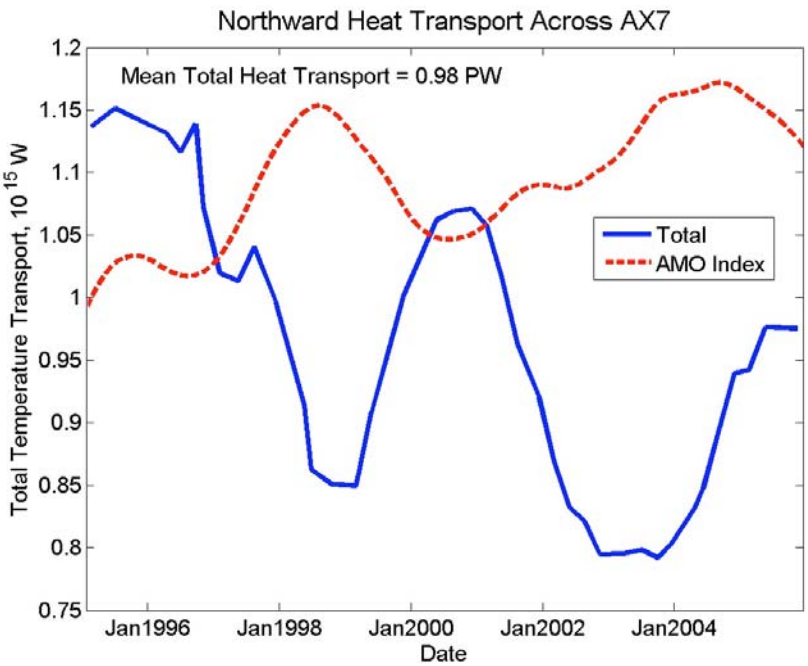

Figure 3: Time series of total heat transport in the center of the subtropical gyre in the North Atlantic Ocean along the XBT lined designated AX7. In the North Atlantic, there has been an apparent decrease in heat transport over the past 10 years (solid blue). Heat transport is inversely related to the Atlantic Multidecadal Oscillation (AMO) Index (red dashed)

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, 2006). The procedure is tested using CTD data collected during the World Ocean Circulation Experiment (WOCE) along the 30°S hydrographic transect (A10) and the output from a numerical model. The results indicate that the methods described here can provide heat transport estimates with a maximum uncertainty of ±0.18 PW. Most of this uncertainty is due to the climatology used to estimate the deep structure and issues related to not knowing the absolute velocity field and most especially characterizing barotropic motions. Nevertheless, when the methodology is applied to temperatures collected along 30°S (A10) and direct model integrations, the results are very promising. From analysis of the numerical model this study also found that ageostrophic non-Ekman motions can contribute less than 0.05 PW to heat transport estimates in the South Atlantic.

Garzoli and Baringer (2006) applied extended these results by applying the 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 form 0 to up to 30 Sv depending of the wind structure. The values obtained for the heat transport, as given 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 shows a pronounced increase from July 2004 to December 2004 and a decrease thereafter (Figure 2). It also indicates some variability

that may either be natural variability or may be related to the difference in cruise track. The variability of the transports is analyzed as a function of the mean latitude. Results indicate 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.

The total heat transport shows apparent interannual variability, but does not show a strong indication of seasonality. The percentage of variance explained by an annual cycle fit to the total transport is 24%, a value similar to the one observed in the model (31% at 30°S and 17% at 35°S). The scatter about the annual cycle fit is in some cases natural interannual variability, and in others is due to the difference in the cruise tracks. For example, the results from the two cruises conducted during the months of July 2002 and July 2004 yield values of 0.40 and 0.50 PW, respectively. In this case, the difference is due to the different routes because the July 2002 cruise was conducted at a mean latitude of 30° 19'S where the Ekman component of the flux is low (0.16 PW) while the 2004 cruise was conducted at a mean latitude of 36° 42'S where the Ekman component of the flux is high (0.24 PW). If only the geostrophic component of the flow is analyzed minimum values of the heat transport are observed for the period July to September (around day 200). In other words, the geostrophic component of the heat transport reaches its lowest values during the austral winter when the Malvinas Current reaches its northernmost latitude. There is only a slight indication that the values are higher during the austral summer (January, February, March) when the Brazil current reaches its southern extension and the Malvinas Current retreats to the South. The heat transport obtained from the POCM model (Baringer and Garzoli, 2006) contains a seasonal cycle similar to the one observed in the Ekman transports (same amplitude and phase). This indicates that in the model, most of the variability is due to Ekman flow while in the real ocean, the geostrophic component of the flux is an important component of the total flux.

The maximum observed value for heat transport is obtained during the month of December 2004, 0.81 PW, and it is mostly due to the geostrophic component (which has a value of 0.79 PW). Average SST anomalies during the cruise indicate a warm anomaly at the eastern boundary (+5°C). The vertical temperature profiles (not shown) indicate anomalously warm waters between 40° and 50°W extending from 100 to 500 m (with respect to climatology). Given the large seasonal and interannual variability, the huge influence of the variable wind field, and the different latitudes of the sections, many more observations would be needed to assess the seasonal cycle much less any climate trend from these observations.

Finally, to put the results from this analysis into context, results are compared to the mean value of the heat transport obtained as the residual calculations from air sea flux in the Atlantic Ocean. The net heat transport obtained by Garzoli and Baringer (2006) (0.54 ± 0.11PW) is similar to the one obtained from the NCEP reanalysis and very close to the one obtained by Lumpkin and Speer (0.60 ± 0.08 PW, 2006) for the WOCE line A11. The high-density lines AX18 are to be continued at the rate of 4 per year. After a sufficient number of realizations, it is assumed that these heat transport estimates will

become more robust. It is concluded that at these latitudes, the mean heat transport observed was 0.54 PW with an uncertainty of 0.18 PW.

Publications

Peer-reviewed:

1. Thacker, W.C., 2006. Estimating salinity to complement observed temperature, Part 1: Gulf of Mexico. *Journal of Marine Systems, In press*.
2. Thacker, W.C., and L.R. Sindlinger, 2006. Estimating salinity to complement observed temperature, Part 2: Northwestern Atlantic. *Journal of Marine Systems, In press*.

Submitted:

1. Baringer, Molly O. and Silvia L. Garzoli, 2006. Meridional Heat Transport using Expendable Bathythermographs. Part 1: Error Estimates, *Deep Sea Research, Submitted*.

2. Garzoli, Silvia L. and Molly O. Baringer, 2006. Meridional Heat Transport using Expandable Bathythermographs Part II: South Atlantic Ocean. *Deep Sea Research, Submitted*.

Technical/Progress Reports:

1. Baringer, M. O., C. S. Meinen and S. Garzoli, 2006. The Meridional Overturning Circulation and Oceanic Heat Transport, In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 68-73.

2. Baringer M., S. Garzoli, G. J. Goni, C. Thacker and R. Lumpkin, 2006. Quarterly Reports on the State of the Ocean: Meridional Heat transport Variability in the Atlantic Ocean. In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 265-268.

3. Baringer, M.O., G.J. Goni, and S.L. Garzoli, 2006. Atlantic high-density XBT lines. In *Annual Report on the State of the Ocean and the Ocean Observing System for Climate (FY-2005),* J.M. Levy, D.M. Stanitski, and P. Arkin (eds.). NOAA Office of Climate Observation, Silver Spring, MD, 181-182.

NATIONAL WATER LEVEL PROGRAM SUPPORT TOWARDS BUILDING A SUSTAINED OCEAN OBSERVING SYSTEM FOR CLIMATE

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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 associated with this effort 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 a new 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 used by the Climate Program Office are very much the same as used for the NOAA National Water Level Program (NWLP) for which the National Water Level Observation Network (NWLON) is a long-term continuous operational oceanographic network that's strives to meet 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 also consists of technology development, continuous quality control, data base management, and operational readiness and fully open web-site for data delivery. These data and related sea level products are made available over the web-site for use by PSMSL, UHSLC, and the WOCE communities.

Routine Sea Level Analysis Reports

A Climate Observation Program Workshop was hosted by the NOAA Office of Global Programs (OGP) on May 13 - 15, 2003. The objectives of the workshop were to:

1. Initiate an Annual Program Review

2. Design a framework for regular reports on the ocean's contribution to the state of the climate and on the state of the observing system.
3. Design a framework for implementing Expert Teams to continually evaluate the skill and effectiveness of ocean products and of the observing system.

There are 62 water level stations identified in the International Sea Level Workshop Report (1997) as being part of the core global subset for long term 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 Climate Observation Program produces an annual report on the state of the ocean and the state of the observing system for climate. CO-OPS produces an annual report on the 62 reference stations that will be one section of that larger report. The current CO-OPS report on sea level (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.

FY2006 Progress

CO-OPS completed the development efforts for the routine analyses for the 62 reference stations that include the 18 NWLON stations and 44 non-NOAA global stations found at:

http://tidesandcurrents.noaa.gov/sltrends/sltrends_global.shtml

The 18 NWLON stations that are part of the 62- station reference network are:

Name:	Series Length (years):
Atlantic City	90
Bermuda	59
Boston	80
Charleston	80
Crescent City	68
Fernandina Beach	104
Guam	53
Hampton Roads	74
Honolulu	96
Ketchikan	82
Key West	88

Kwajalein	55
Neah Bay	67
New York City	144
Pensacola	78
Portland	89
San Diego	95
San Francisco	150

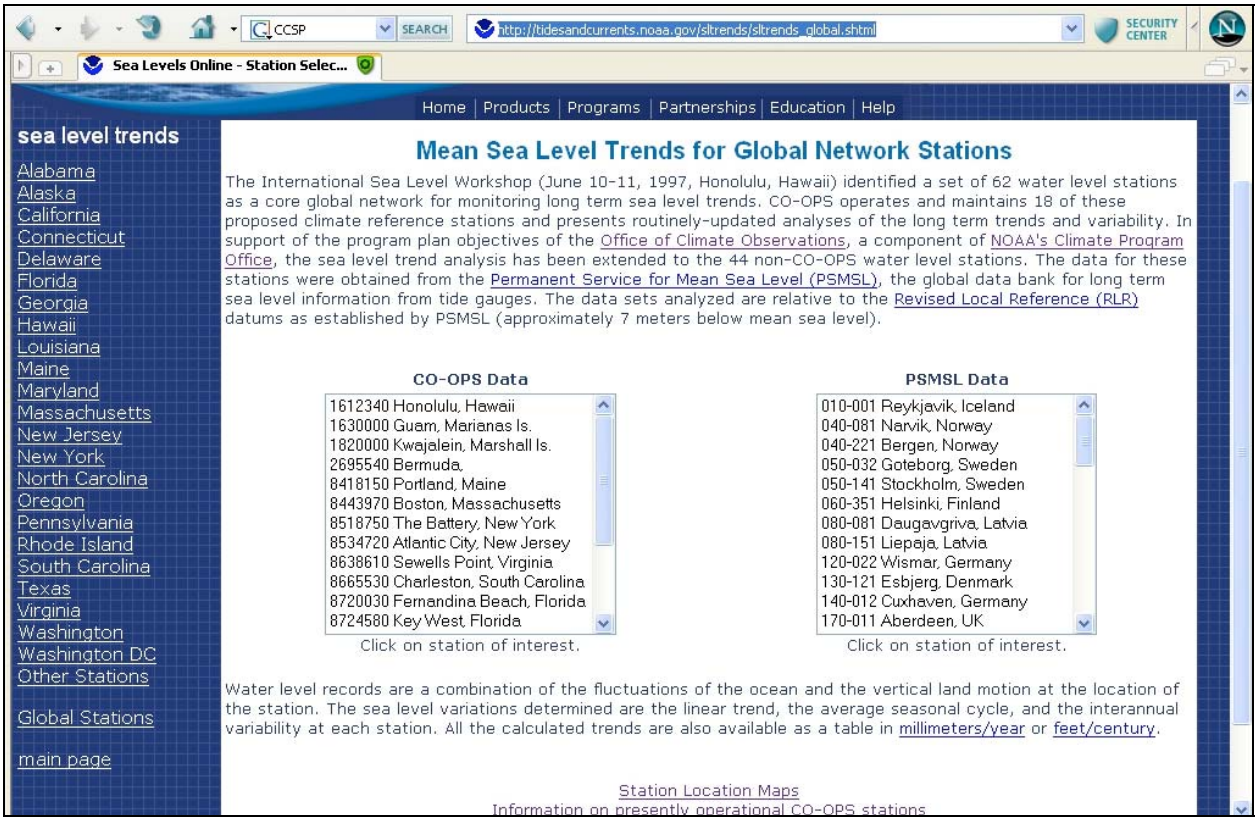

Figure 1. The new NOAA web-site for viewing information on sea level trends and monthly mean sea level anomalies at global tide stations.

The following figures illustrate the types of analyses being prepared for Honolulu:

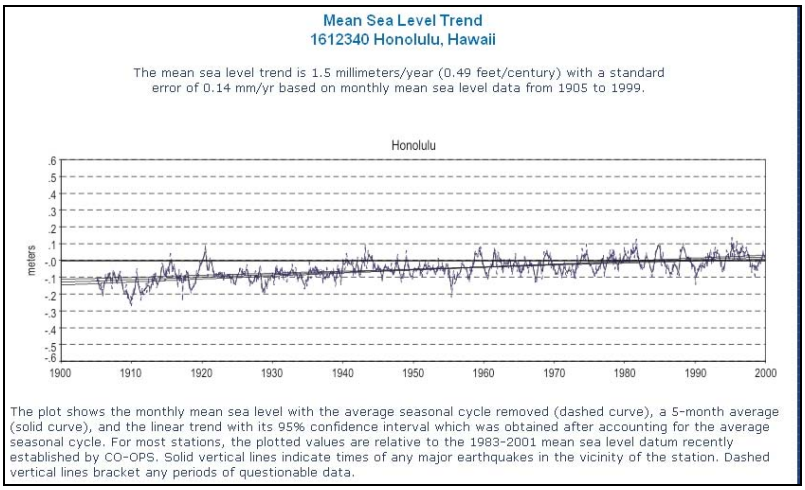

Figure 2. Sea level Trends Analyses are routinely updated.

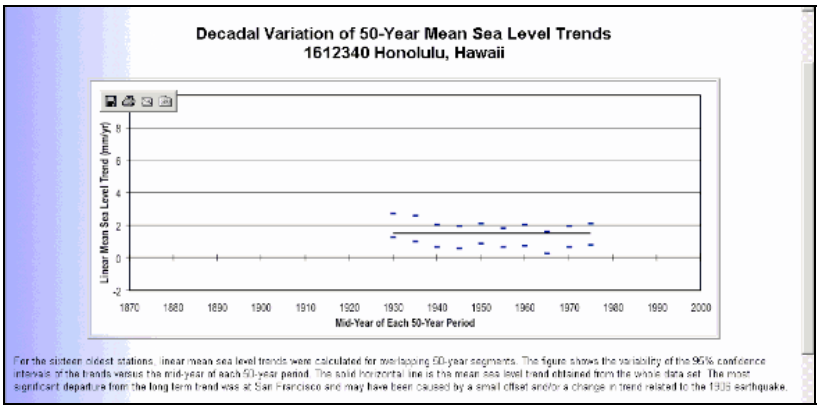

Figure 3. Long-term Variation in Trends are routinely updated.

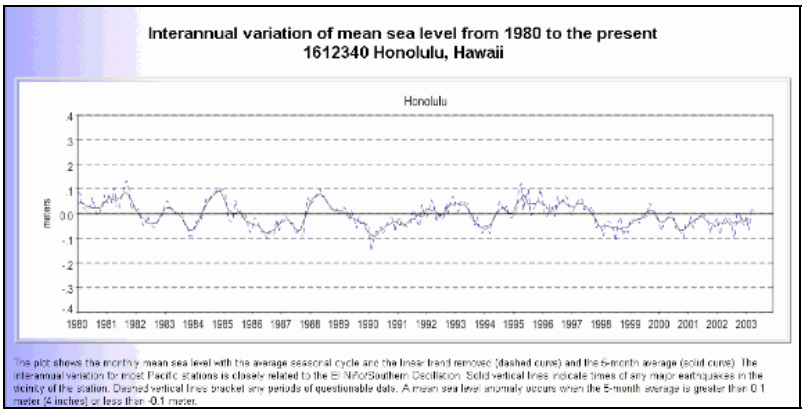

Figure 4. The Monthly Mean Sea Level anomalies are updated annually.

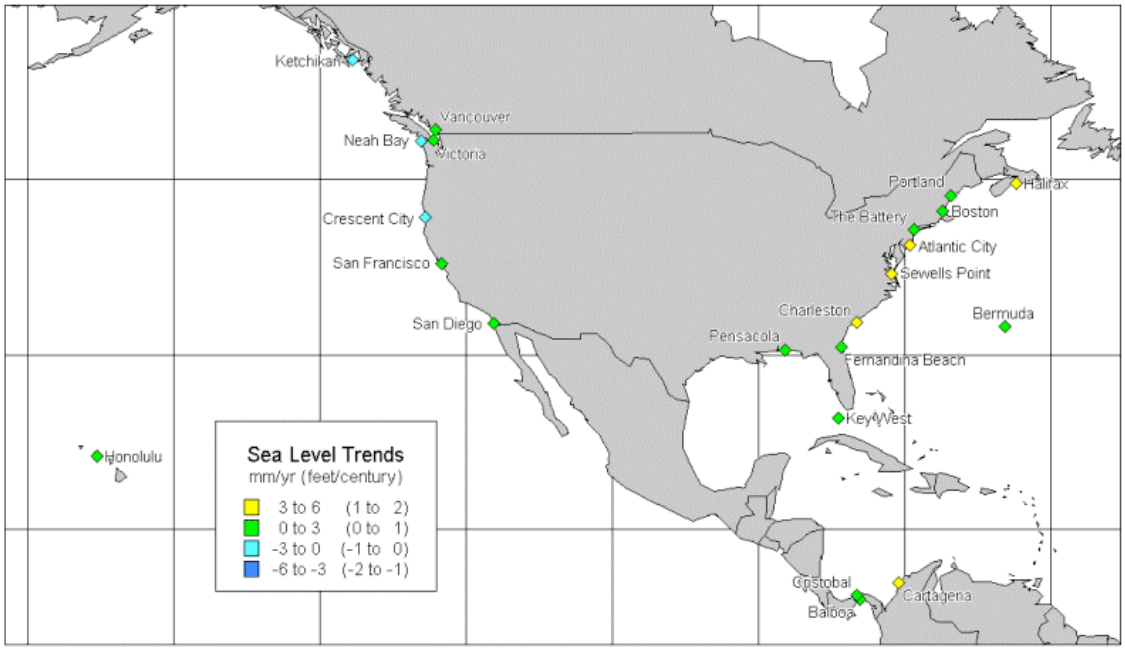

Figure 5. North America Relative Sea Level Trends

Similar sea level analyses have now been completed for the 44 non-NWLON stations. The monthly mean sea level data for these 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. The 44 stations are:

Station Name	Country	Year Range
Reykjavik	Iceland	45
Narvik	Norway	73
Bergen	Norway	118
Goteborg	Sweden	116
Stockholm	Sweden	114
Helsinki	Finland	122
Daugavgriva	Latvia	66
Liepaja	Latvia	71
Wismar	Germany	155
Esbjerg	Denmark	108
Cuxhaven	Germany	159
Aberdeen	UK	141
North Shields	UK	108
Newlyn	UK	88
Brest	France	193
Cascais	Portugal	111
Marseille	France	115
Genova	Italy	113
Trieste	Italy	96
Tuapse	Russia	85

Tenerife	Spain	72
Takoradi	Ghana	41
Aden	Yemen	90
Mumbai/Bombay	India	116
Vishakhapatnam	India	59
Ko Lak	Thailand	62
Xiamen	China	48
Mera	Japan	70
Aburatsubo	Japan	69
Tonoura/Hamada	Japan	108
Wajima	Japan	69
Manila	Philippines	68
Sydney	Australia	117
Fremantle	Australia	106
Auckland	New Zealand	97
Lyttelton	New Zealand	76
Vancouver	Canada	89
Victoria	Canada	90
Balboa	Panama	88
Quequen	Argentina	64
Buenos Aires	Argentina	82
Cartagena	Colombia	43
Cristobal	Panama	71
Halifax	Canada	107

The following example for these international stations follows the same presentation template using available data:

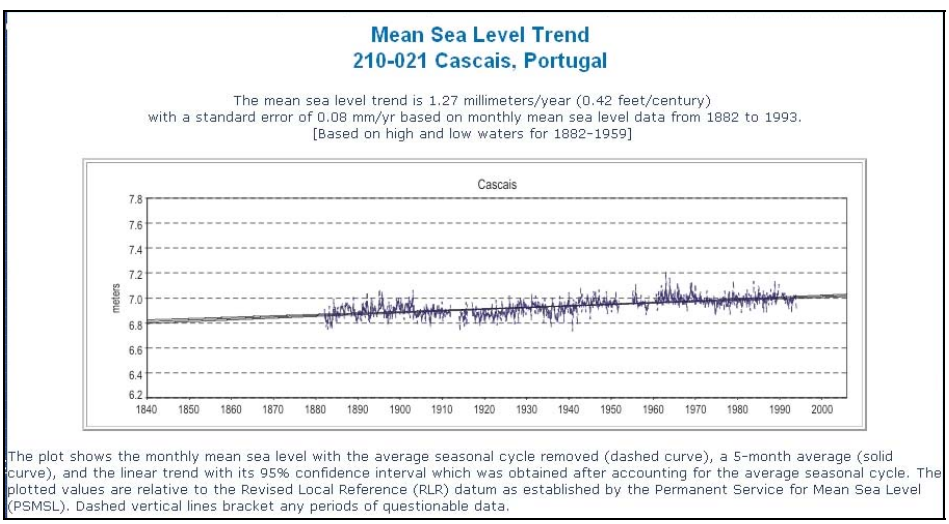

Figure 6. The Sea Level Trend Analysis

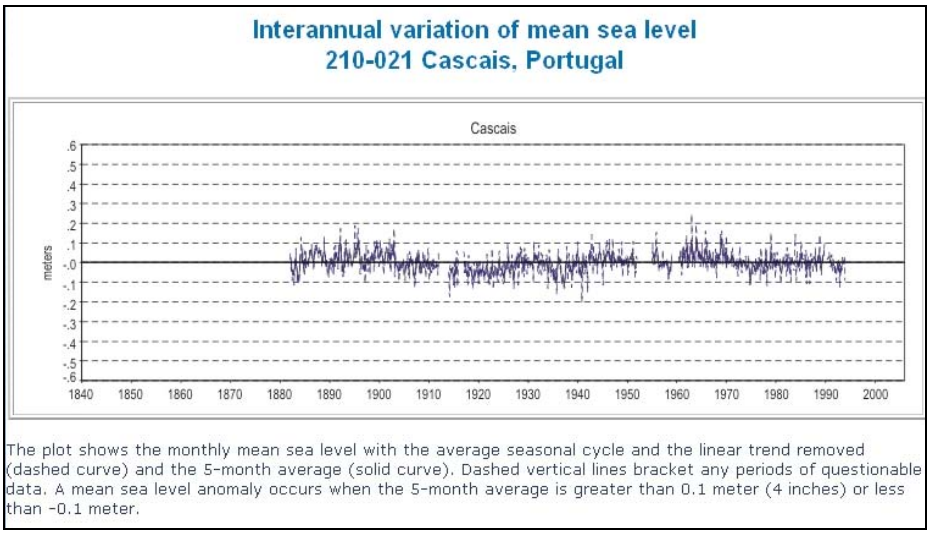

Figure 7. The interannual variation analysis.

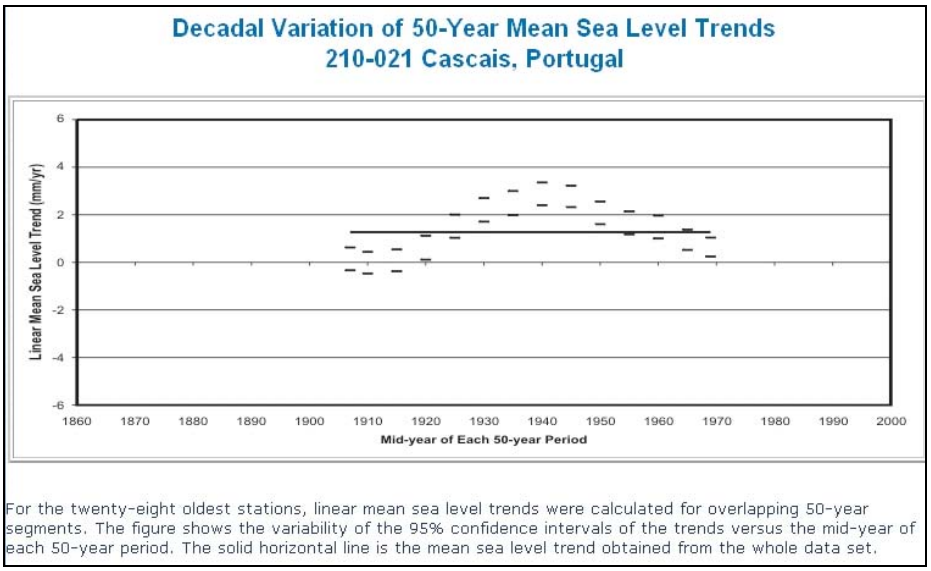

Figure 8. The decadal variation analysis.

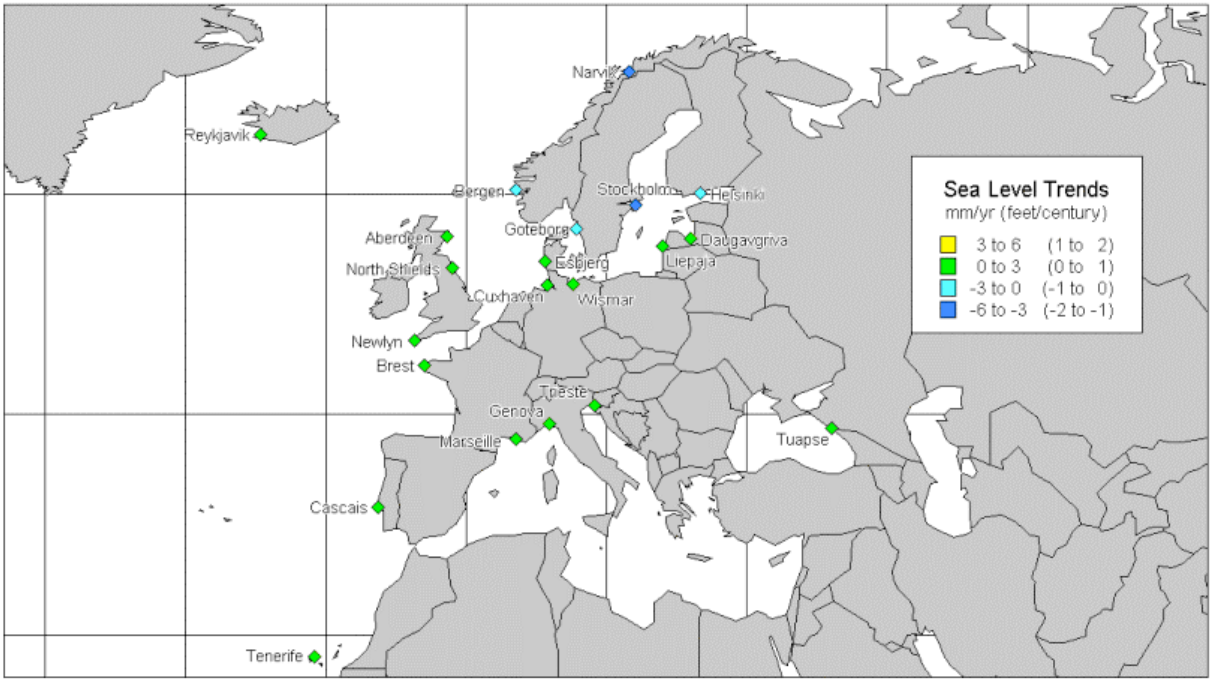

Figure 9. European Relative Sea Level Trends

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

Satellite Altimetry

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1. Project Summary

Sea level rise is potentially one of the more devastating consequences of global warming. As documented in a recent World Climate Research Programme workshop report[1], by 2010, 20 out of 30 of the world's meg-cities will be threatened by various degrees of inundation, enhanced erosion, and increased storm surge damage. The continuing rapid pace of U.S. coastal development is a particular concern, as Hurricane Katrina recently demonstrated in New Orleans.

The most compelling evidence of sea level rise comes from satellite radar altimeter observations. Figure 1 shows the altimeter-determined trend over the past 14 years compared with two historical estimates based on tide gauge observations. During the late 1800's – early 1900's the global mean level increased about 1 mm/yr, while during the second half of the 20th century the rate was 1.8 mm/yr. *The satellite altimeter observations indicate an even greater rate for the past decade, 3.1 mm/yr.* Measuring and explaining the cause of this apparent acceleration is a principle goal of the OCO Satellite Altimetry Program.

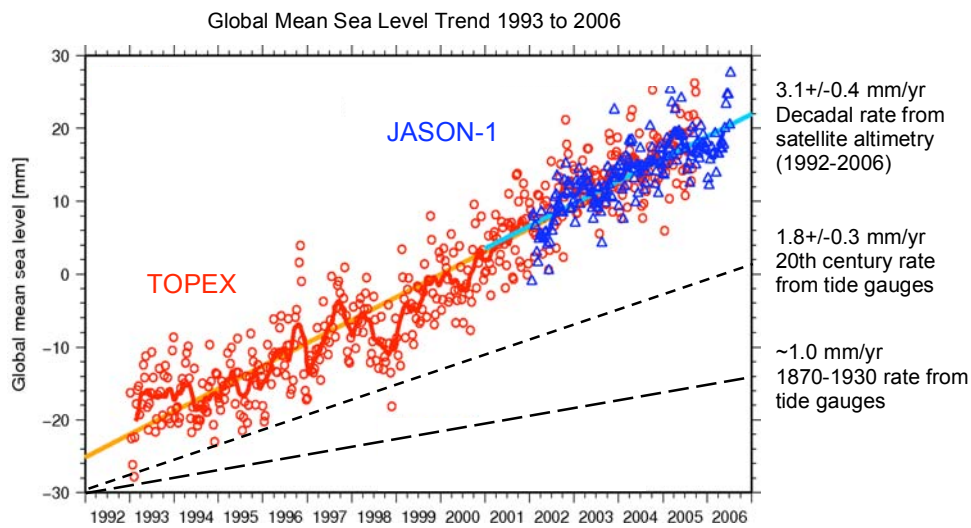

Figure 1. Global mean sea level trend from 1993 to 2006 based on TOPEX and JASON-1 altimeter observations. The trend over the past 14 years is roughly 2 times greater than the trend over the last half century and 3 times greater than the trend over the late 1800's – early 1900's. The latter two trends are based on tide gauge observations that only produce useful global estimates on intervals greater than 50 years, due to their limited geographical coverage.

Over the past several years we have developed several program elements that contribute toward this goal. They include:

- The design and maintenance of the NOAA Radar Altimeter Database System (RADS), a

collection of all of the different satellite missions processed and inter-calibrated in a consistent manner, widely used by the research community.

- The production of high precision Geosat and Geosat-Follow-On (GFO) orbits. Through an agreement with the U.S. Navy, NOAA is responsible for producing and distributing a research grade GFO data set. Producing enhanced GFO orbits makes the data from this particular mission more useful for climate research purposes.
- The reconstruction of past sea level change from a combination of satellite altimeter and tide gauge measurements. Our understanding of sea level change over the past century is largely derived from tide gauge measurements that, by their nature, don't provide good spatial sampling. In contrast, the altimeter data set provides dense spatial, but short temporal (~15 years) sampling. This project investigates ways of combining these two complementary sets of observations to improve our estimates of past sea level change.
- Research into new methods of calibrating altimeter observations with tide gauge measurements. Although each altimeter is subjected to a rigorous pre-launch calibration procedure, 15 years of experience has taught us that each mission must be continuously calibrated for bias and drift errors with in-situ observations that only tide gauges can provide. This project investigates ways of improving our calibration procedures, with a particular emphasis on learning how to connect non-overlapping satellite missions for the estimation of sea level rise.
- The design and maintenance of a web-based, public source of altimeter/tide gauge calibration information for all current and past satellite missions.

The NOAA Laboratory for Satellite Altimetry (LSA) has long been involved in climate related studies of sea level, having participated in every satellite altimeter mission: Geos-3, Seasat, Geosat, ERS-1, Topex/Poseidon (T/P), ERS-2, Geosat Follow-On (GFO), Jason-1, and Envisat. Many of these have been research programs or operational demonstrations. However, since the mid-1990s it has been possible to produce quick-look, altimeter-generated analyses of sea surface height with sufficient accuracy and resolution to have operational utility. This capability is largely due to advanced satellite orbit determination techniques based on systems like the Global Positioning System. As a result, NOAA now incorporates satellite altimetry in a number of its operational products. For example, near-real time sea surface height analyses are assimilated into NCEP ocean models used to forecast El Niño, hurricane intensification, and coastal circulation. NOAA/LSA also maintains the Radar Altimeter Database System (RADS), used to analyze climate time scale phenomena, such as global sea level rise.

Because of the value of altimetry to NOAA and the U.S. Navy, a commitment has been made to fly altimeters operationally as part of the National Polar-Orbiting Operational Satellite System (NPOESS). Negotiations are presently underway between NOAA, Navy and NASA, to determine how to best meet this commitment. In the meantime, NOAA must continue to leverage its resources to take advantage of existing satellite altimeter missions, and prepare to assume responsibility for the Jason-2 ground system beginning in 2008.

LSA maintains connections with many agencies, institutions, and programs. LSA staff members serve on NASA's Ocean Surface Topography Science Team, the Envisat altimeter advisory group, and science teams for CryoSat, and IceSat. See http://ibis.grdl.noaa.gov/SAT/

This project contributes to the NOAA goals (1) Understand climate variability, and (2) Serve society's needs for weather and water information. It provides the satellite altimeter "research-to-operations" component of NOAA's Program Plan for Building a Sustained Ocean Observing System for Climate.

2. FY06 Accomplishments.

a.) Support of the NOAA Radar Altimeter Database System (RADS)

In order to monitor global sea level rise and other ocean climate phenomenon with satellite altimetry, it is essential that records from different satellite missions be processed and inter-calibrated in a consistent manner. The NOAA Radar Altimeter Database System (RADS), designed and maintained by Remko Scharroo serves this purpose, as well as providing a tool for studying important ocean "weather" problems such as hurricane intensity forecasting. Over the past year, this project has processed and incorporated into RADS the data from the three currently functioning altimeters (Jason-1, Envisat, GFO). Many significant improvements have also been made to the Geosat data set (1985-1988), including waveform re-tracking corrections and the incorporation of new, more precise orbits (Scharroo et al., 2006). The impact of all of these improvements on the estimation of sea level rise will be described in a talk to be presented at the upcoming Jason-1/OSTST meeting in March (Miller et. al, 2007). In addition to these climate related activities, Remko Scharroo has continued his investigation into the use of altimeter observations for hurricane intensity forecasting (Scharroo et. al, 2005, 2006).

b.) GFO and Geosat Precise Orbit Determination

The U.S. Navy's Geosat Follow-On (GFO) altimeter mission has been operational since 2000. During 2006, the LSA used OCO funds to support the computation of precise orbits (F. Lemoine, NASA/Goddard) and worked closely with the Navy, NASA, universities, and project contractors to prepare and distribute final, research-quality Geophysical Data Records (GDRs). Thus far, LSA has produced 5 years of GDRs and distributed the data to users on DVD http://ibis.grdl.noaa.gov/SAT/gfo/). GDR production and distribution will continue routinely for the life of the GFO mission. In addition to the research data sets, GFO is a source of near-real time sea surface height that is used by the Navy and NOAA for ocean and atmosphere operations. As an example, the National Hurricane Center uses all available altimetry to compute "hurricane heat potential" maps as an aid to forecasting storm intensification. GFO contributes significantly to this activity as evidenced by recent *EOS* articles on Katrina published by members of the LSA (Scharroo, et. al, 2005, 2006).

OCO funds were also used to pay for the computation of new, more precise orbits for the first 1.5 years of the original Geosat mission, using an improved gravity field based on GRACE measurements. The new orbits greatly have reduced the random errors from 10 to 5 cm rms.

c.) Reconstruction of Past Sea Level Change from a Combination of Satellite Altimeter and Tide Gauge Measurements

There are two primary datasets used for measuring sea level change. Tide gauge measurements provide estimates of sea level change over the past century, but with relatively poor spatial sampling. The tide gauge data have shown an average rate of sea level rise of ~1.8 mm/year over the last 70 years. Satellite altimeter measurements from the TOPEX/Poseidon (T/P) and Jason satellites provide precise global measurements of sea level since 1992, but the record is relatively short. T/P and Jason have observed a rise of global mean sea level of +3.2 ± 0.4 mm/year [*Nerem and Mitchum*, 2001a; *Nerem and Mitchum*, 2001b]. While this result is reasonably certain, critical questions still exist about the interpretation of this result in the context of long-term climate variations. Uncertainties in the interpretation of the tide gauge record make it difficult to determine if the altimeter-derived rate represents a significant acceleration of sea level rise relative to the historical record. The tide gauge record is over a century long, but suffers from poor spatial distribution and uneven coverage in time. The altimeter record is relatively short, but has excellent near-global coverage. Therefore, it is natural to consider trying to take advantage of the best features of each dataset to investigate long-term sea level change.

The primary purpose of this research is to develop improved techniques to reconstruct sea level change over the past century using a combination of tide gauge measurements and satellite altimeter data. There has been considerable interest recently in reconstructing past sea level change [*Chambers, et al.*, 2002; *Church and White*, 2006]. There are a variety of different ways to combine altimeter and tide gauge sea level measurements to reconstruct past sea level change. We have been examining the advantages and disadvantages of different reconstruction techniques in order to select an optimal approach. However, all of the techniques are limited by the relatively short altimeter sea level record. This is because the variance of the altimeter record does not span the variance of the sea level record over the last century. Fortunately, as the altimeter time series lengthens, the results from the reconstruction techniques will improve.

Over the past year, we conducted sea level reconstruction simulations using output from the Parallel Climate Model (PCM) to better understand the impact of the reconstruction techniques and their errors on recovered GMSL records,. Basically, we used the model output to simulate both a 13-year altimeter record (1987-2000) and a 100-year tide gauge record (1900-2000), and then tried to recover the PCM global mean sea level variations using EOFs of the alimeter record combined with the simulated tide gauge data. The reconstruction appears to perform quite well for periods longer than 10 years. However at shorter periods, there are significant errors in the reconstruction. The results of this study form the basis of a University of Colorado Masters thesis (Jakubs, 2006). A journal article version of this work is currently being prepared

d.) Altimeter/Tide Gauge Calibration Research

This project investigates ways of improving altimeter/tide gauge calibration procedures, with a particular emphasis on learning how to connect non-overlapping satellite missions for the estimation of sea level rise. This is an important goal for two reasons. Looking forward in time, there is a strong possibility of an altimeter gap emerging some time after 2013, due to

funding problems and poor coordination between the various domestic and national programs. If there is a gap in the altimetric record of global mean sea level, it may be difficult to detect an acceleration in sea level rise due to uncorrected bias errors in the individual records. Looking backward in time, if a procedure could be developed for connecting non-overlapping missions it might be possible to lengthen the current time series by nearly 40% by combining the Geosat record with the TOPEX/Jason-1 records. A University of Maryland undergraduate student, Caroline Harbitz, was hired through CICCS to work with several members of the LSA on this problem over the summer of 2006 and also during the Winter 2007 semester break. The preliminary results from this study are very encouraging. Figure 2a shows a simultaneous fit to the unimproved (old orbits) Geosat, TOPEX, and Jason-1 data sets prepared by Remko Scharroo. Figure 2b shows the same fit using the improved Geosat data and a Geosat drift correction obtained from a comparison with tide gauge observations. The Geosat record has flipped from a steep downward trend a slight upward trend. Considerable work remains to be done to identify the cause of the Geosat drift and to reduce the bias errors. (Figure 2b does not use the bias correction derived from the altimeter/tide gauge comparison; it's still too poorly determined.) A paper describing work will be presented at the Jason-1/OSTM Science Working Team meeting in March (Miller, et al, 2007)..

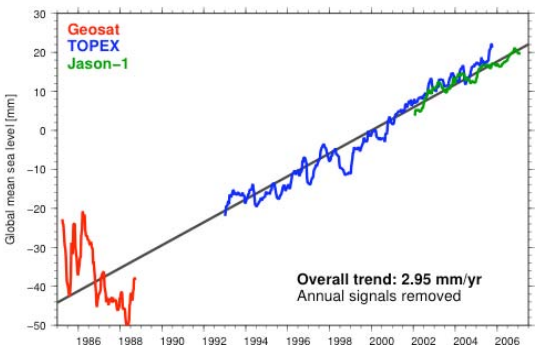

Figure 2a

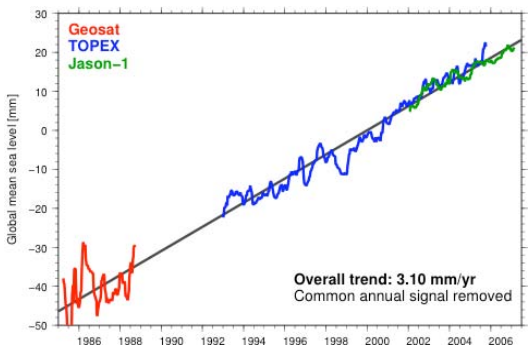

Figure 2b.

e.) Altimeter/Tide Gauge Calibration Web Site: Nancy Soreide, PMEL

The purpose of this project is to provide on a routine monthly basis a consistent set of tide gauge datasets (developed under other funding) for the calibration of current and historical satellite altimeter datasets. Although funds were received late in the fiscal year, progress has been made on this project. Funds have been put into contracts supporting the development effort. Dr. Gary Mitchum (University of South Florida) has reviewed existing successful websites providing similar data sets in order to determine the most effective and efficient way to provide data for this project. Two relevant websites included in the review include the OSCAR website (http://www.oscar.noaa.gov) and the Bering Sea Climate and Ecosystem website (http://www.beringclimate.noaa.gov). Out of these reviews, and after consultation with web experts at PMEL, the overall structure and layout of the website has been decided. It is possible some efficiencies can be achieved by code-sharing with the Bering Sea website. Preliminary design has been completed, but the implementation of the page may be delayed until the release of NOAA's new "One NOAA web page banner", which was approved in draft form by the

NOAA Executive Panel in mid-October 2006. Meanwhile, website navigation has been decided and we have a strategy for data presentation. If the release is delayed, we will need to revisit this decision, and perhaps proceed without the One NOAA web page banner.

3. Publications and Reports:

Jakub, T.D., "A Sensitivity and Error Analysis of a Sea Level Reconstruction Using Satellite Altimeter and Tide Gauge Data", Masters Thesis, University of Colorado, 2006.

Lillibridge, J.L., W.H.S. Smith, D. Sandwell, R. Scharroo, F. Lemoine, and N. Zelensky, "20 Years of Improvements to Geosat Altimetry", ESA 15 Years of Progress in Radar Altimetry Symposium, Venice, Italy, 2006.

Lillibridge, J.L., S. Calmant, "Geosat Follow-On Waveforms: Retracking for Hydrology Applications", ESA 15 Years of Progress in Radar Altimetry Symposium, Venice, Italy, 2006.

Miller, L., and B.C. Douglas, "Comparing Global Sea Level Rise Estimates from Satellite Altimetry and a Global Ocean Reanalysis: 1993-2001", ESA 15 Years of Progress In Radar Altimetry Symposium, Venice, Italy, 2006.

Miller, L., and B.C. Douglas, "On the Rate and Causes of 20th Century Sea Level Rise", *Phil. Trans. Royal Soc.,* **364***,* 805-820*,* 2006.

Miller, L., R. Scharroo, J. Kuhn, C. Harbitz, "Extending the TOPEX/Jason global mean sea level time series with GEOSAT observations", Jason-1/OST Science Working Team Meeting, Hobart, Tasmania, 2007.

Scharroo, R., W.H.F. Smith, J.L. Lillibridge, "Satellite Altimetry and the Intensification of Hurricane Katrina", *EOS Trans. AGU,* **38**, (40), 366, 2005.

Scharroo, R., W.H.F. Smith, J.L. Lillibridge, "Reply to Comment on Satellite Altimetry and the Intensification of Hurricane Katrina", *EOS Trans. AGU,* **87**, (8),89, 2006.

Scharroo, R., L. Miller, A. Ridout, and S. Laxon, "Global and regional sea level change from multi-satellite altimeter data", ESA 15 Years of Progress in Radar Altimetry Symposium, Venice, Italy, 2006.

Reconstruction of Past Sea Level Change from a Combination of Satellite Altimeter and Tide Gauge Measurements

R. S. Nerem
Cooperative Institute for Research in Environmental Sciences
University of Colorado at Boulder

PROJECT SUMMARY

There are two primary datasets that are used for measuring sea level change. Tide gauge measurements provide estimates of sea level change over the past century, but with relatively poor spatial sampling (Figure 1). The tide gauge data have shown an average rate of sea level rise of ~1.8 mm/year over the last 70 years. Satellite altimeter measurements from the TOPEX/Poseidon (T/P) and Jason satellites provide precise global measurements of sea level since 1992, but the record is relatively short. T/P and Jason have observed a rise of global mean sea level of +3.2 ± 0.4 mm/year (Figure 2) [*Nerem and Mitchum*, 2001a; *Nerem and Mitchum*, 2001b]. While this result is reasonably certain, critical questions still exist about the interpretation of this result in the context of long-term climate variations. Uncertainties in the interpretation of the tide gauge record make it difficult to determine if the altimeter-derived rate represents a significant acceleration of sea level rise relative to the historical record. The tide gauge record is over a century long, but suffers from poor spatial distribution and uneven coverage in time. The altimeter record is relatively short, but has excellent near-global coverage. Therefore, it is natural to consider trying to take advantage of the best features of each dataset to investigate long-term sea level change.

The primary purpose of our research is to develop improved techniques for reconstructing sea level change over the past century using a combination of tide gauge measurements and satellite altimeter data. There has been considerable interest recently in reconstructing past sea level change [*Chambers, et al.*, 2002; *Church and White*, 2006]. There are a variety of different ways to combine altimeter and tide gauge sea level measurements to reconstruct past sea level change. We have been examining the advantages and disadvantages of different reconstruction techniques in order to select an optimal approach. However, all of these techniques are limited by the relatively short altimeter sea level record. This is because the variance of the altimeter record does not span the variance of the sea level record over the last century. Fortunately, as the altimeter time series lengthens, the results from the reconstruction techniques will improve.

The basic reconstruction method is summarized in Figure 3. An Empirical Orthogonal Function (EOF) analysis is used to decompose the gridded altimeter sea level maps into a series of dominant spatial and temporal modes. The temporal modes are discarded and the spatial modes are retained. The tide gauge data are then projected on to the spatial map in order to reconstruct the temporal modes over the entire length of the available tide gauge record.

Recently, *Church and White* [2006] used a similar reconstruction over the past century and claimed to have detected an acceleration in sea level rise. While this is an interesting result, it should be regarded with caution due to the limitations of the reconstruction technique. One of the limitations of this result is that it depends on sea level measured by only a half dozen tide gauges at the beginning of the 20th century. The varying distribution of the tide gauges as a function of time and space is an issue we plan to investigate further. Among the issues we plan to investigate are:

1) The uneven distribution of the tide gauges in both space and time.
2) The relative weighting of the tide gauges in the reconstruction process.
3) The treatment of the altimeter data in the reconstruction process (number of EOFs, smoothing, etc.)
4) Investigation of different reconstruction methods.

As part of this research, we plan to develop improved techniques for reconstructing past sea level change. In addition, we plan to develop a realistic description of the errors in these reconstructions, which has not been done in past studies. Determining the errors in these sea level reconstructions is critically important if the results are to be used by decision-makers in the sea level community. Among the errors sources we will investigate are:

1) Error caused by the changing number of tide gauges through time.
2) The error caused by the altimeter data not spanning the variance of the century-long sea level record.
3) Random error caused by tide gauge errors, altimeter errors, etc.

Figure 4 shows an example of a reconstruction of GMSL using the available tide gauge and altimeter data, as compared to the *Church and White* [2006] reconstruction. We have only reconstructed sea level from 1950-2000, because the availability of fewer tide gauges before 1950 requires adjustments to the reconstruction techniques (reducing the number of EOFs, etc.)

Our recent efforts have been focused on understanding the errors in the reconstruction, so that we can better judge how significant the detection of an acceleration is [*Church and White*, 2006]. As part of developing an error budget for the reconstruction, we have been conducting simulations using the output of the Parallel Climate Model, as discussed below.

FY2006 Progress

In order to understand the impact of the reconstruction techniques and their errors on the recovered GMSL record, we conducted sea level reconstruction simulations using output from the Parallel Climate Model (PCM) [*Jakub*, 2006]. Basically, we take the model output, simulate both a 13-year altimeter record (1987-2000) and a 100-year tide gauge record (1900-2000), and then try to recover the PCM global mean sea level variations using EOFs of the alimeter record combined with the simulated tide gauge data. Figure 5 shows the results of this simulation. It shows a) the true GMSL variations computed from the PCM model, b) the reconstructed GMSL sea level record, and c) the sea level record constructed from a simple weighted average of the tide gauge data. Figure 6, which shows the difference between the true and reconstructed sea level records, similarly illustrates this. Not surprisingly, the reconstruction performs better after 1987, when the altimeter data better describes the sea level variance.

The reconstruction simulation using the PCM model has been a very useful tool for understanding the different errors inherent in such techniques. The results of the simulation are being used to assemble an error estimate that can be applied to reconstructions using real altimeter and tide gauge data.

References

Chambers, D. P., et al. (2002), Low-frequency variations in global mean sea level: 1950–2000, *J. Geophys. Res.*, *107*, 1-1 to 1-10.

Church, J., and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett.*, *33*, doi:10.1029/2005GL024826.

Jakub, T., A Sensitivity and Error Analysis of a Sea Level Reconstruction Using Satellite Altimeter and Tide Gauge Data (2006), M.S. Thesis, University of Colorado, Boulder.

Nerem, R. S., and G. T. Mitchum (2001a), Observations of Sea Level Change from Satellite Altimetry, in *Sea Level Rise: History and Consequences*, edited by B. C. Douglas, et al., pp. 121-163, Academic Press.

Nerem, R. S., and G. T. Mitchum (2001b), Sea Level Change, in *Satellite Altimetry and Earth Sciences: A Handbook of Techniques and Applications*, edited by L. Fu and A. Cazenave, pp. 329-349, Academic Press.

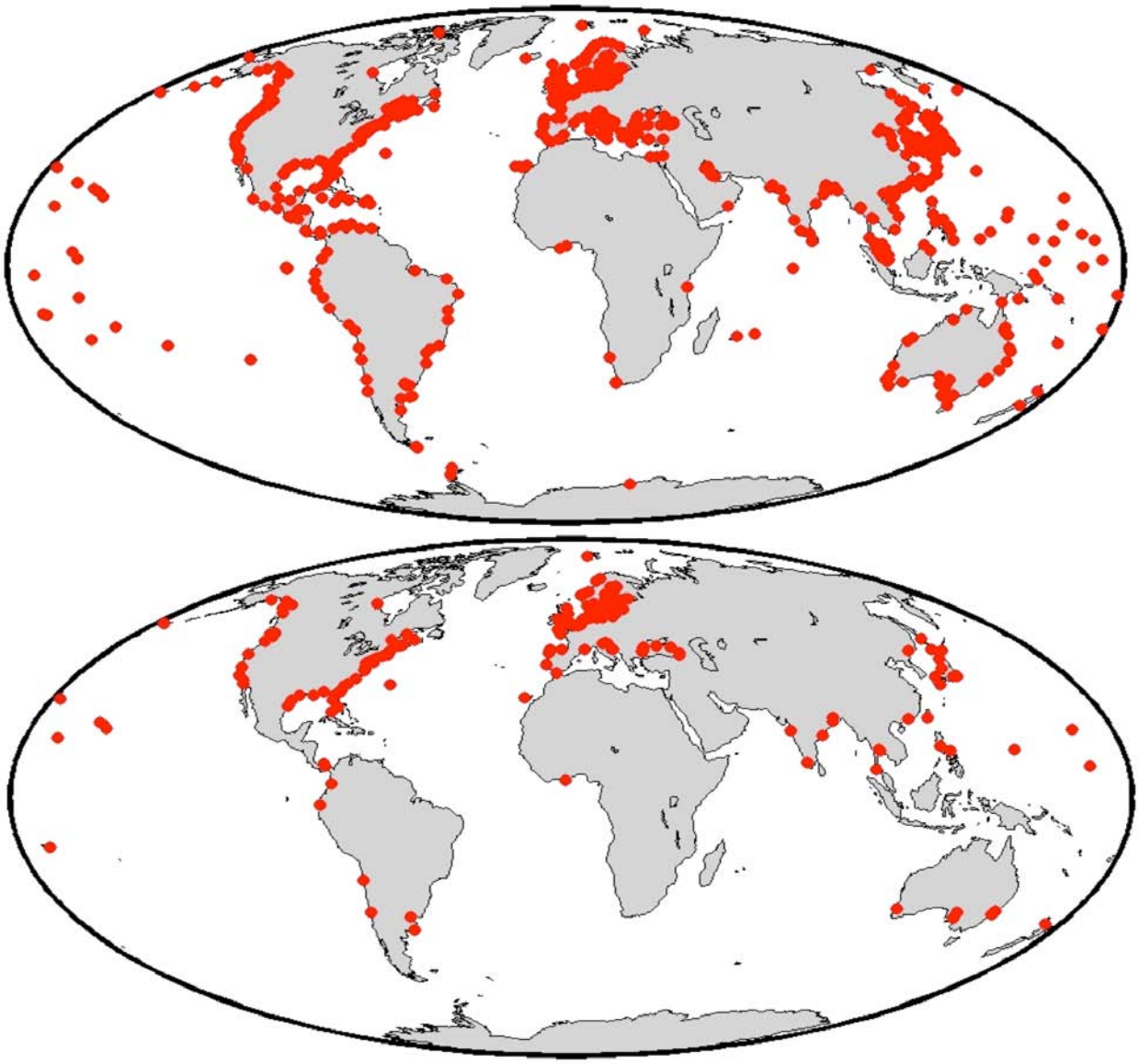

Figure 1. Tide gauge records in the holdings of the Permanent Service for Mean Sea Level (PSMSL) that have records longer than 10 years (top) and 50 years (bottom).

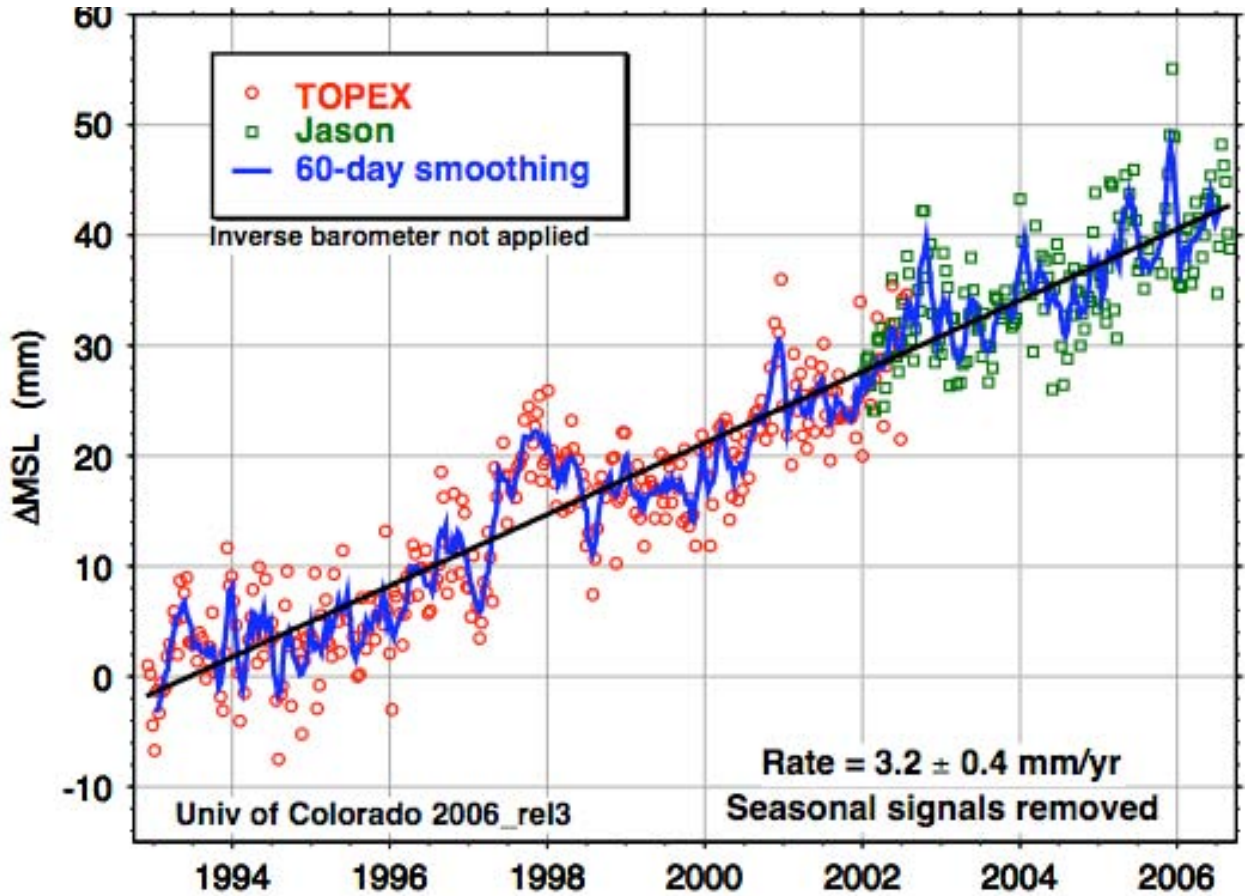

Figure 2. Global mean sea level (GMSL) reconstruction derived from a combination of TOPEX and Jason satellite altimeter data (1993-present) and globally distributed tide gauge measurements (1920-present).

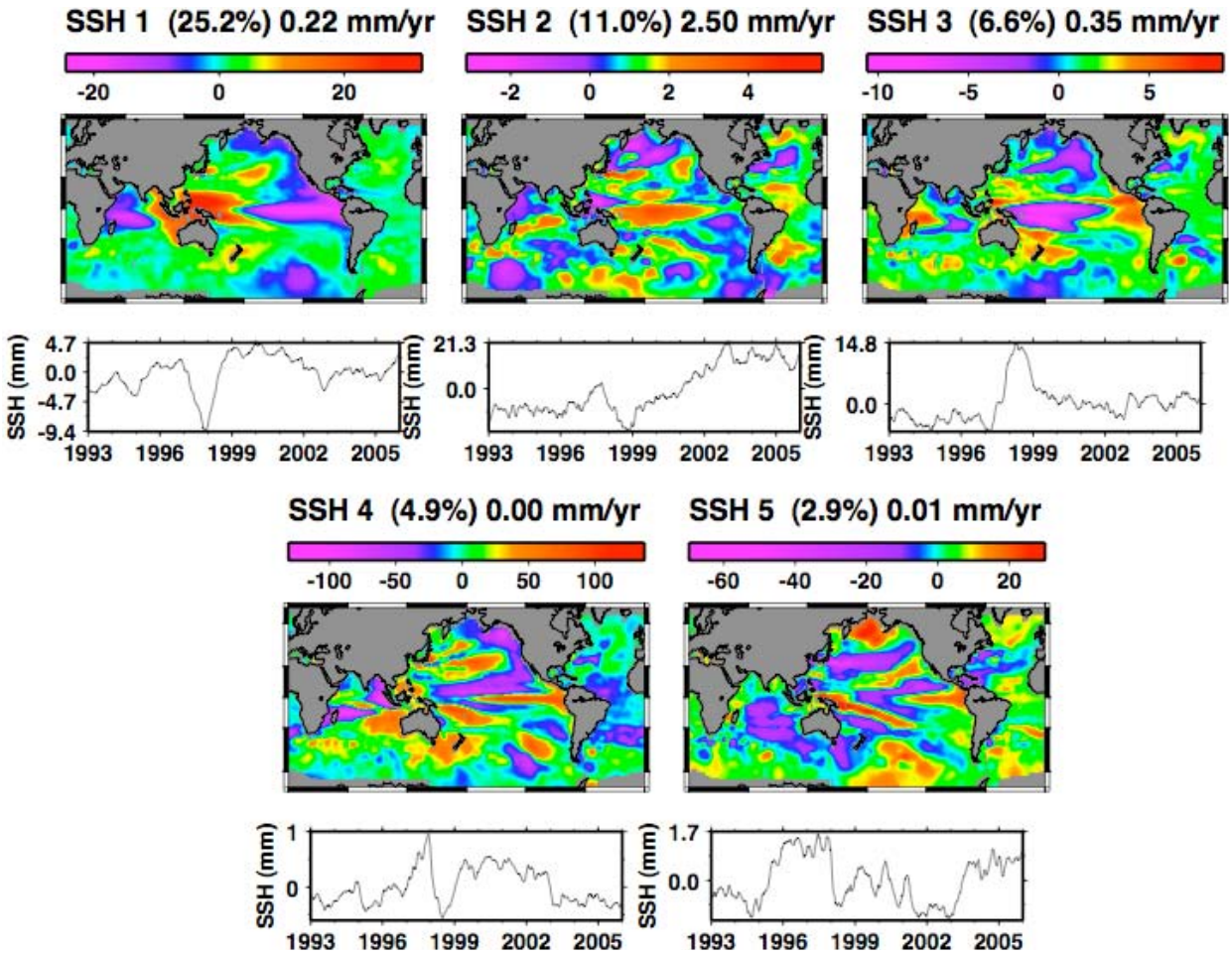

Figure 3. Empirical Orthogonal Function (EOF) decomposition of sea level variations from the TOPEX/Poseidon and Jason missions (first 5 modes only).

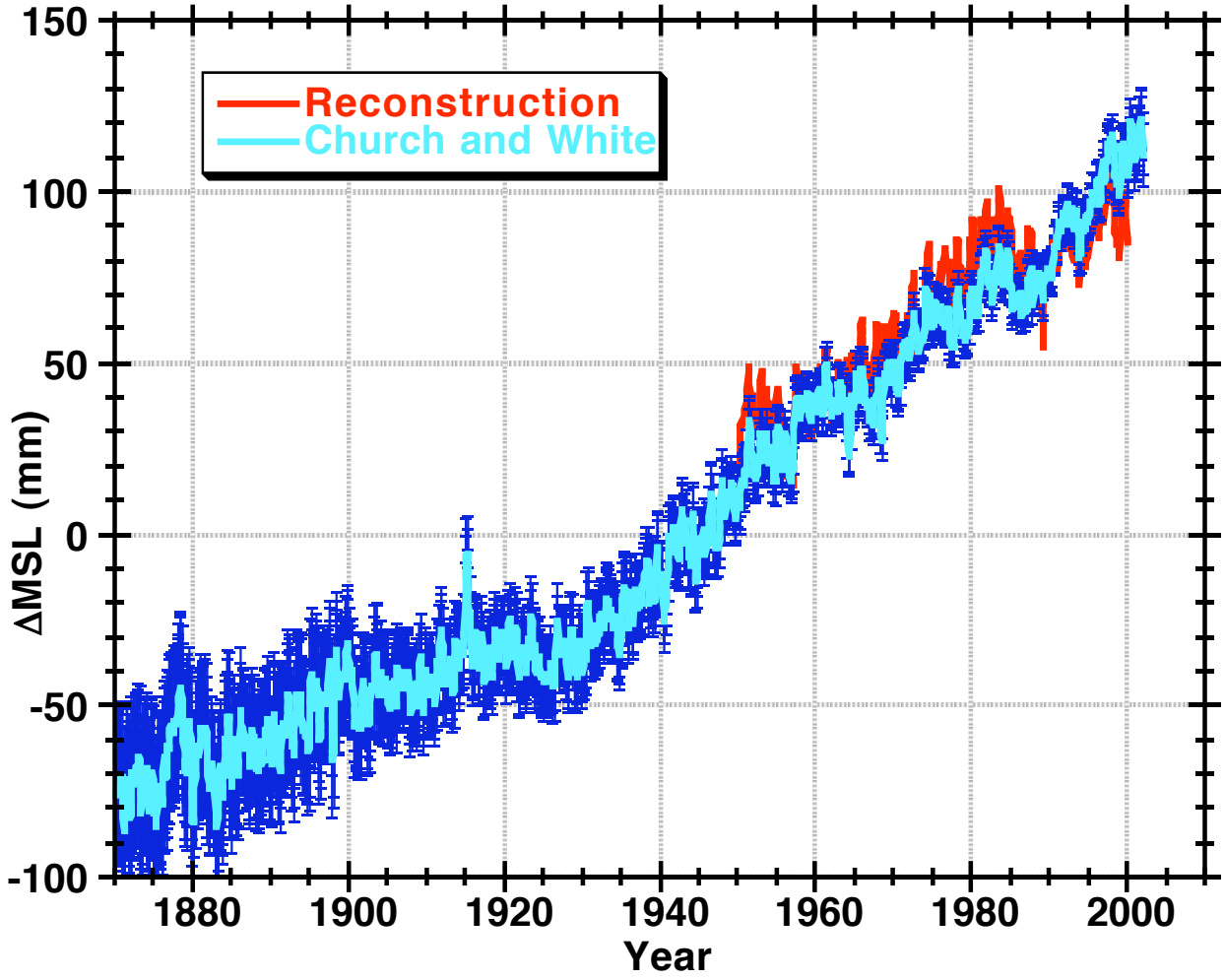

Figure 4. A comparison of two global mean sea level (GMSL) reconstructiosn derived from a combination of TOPEX and Jason satellite altimeter data (1993-present) and globally distributed tide gauge measurements (1870-present) [Church and White, 2006].

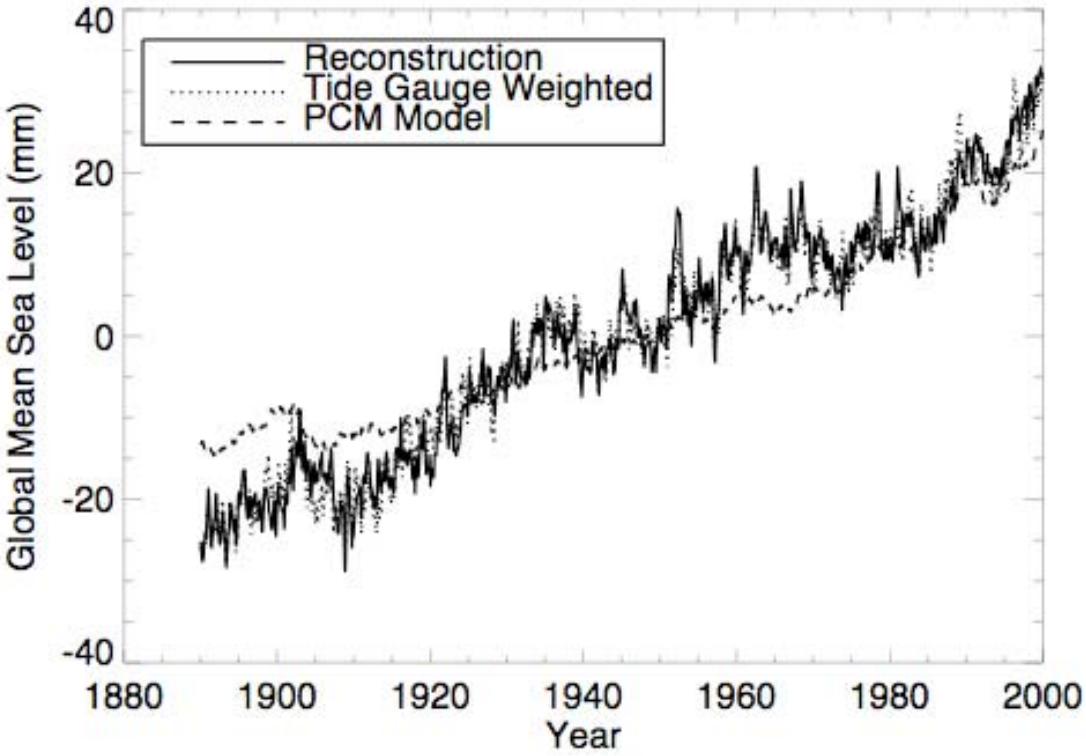

Figure 5. Time series of GMSL from the PCM model, the weighted tide gauges and a reconstruction from simulated altimeter and tide gauge data.

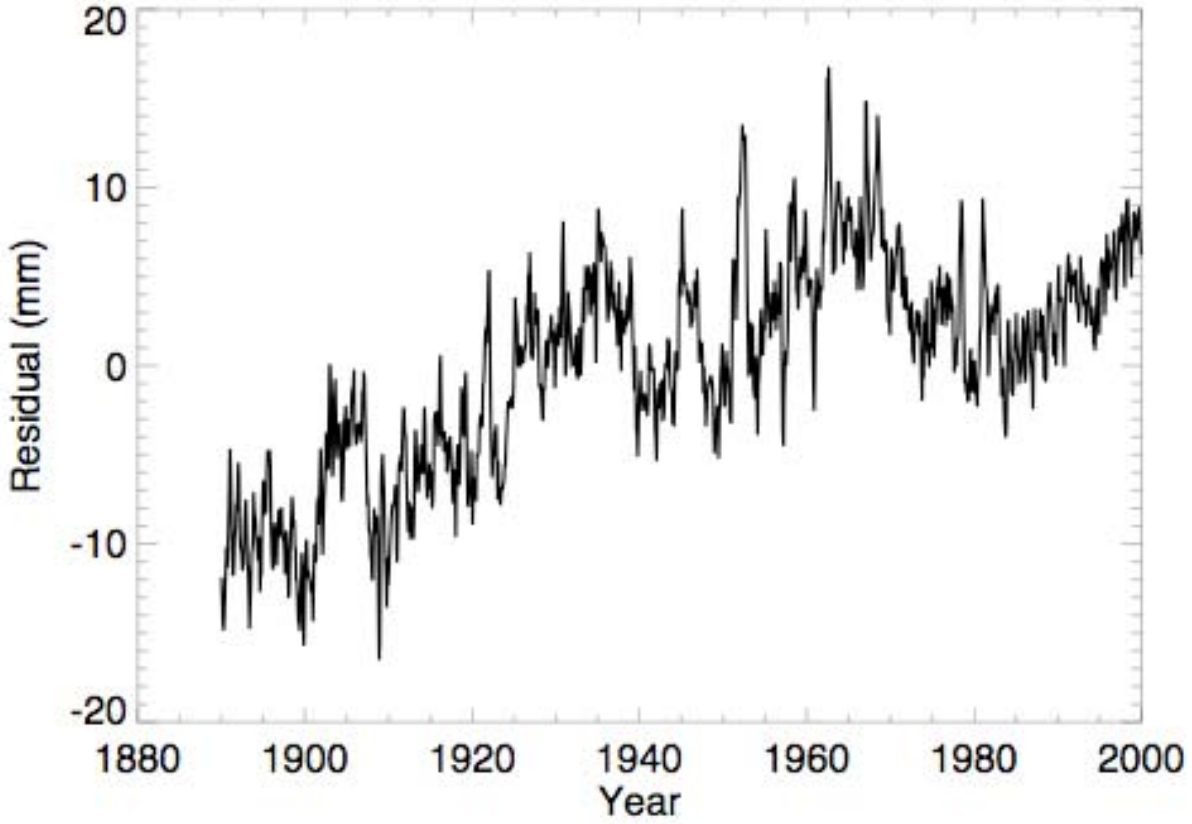

Figure 6. The difference of GMSL residual between the reconstruction and the PCM model has a different amount of variance before and after 1987 (corresponding to when the simulated satellite altimeter data begins), 5.85 mm^2 and 36.81 mm^2 respectively.

Global Carbon Data Management and Synthesis Project

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This project report combines three closely linked OCO projects:

Project 1: CLIVAR/ CO_2 Repeat Hydrography Program CO_2 Synthesis Science Team
Project Manager: Richard A. Feely[1]

Project 2: End-to-end Data Management System for Ocean pCO_2 Measurements
Project Manager: Steve Hankin[1]

Project 3: Understanding the Temporal Evolution of the Global Carbon Cycle Using Large-Scale Carbon Observations
Project Manager: Christopher L. Sabine[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 in a global change environment. 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. Because three of these OCO projects are very closely linked and often work together to generate an end product, we have combined the projects into one management and synthesis project as of this report. 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.

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 is 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 FY06 are discussed below.

ACCOMPLISHMENTS

Measurement Coordination and Initial Quality Control

Repeat Hydrography

Annual CO_2 science team meetings held by the Department of Energy (DOE) proved to be a valuable contributor to the coordination and quality control of the WOCE/JGOFS global survey data collected in the 1990s. These meetings provided an opportunity to discuss past data quality, potential refinements of the methods, and plans for future cruises (e.g. coordination of shipping, needs for reference materials, personnel issues). Learning from that approach, the scientists involved in the US CLIVAR/CO_2 Repeat Hydrography Program regularly meet to discuss measurement coordination and data quality issues. The last formal meeting of the measurement group was organized by Feely in September 2005 in Boulder, CO. This meeting examined the data quality issues for the recently completed A16S and P16S cruises as well as plans for future cruises including the NOAA led 2006 P16N cruise. Additional informal meetings of the group were held at the Fall AGU meeting in December, 2005 and the Ocean Sciences meeting in February, 2006. The group remains in frequent contact via email and phone and also works closely with the US CLIVAR/CO_2 Repeat Hydrography Steering committee through Richard Feely (co-chair), Gregory Johnson (committee member), Frank Millero (committee member) and Christopher Sabine (committee member).

The US activities are also coordinated with the international carbon community through the International Ocean Carbon Coordination Project (Christopher Sabine,

chair). Recognizing the immediate need for global-scale coordination of carbon observations and research efforts to achieve the goal of a global synthesis, the IOC-SCOR Ocean CO_2 Panel (http://www.ioc.unesco.org/iocweb/co2panel/) and the Global Carbon Project (GCP; http://www.globalcarbonproject.org/) initiated the International Ocean Carbon Coordination Project in 2002 (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 is being implemented.

In addition to overall coordination activities, the Global Carbon Data Management and Synthesis group has been working to ensure the timely submission of fully documented data to the Carbon Dioxide Information Analysis Center (CDIAC) for release to the public. CDIAC is also working closely with the IOCCP to help facilitate international coordination of cruises by creating a clickable map of completed CLIVAR repeat hydrography cruises (http://cdiac.ornl.gov/oceans/RepeatSections/repeat_map.html) that is linked to the IOCCP map of planned repeat hydrography cruises (http://ioc.unesco.org/ioccp/Hydrography/Hydro_Map.htm). Thus far, CDIAC has received and processed 12 international data sets from the repeat hydrography program. Data from two US cruises, A16N and A16S, have already been published as numeric data packages (NDP-085 & NDP-087) and are available in both hard copy and electronic (HTML) format from CDIAC.

Within this last fiscal year, we have produced two comprehensive cruise reports for the NOAA led cruises: A16S in 2005 (http://www.aoml.noaa.gov/ocd/gcc/a16s/) and P16N in 2006 (http://whpo.ucsd.edu/data/co2clivar/pacific/p16/p16n_2006a/index.htm). A separate report on the internal consistency of the carbon system parameters on A16S was published with the CDIAC NDP-087 (Wanninkhof et al., 2006a). Internal consistency calculations have been performed for the A16 and P16N cruises, taking advantage of the high quality pH, pCO_2, DIC, and TA data. The comparisons show that to fully constrain the carbon system, measurements of water column pCO_2 and/or pH are critical. These results suggest that the pCO_2 and/or pH measurements should be elevated to a level 1 parameter (from the current level 2 status). This proposal will be brought to the US CLIVAR/CO_2 Repeat Hydrography Steering Group and is one clear example how subsequent analysis of the data can feed back to decisions on measurement protocols.

The group is also working with Dr. Robert Byrne (University of South Florida) and others to evaluate new instruments capable of making high precision ship-board carbon measurements. A paper describing a novel underway system to measure pH, pCO_2, and DIC, used for the first time on a major cruise, A16S, is in preparation (Wang et al., in prep). Analysis was performed to compare the underway data with the discrete data obtained at the stations as a robust indicator of system performance.

Surface CO_2

A meeting of the NOAA funded surface pCO_2 investigators was organized by Wanninkhof in Miami, FL early in FY06 to discuss standardization of measurement protocols and data processing routines (http://www.aoml.noaa.gov/ocd/gcc/pco2/). As part of the meeting there was a round robin exchange of shipboard data between the groups to compare data reduction software. This exercise proved to be very useful for identifying the impact of differing data reduction routines. Many important agreements were reached that should improve the uniformity of data products coming from these groups in the future. The participants also discussed future improvements to the systems, agreements on running the systems in coastal regions, and efforts to work with a private company, General Oceanics, to build standardized instrumentation for the community. Working with the IOCCP, these agreements have been provided to the international community in an effort to promote a more uniform handling of surface pCO_2 data in the international community.

A joint meeting of the surface CO_2 group and the repeat hydrography group is planned for FY07 because there is some overlap in the coordination of all these measurements. This joint meeting should also promote a more integrated approach to data management and synthesis.

Data Management and Contextual Quality Control

Repeat Hydrography

All of the US CLIVAR/CO_2 Repeat Hydrographic data is managed by CDIAC and the CLIVAR and Carbon Hydrographic Data Office (CCHDO) at Scripps. As a world data center, CDIAC also collects and manages carbon data from many international cruises. Alex Kozyr from CDIAC is an active member of the Global Carbon Data Management and Synthesis Project and has been working with the group to improve the utility of the CDIAC data sets. The latest advancement is the development of a Web-Accessible Visualization and Extraction System (WAVES). This is a data management system that allows one to subset a large oceanographic data set based on a variety of spatial, temporal, or meta-data criteria (Figure 1). This program was developed at CDIAC with DOE funding but is benefiting the NOAA data management project. Currently, all of the CDIAC water column measurements are available through the system. The CDIAC surface CO_2 data should be completed and opened for public use in 2007.

In addition to the individual cruise files maintained at CDIAC, Robert Key at Princeton University also maintains a collection of cruises that have been merged together for the group's scientific analyses. The WOCE/JGOFS version of this collection is called GLODAPv1.1 and has been described in the literature (Key et al., 2004; Sabine et al., 2005). Over the past year significant progress has been made on the construction of a new data base which includes a temporal component. In large part the mechanics of constructing this data base are very similar to those used for GLODAPv1.1. The primary difference is that the new collection is based largely on cruise results generated by the European ocean carbon community. These data have not previously been available for use by U.S. scientists. Also significant is the fact that the vast majority of these new data are from the northern North Atlantic. Coverage of that area in GLODAPv1.1 was sparse to none.

The original "CARINA" collection of European cruises was transferred to

CDIAC for archiving and subsequently to Princeton for synthesis. The initial synthesis phase has consisted of primary quality control and collection of metadata. During the first two years of this effort Key attended all the CARBOOCEAN meetings (participation funded by CARBOOCEAN) and developed a close collaboration with the European community. This interaction combined with the initial data synthesis directly resulted in a significant increase in the data collection from 30 to 80 cruises (by mid summer 2006). In many cases the data from the new cruises is significantly better than the original collection. Primary quality control of all measured parameters from these 80 cruises and metadata collection has been largely completed. The task continues because previously unknown (yet relevant) data are continually being "discovered" for existing cruises and new cruises are still being added.

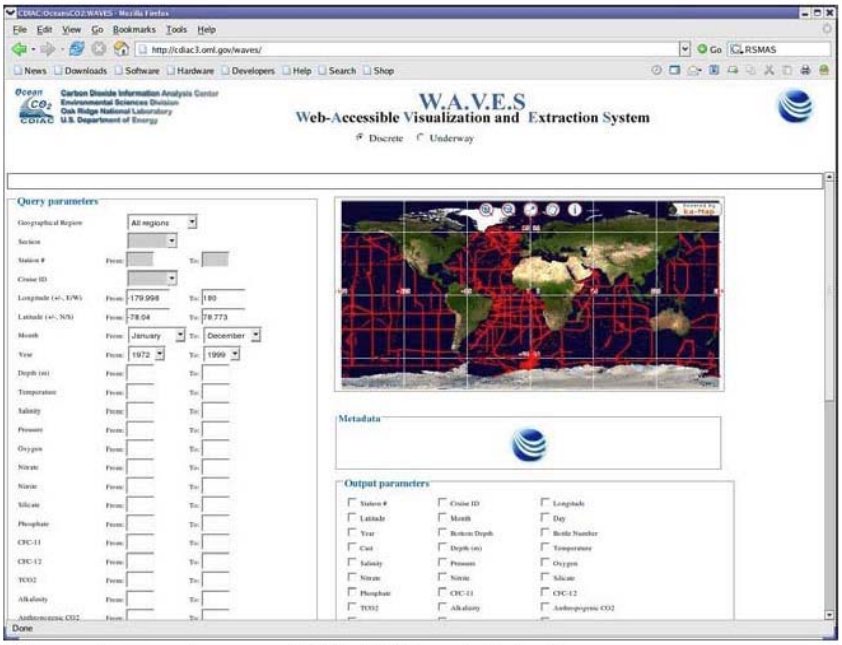

Figure 1. Front page of WAVES web interface.

CLIVAR data collection and processing has been progressing smoothly. With a couple of notable exceptions, all of the CLIVAR carbon data have been submitted to both CCHDO and CDIAC well ahead of the minimum time requirement of this program. The new U.S. data (and the Japanese CLIVAR data) have been extremely high quality. The combination of initial high data quality together with the fact that the Carbon Data Management and Synthesis group has extensive experience working together has made the quality control of these data almost routine. For example, Figure 2 shows a recent comparison of data from two CLIVAR/CO_2 Repeat Hydrography cruises in the North Pacific: the 2004 P2 cruise along 30°N and the 2006 P16N cruise along 152°W. The deep water values for temperature, salinity, DIC and total alkalinity agree very well between these cruises. Figure 3 also shows a comparison between the 2006 P16N data and the previous occupation of this line in 1991 along the relatively deep 41.425-41.450 σ_3 isopycnal surface. There appear to be no significant differences in any of the parameters examined at this surface indicating that the data are consistent with each other. Over determination of the carbon system on all NOAA led CLIVAR/CO_2 Repeat Hydrography

cruises has been extremely beneficial both for technical issues and scientific reasons. We encountered one major data issue during the past year when NODC imported (from CCHDO) and distributed raw shipboard carbon data from three cruises. However, the problem was quickly discovered by A. Kozyr (CDIAC) and steps have been taken to assure that this does not happen again.

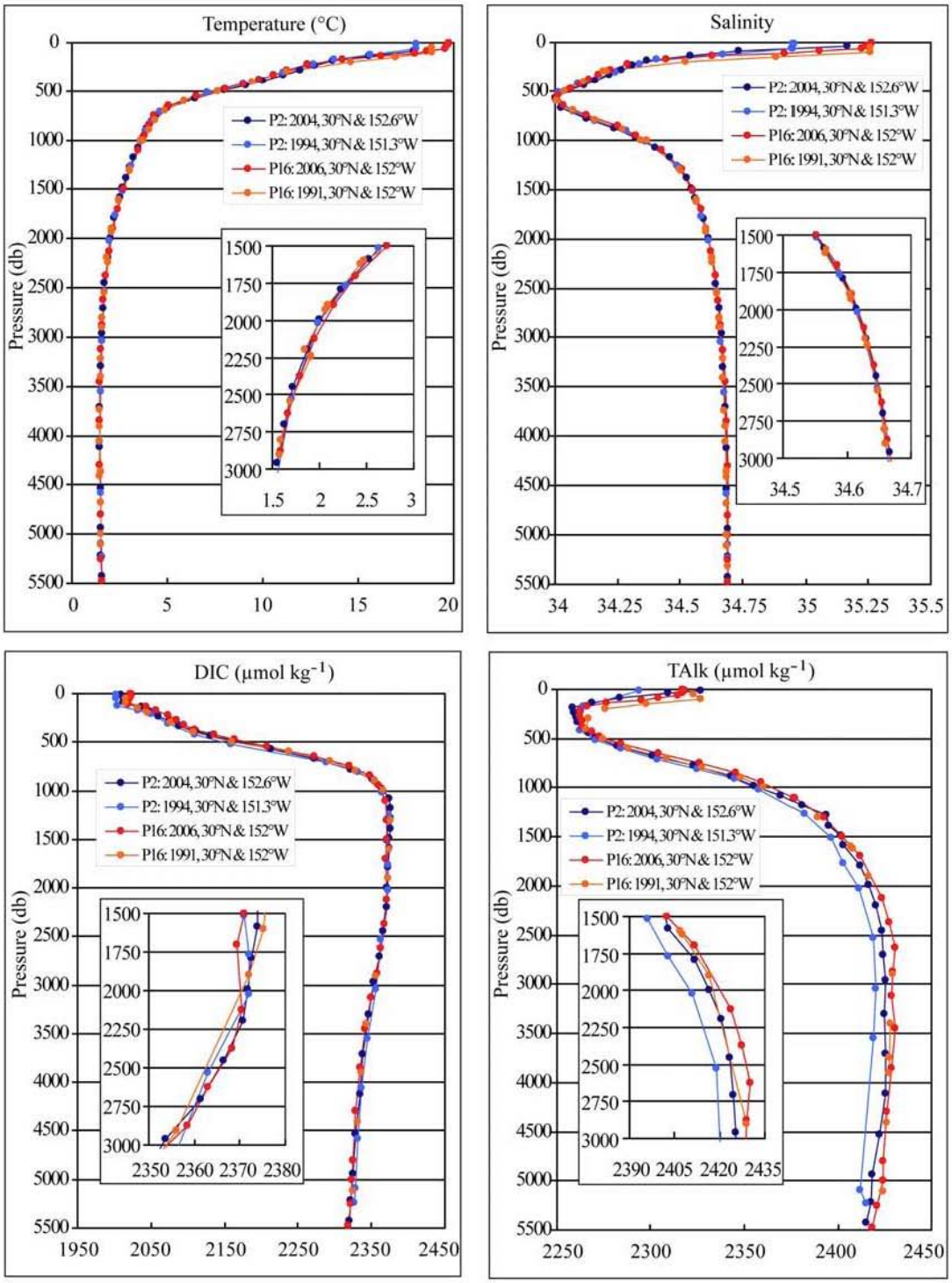

Figure 2. Comparison of profiles from stations near the intersection of P2 and P16N.

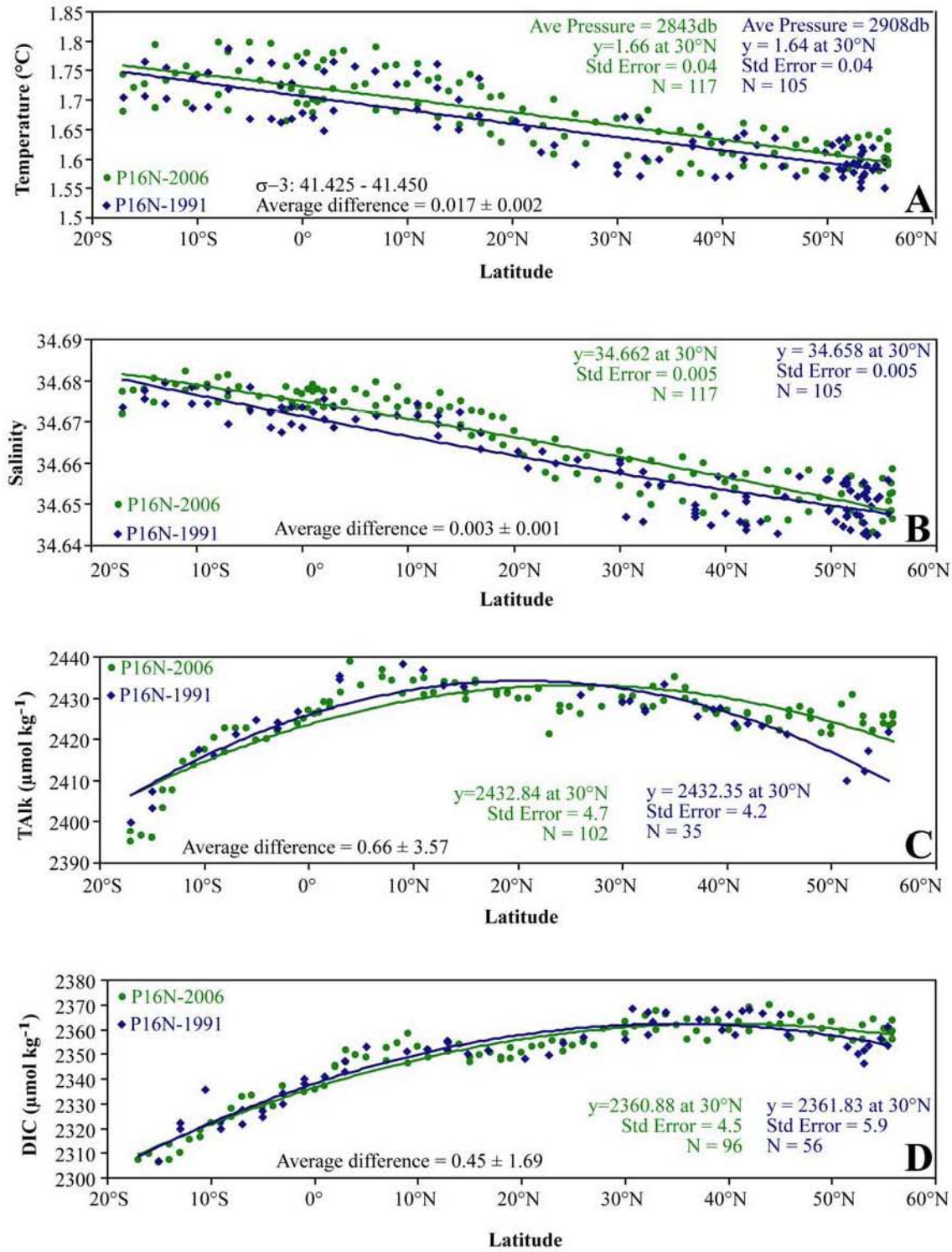

Figure 3. Comparison of 1991 P16N data with 2006 P16N data along 41.425-41.450 σ_3 isopycnal surface.

Surface CO_2

The PMEL data management infrastructure (software and hardware) is now in place to efficiently handle existing and new surface CO_2 datasets. Development of the Live Access Server (LAS) to make meaningful manipulations and displays of surface CO_2 measurements has been ongoing at PMEL for several years under Hankin's guidance. A prototype of this system based on the new LAS software has been populated with 1.2 million data records from the PMEL, AOML, and LDEO archives. The advantages of an integrated data management approach are already bearing fruit as the automated ingestion process was able to identify inconsistencies in several of the data sets such as duplicate records, out-of-range values, invalid dates, etc. Interaction between Dr. Callahan (PMEL) and the data providers resulted in corrections to data files that had been considered 'final'.

The Ocean Carbon Data Management System (OCDMS) at PMEL takes advantage of the latest LAS code that has been completely rewritten in the last two years with a new, more robust design and using recently available technologies. The new LAS code will allow for easier maintenance, installation and product development going forward. Many enhancements were made to the LAS user interface and output products so that individual cruises may be identified by name on plots. These plots show multiple cruise tracks which may be individually selected for inspection of metadata, single cruise visualization or subsetting. Subsampled versions of the complete database were created to optimize LAS performance when users request large regions of space and time. It is now possible to interactively produce LAS plots showing all data from all cruises – a significant achievement for a database of this size.

Once the OCDMS has been thoroughly tested by the Carbon Data Management and Synthesis group, it will be replicated at CDIAC for large-scale community use. Efforts are currently underway to ingest the recently acquired Takahashi data set which contains in excess of 3 million data points. While these data will be preserved as a unique data set, the LAS system will allow users to subset and explore the data efficiently.

CDIAC and the rest of the group are also working with the international community through the IOCCP to standardize data and metadata reporting for surface CO_2 data. However, not all investigators measure exactly the same parameters. Calculations to convert measured values to standard units have not always been well documented. In an effort to support this move towards standardized reporting, AOML, PMEL, and LDEO have reformatted all of their historical data to be consistent with the internationally agreed upon formats.

CDIAC has generated a web site with clickable maps showing past and current Volunteer Observing Ship (VOS) lines (http://cdiac.ornl.gov/oceans/VOS_Program/VOS_home.html) and CO_2 mooring locations (http://cdiac.ornl.gov/oceans/Moorings/moorings.html). These maps are closely linked with IOCCP maps showing current and planned VOS lines and CO_2 moorings.

Synthesis and Interpretation

Repeat Hydrography

The repeat hydrography cruises have received a lot of attention in the scientific community. All of the members of the Global Carbon Data Management and Synthesis group have given talks at a wide variety of meetings based on the repeat hydrography data and papers are starting to come out presenting some of the results. This past year a special session was organized by L. Talley and R. Feely at the AGU/ASLO Ocean Sciences meeting in Honolulu, Hawaii titled "Decadal Variations in Ocean Interior Circulation and Biogeochemistry: Results From the CLIVAR/CO_2 Repeat Hydrography Program". Feely has organized a similar session at the Fall AGU meeting this December. He has also published an article in EOS describing the repeat hydrography program and summarizing the results to date (Feely et al., 2005). The community has recognized that these cruises are a great contribution to our improved understanding of ocean carbon changes.

Now that we are approximately half way through the first global repeat hydrography survey, many international synthesis and interpretation efforts are developing. Our group has been actively involved in several efforts including an Atlantic synthesis meeting in Laugarvatn, Iceland in June 2006, discussions of a Pacific synthesis at the PICES annual meeting in Yokohama, Japan in October 2006, and discussions of an Indian Ocean synthesis at the SIBER meeting in Goa, India in October 2006. There have also been recent email discussions of forming a Southern Ocean synthesis activity through CARBOOCEAN including members of our group. Our NOAA project is one of the only organized groups that are affiliated with synthesis activities in all of the major ocean basins.

Our group has been actively sought out to participate in the synthesis activities because we have valuable experience from our GLODAP synthesis of the WOCE/JGOFS data, because we have important data holdings to contribute to a synthesis effort and because we are seen as leaders in promoting and organizing data synthesis activities. We have been actively involved in data synthesis for many years and have been important contributors to a growing realization among scientists that interpretation of the repeat hydrography data will not be as straightforward as initially thought.

During the initial GLODAP synthesis the steady state assumption (in one form or another) was core to many of the analyses. Subsequent analysis by this group and many others has demonstrated that our assumptions were reasonable under the conditions we had for that synthesis. Paramount among these was the simple fact that the time separation between WOCE and previous measurement programs was 15-25 years. Over that time span changes due to the invasion of anthropogenic carbon effectively masked any changes due to biology or physics. CLIVAR is repeating WOCE/JGOFS lines with a time separation of about 10 years. Over this time frame the signal to noise ratio is much smaller and we are now strongly focused on change rather than simply asking distribution and inventory questions. In other words, the scientific analysis is significantly more difficult than anyone imagined.

We initially hoped that a reasonable estimate of the change in anthropogenic carbon could be obtained simply by repeating measurements along the WOCE/JGOFS

sections then using either simple Multiple Linear Regressions (MLR) or subtraction to find the decadal change. Either of these techniques do show the absolute change in inorganic carbon, however a significant fraction of that change is due to processes other than simple invasion of the anthropogenic signal. Probably the two most important factors which were not initially considered are interannual circulation variations and changes in oxygen ventilation. Recently Feely, Sabine and Wanninkhof have worked with other researchers to develop various new analysis techniques including oxygen corrections and MLR variants to isolate the anthropogenic component. For example, Figure 4 shows a series of sections from the P16 line along 152°W in the central Pacific. This line, completed in 2006, was last occupied in 1991. The top plot shows a section of the observed change in dissolved inorganic carbon (DIC) during the 15 years between cruises. These results are based on a multiple linear regression to remove small variations in the water mass locations. Figure 4B shows the change in apparent oxygen utilization (AOU) along the section. These changes in AOU could result from changes in biological production/decomposition, from changes in water mass age, or from changes in oxygen ventilation at the surface. Figure 4C shows the AOU change converted to carbon units based on a Redfield C/O ratio of 117/170. Figure 4D is the difference between the observed carbon changes (4A) and the non-gas exchange impacts on carbon (4C). This difference should represent the anthropogenic CO_2 uptake in the Pacific over the last 15 years. We are still working to validate these preliminary results, but the initial conclusion is that the ocean carbon cycle is responding to more than just the simple invasion of anthropogenic CO_2 and these other processes can be of the same order of magnitude as the anthropogenic signal.

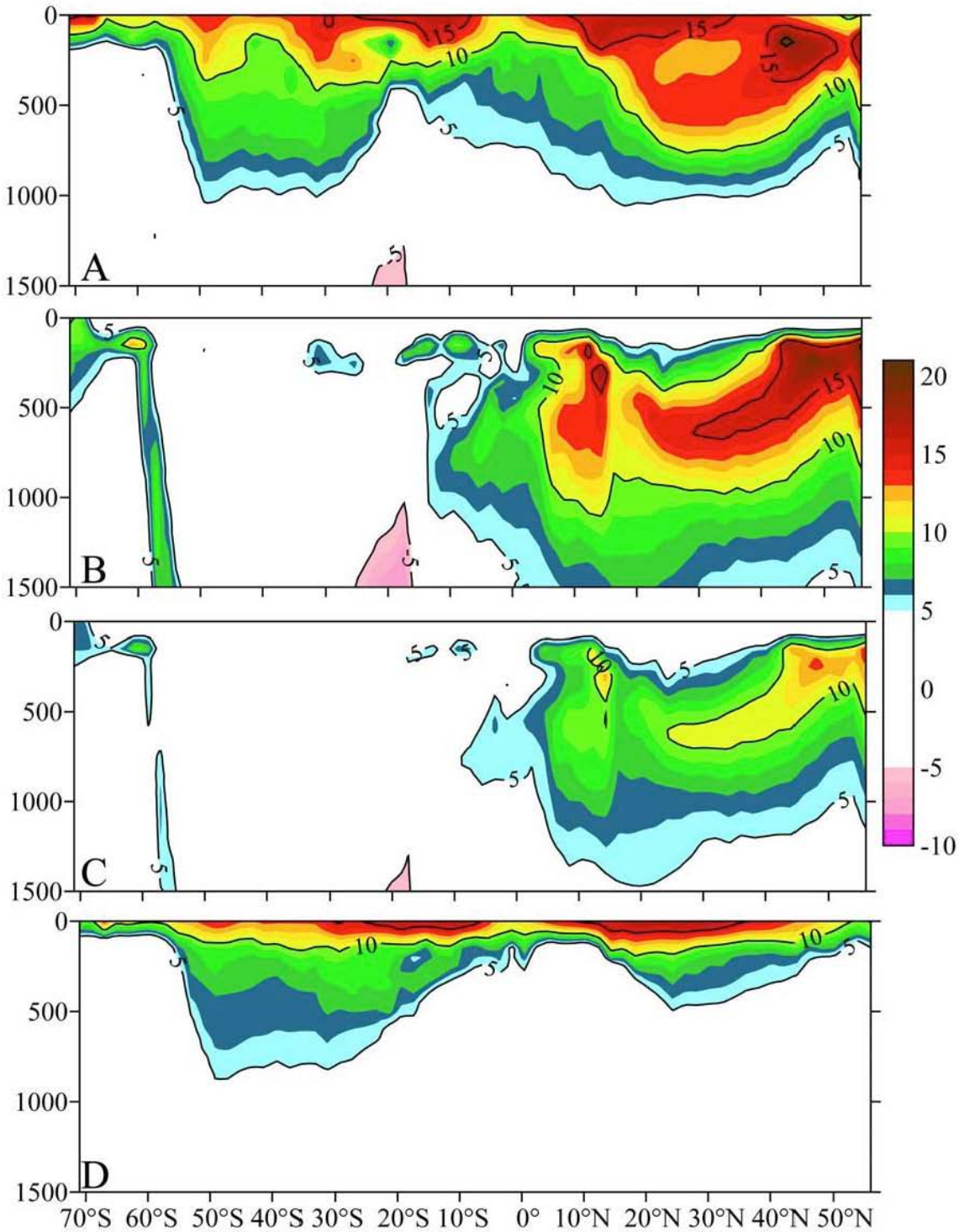

Figure 4. Sections of (A) observed DIC change, (B) changes in apparent oxygen utilization rate, (C) DIC change from AOU based on Redfield conversion from oxygen to carbon, and (D) anthropogenic DIC change (observed DIC – AOU based DIC change) between 1991 and 2006 along P16 (150°W).

Members of the Global Carbon Data Management and Synthesis group have also

been involved in model-data comparisons, further evaluations of the ΔC* based anthropogenic CO_2 distributions and the evaluation of alternative independent approaches for estimating anthropogenic CO_2 total inventories. As part of a continuing effort to increase the global carbon database, Peng has been working to evaluate historical carbon data sets relative to the WOCE/JGOFS data. The carbon data collected during the GEOSECS program in early 1970s represent the first systematic survey of inorganic carbon parameters on a global scale. These data can provide a critical time period for evaluating changes in ocean carbon inventory relative to later cruises. It is essential, however, that the historic GEOSECS data set is consistent with recent high quality carbon data collected using improved measuring techniques and validated with the use of reference materials. Re-evaluation of GEOSECS carbon data in the Atlantic Ocean by examining properties in deep water at crossover stations between GEOSECS and WOCE cruises shows that DIC measurements made during the GEOSECS program are systematically higher than those made during the WOCE/JGOFS global CO_2 survey (Figure 5). These systematic changes, however, vary from one GEOSECS expedition to the next. Atlantic DIC offsets range from 5 ± 5 μmol kg^{-1} south of 15°S to 27 ± 9 μmol kg^{-1} north of 15°N.

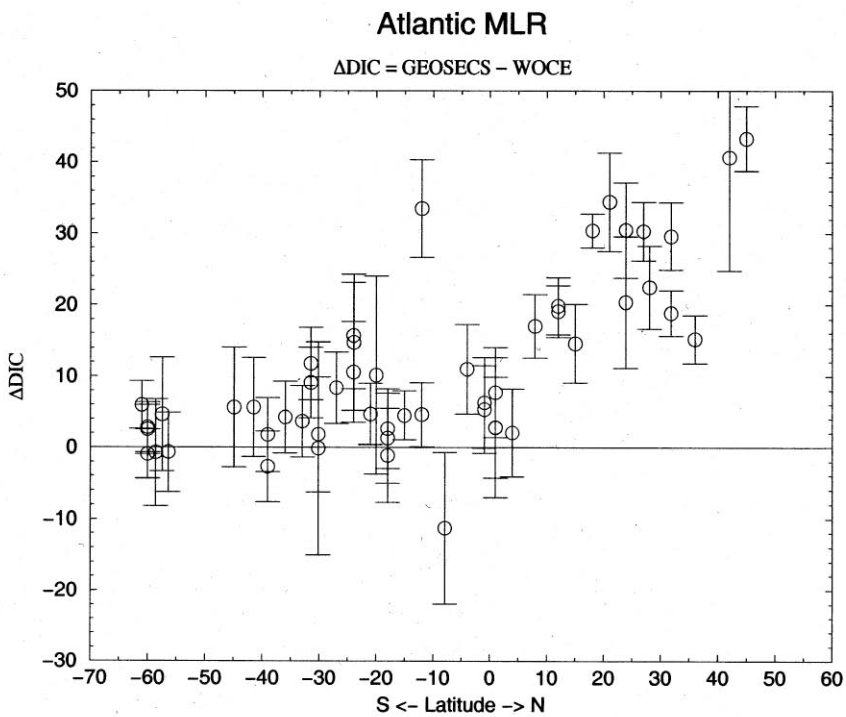

Figure 5. Systematic offsets of DIC in the Atlantic between GEOSECS and WOCE as determined by MLR method using crossover station deep-water properties.

Using MLR approaches to evaluate the water column changes in DIC between the bias corrected GEOSECS and WOCE cruises gives uptake estimates ranging from 0.28 mol m^{-2} yr^{-1} for the eastern South Atlantic (south of 15°S) to 0.97 mol m^{-2} yr^{-1} for the eastern North Atlantic (north of 15°N). The uncertainty of these estimates is high due to insufficient GEOSECS data and because the quality of these baseline data is not as good

as recent WOCE data, but the observed patterns in uptake will provide valuable information when compared to recent re-occupations in these regions.

Surface CO_2

One of the premier ocean data products used in global carbon cycle research has been the global air-sea CO_2 flux climatology by Taro Takahashi (LDEO). The first climatology was published in 1990 and contained less than half a million data points (Tans et al., 1990). Over the years, the Takahashi climatology has been updated and revised. The most recent climatology, published in 2002, contained approximately one million data points (Takahashi et al., 2002). With valuable contributions from the NOAA VOS and mooring program, the Takahashi data set is now over three million data points. The Carbon Data Management and Synthesis group is working with Takahashi to prepare the latest climatology, which hopefully will be submitted within the year.

Although the climatology is a valuable contribution, the first step to decrease the uncertainty in ocean CO_2 uptake is to determine the natural variability in air-sea CO_2 fluxes. This can be done with models or through an innovative technique of utilizing the Takahashi CO_2 climatology and annual changes in sea surface temperature. This method takes advantage of the strong and regionally unique correlation of SST with surface water pCO_2. The method was first proposed in Lee et al (Lee et al., 1998) and expanded upon in Park et al. (Park et al., 2006). We have utilized the algorithms provided in Park et al. and global SST products from AVHRR (through the NOAA Coastwatch program) and winds from the NCEP assimilation product to estimate the global air-sea fluxes on annual timescales. The results of the analysis of Park et al. and our effort are shown in figure 6. While the trends during the period of overlap are the same there is an appreciable offset in the datasets that is attributed to use of different wind speed products. Using data obtained by the OCO funded pCO_2 on moorings and ships projects, and a pending proposal to GCC we will improve the regional pCO_2-SST relationships and decrease the uncertainty in the estimates.

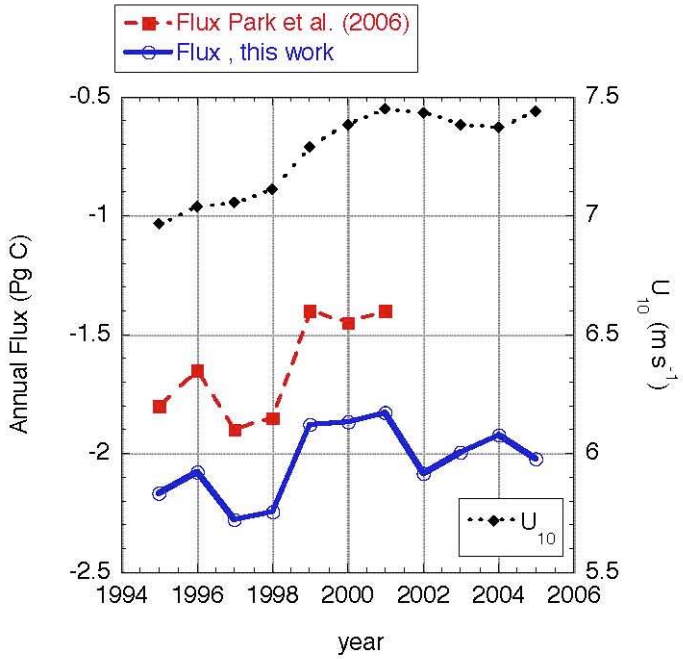

Figure 6. Preliminary analysis of interannual variability of air-sea CO_2 fluxes based on SST anomalies from 1995-2005. The average global wind used, U_{10}, is shown on the right axis. The recent analyses of Park et al. 2006 is shown as comparison.

In an effort to improve the algorithms used in the flux maps described above, we are working to develop improved regional empirical relationships between surface seawater pCO_2 and parameters that can be observed with satellites. PMEL has recently improved the algorithms for the equatorial Pacific, a region with very large fluxes of CO_2 out of the ocean but also large interannual variability (Feely et al., 2006). AOML has been examining empirical relationships for the eastern Caribbean where sea surface temperature appears to be a good proxy for surface water pCO_2 (Wanninkhof et al., 2006b). We anticipate implementing these new algorithms in future calculations of the CO_2 flux maps in an effort to reduce the overall uncertainty.

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Determination of the information content in long-occupied Voluntary Observing Ship (VOS) Expendable Bathythermograph (XBT) transects.

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Project Summary:

Smith et al. (1999) developed a strategy for evolving the Upper Ocean Thermal (UOT) network that considered the Ten Climate Monitoring Principles. This strategy included the discontinuation of the XBT deployments in Low Density (LD) mode from ships of the Ship of Opportunity Program (SOOP) as the Argo program coupled with satellite imagery were viewed as suitable replacements. However, the development and the application of the principles were accomplished in a qualitative manner with no quantitative assessment of the impact of ending the SOOP LD network, particularly with respect to the following three monitoring principles:

- ***Principle 1***: The impact of new systems or changes to existing systems should be assessed prior to implementation.
- ***Principle 2:*** A suitable period of overlap for new and old observing systems is required.
- ***Principle 6:*** Operation of historically uninterrupted stations and observing systems should be maintained.

This add-on is directed at the quantitative assessment needed to ensure that the Monitoring Principles are followed in the evolution of the UOT system. Specifically, the information content in LD lines with respect to decadal and other time-scale signals of variability will be quantified. Particular attention will be directed at decadal signals as historical observational and modeling studies have shown that oceanic variability at these time-scales could be coupled to atmospheric climate and several low-density lines have sufficient length to resolve such variability. Decisions on the value of specific lines and the desirability of continuing a portion of the LD XBT network will then be based on the monitoring principles given above. In the following the evolution of the UOT network is described (i.e., this evolution formed part of the information used by Smith et al. (1999) to design a new network). The information content that has been obtained on decadal signals from analysis of several lines is then briefly described to demonstrate the importance of these lines to climate studies.

The history of low-density sample begins with mechanical bathythermographs (MBT), which were available from World War II to the mid-1960s and provided profiles to 200-250 m. XBT were first introduced to oceanography in the mid-1960s and sampled temperature profiles to 450m. In the early 1970, XBTs that measure to 750m were introduced. MBT coverage immediately after WW II and early XBT coverage was concentrated in the vicinity of the intense boundary currents of the northern western subtropics (see Molinari, 2004). Few repeat transects were regularly occupied in the 1960s and 1970s. New sampling strategies that employed SOOP, primarily commercial vessels, were developed in recognition of the need for repeat sections in climate studies. Both the Tropical Ocean Global Atmosphere (TOGA) and World Ocean

Circulation Experiment (WOCE) were responsible for the institution of regularly occupied SOOP transects. The resulting transition from research cruise coverage in the 1960s and 1970s to repeat transect coverage in the 1990s is illustrated in Molinari (2004).

The data coverage from the early MBT and XBT research cruises often overlap the TOGA/WOCE transects permitting generation of upper layer (i.e., typically above 200 m) temperature time series that would include several phases of existing decadal signals. For instance, A-10 and A-7 in the Atlantic cross the Gulf Stream at about 73ºW and subtropical gyre at about 30ºN-35ºN, respectively. By combining MBT and XBT data it is possible to generate time series from 1950 through 2005 to study decadal signals (i.e., among the longest in situ time-series available to oceanographers). Molinari (2004) generated time-series of Gulf Stream transport and position from data collected along A-10 that clearly show decadal signals as found in the NAO record and other representations of these two Gulf Stream characteristics. Watanabe et al. (1999) used XBT data collected along A-7 to demonstrate that model explanations for decadal signals in the Atlantic are not correctly simulating these features. Similar analyses are possible using data from lines in the Pacific and Indian Oceans.

The two-year project proposed here has two-components. During the first year, data collected along lines that have been occupied for more than 30-years in all ocean basins will be analyzed statistically to identify significant interannual to decadal signals. For the lines that include MBT data, records can be generated back to the late 1940s for the upper 200m of the water column. Various variables will be analyzed (e.g., temperature on various depth surfaces, depth averaged temperature to various depths as a measure of heat content changes, etc.) to evaluate the 3-dimensional (depth, horizontal distance along the line and time) structure of the variability.

Analysis of the selected variables will allow characterization of the surface and subsurface properties of the interannual and interdecadal climatic signals. A simple averaging analysis was used to generate the time-series in Molinari (2004). The decadal signals have large enough amplitude that even this simple technique demonstrates their presence. More sophisticated analyses will be applied to provide additional quantification of the existing signals. For example, the space-time signature of this variability will be explored and described using multivariate statistical analyses (e.g. EOFs). The climatic signatures extracted with the multivariate techniques will be compared with the known modes of climatic variability (e.g. Pacific and Atlantic El Nino, North Atlantic Oscillation, Pacific Decadal Oscillation) using conventional correlation analysis. Our analyses will characterize the subsurface structure of the known climatic modes. Confidence limits on these signals as well as their association with the climatic indices (i.e., nowcasts of the phase of a particular interannual or decadal signal) will also be estimated.

During the second year, the ability of other observing systems to continue the important records initiated by MBTs and XBTs will be determined. For example, many of the lines in LD mode are now occupied in high-density (HD) mode. Observing System Experiments will be conducted with data and model results to determine if the seasonal sampling provided by HD sampling can resolve the important signals previously identified by monthly LD sampling. Sea height anomaly fields derived from a constellation of available altimetry missions since 1992 will be used to determine correlations between these data along XBT transects and the upper

layer heat content changes from XBT data. These correlations will be used to determine (1) the ability of the satellite data to replicate decadal signals (the 12 years of data include important phases of decadal signals, Molinari, 2004), (2) the ability of the altimetric data to fill spatial and temporal gaps in the in situ observations, where needed, and (3) regions where in situ can provide the only measure of decadal signals (e.g., regions where steric effects mask thermocline effects on sea surface height anomalies).

Accomplishments:

This annual report provides accomplishments since receipt of project funding from the Office of Climate Observations in June, 2006 (i.e., a full year of effort has not been performed). In addition, accomplishments have been slowed by the departure of Dr. Alberto Mestas Nunez, co-Principle Investigator, from AOML in July 2006. In spite of these factors, we have made progress in developing the generic software that can be used to perform analyses on all the selected lines.

Specific software included:

(1) Software to generate time-series of temperature as a function of depth, typically 25m increments, and location along the line, at various spatial resolutions depending on coverage and features observed. The time series from various depths were then band-passed filtered to generate time-distance plots that high lighted the energy in specific period bands (typically surrounding decadal periods). The zonal time-distance plots will also be reviewed to determine if there is signal propagation along the line (e.g., planetary wave propagation should appear at thermocline depths with phase speeds dependent on the latitude of the section).

(2) Software to generate geostrophic velocity sections using climatological temperature-salinity relations to estimate density and thus dynamic height has been developed. Geostrophic transports for particular segments of a section are then calculated and time-series plotted to search for periodicity in the transport record. Transport variability existing in boundary currents such as the Gulf Stream and Kuroshio and Gulf Stream and equatorial currents in the Atlantic and Pacific such as the Equatorial Countercurrents can be estimated from this software.

(3) Programs that for a particular grid point compute spectra and estimate the terms in a simplified vorticity relation were developed for earlier research have been retrieved and will be modified for application in this project.

Deliverables:

One year from receipt of funding, 31 May 2007:

(1) Characterization of the global upper layer temperature structure and variability from those lines with sufficient data to generate time-series.

(2) Nowcasts of the state of the ocean along these lines with respect to known decadal climate signals (i.e., the phase of the PDO, NAO, TAV, etc.) will be generated.

(3) Identification of low-density lines with sufficient information content to justify

continuation.

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Arctic Ice Thickness: State of the Arctic Report

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PROJECT SUMMARY

The objective of this work is to directly support NOAA's Program Plan for Building a Sustained Ocean Observing System for Climate by expanding current efforts to monitor and document the state of the ocean to include the Arctic Ocean.

Recent observations are consistent in their indication that the Arctic region is undergoing significant environmental changes caused by a general warming of the climate. The heightened sensitivity of this environment is due, in part, to strong feedback processes that exist over both the ocean and land and are unique to this region. These amplifications create an environment that acts both as an indicator of climate change and as a potential amplifier of climate change. Because of this and the key role the polar regions play in determining the global climate, it is important to describe and to understand the state of the Arctic.

FY2006 ACCOMPLISHMENTS

- Conducted workshop to assist in formulating the State of the Arctic report 24-26 October 2005 at the Woods Hole Oceanographic Institute, Woods Hole, MA.

The workshop featured invited presentations by team members on the state of key atmosphere, ice, ocean and land parameters, as well as small discussion sessions. Lead authors for each section of the report, Richter-Menge (CRREL: Sea ice), Overland (NOAA PMEL: Atmosphere), Proshutinsky (WHOI: Ocean) and Romanovsky (UAF: Land) were joined by a science advisory team. The science advisory team consisted of 9 national and international Arctic experts from universities and government laboratories. Input from the workshop determined the observations highlighted in the State of the Arctic Report.

- Completion, publication and dissemination of State of the Arctic Report

On November 13, 2006, a NOAA report on the state of the Arctic will be released. The report represents the consensus of a team of 20 international scientists, covering observational data from 2000-2005. It highlights recent trends in physical components of the Arctic system, including the atmosphere, ocean, sea ice cover, and land. The observations presented in the report show convincing evidence of a sustained period of warming in the Arctic and the effects of that warming on environmental conditions such as sea ice extent and vegetation. While the report highlights a general warming of the Arctic during 2000-2005, there are a few indications that some elements of the physical system, such as the central Arctic Ocean and some wind patterns, are returning to environmental conditions more typically observed from 1950-1980.

The executive summary of the report is provided in the appendix.

Portions of the State of the Arctic Report appeared in BAMS Annual State of the Climate Report and OCO Annual State of the Ocean Report.

NOAA's Public Affairs Office will provide a press release and hold a media telephone conference on the findings of the report on November 16, 2006.

- Initiation of a web-based version of State of the Arctic Report

As a first step in completing this deliverable, an electronic version of the State of the Arctic Report has been posted on NOAA's Arctic Theme Page (http://www.arctic.noaa.gov/). The observations in the report will serve as a basis for a separate educational outreach section directed at the general public that will present information on the changing Arctic in a clear and accessible fashion. The web-based version of the report will be updated, at least annually, to provide a current summary of conditions in the Arctic as a function of climate variability.

- Incorporate data from in situ observation platforms into the International Arctic Ocean Observing System (iAOOS), which will be a subcomponent of the NOAA Integrated Ocean Observing System.

During FY2006, 5 Ice Mass Balance (IMB) buoys were deployed in the Arctic Ocean to monitor changes in the thickness of the ice cover as a function of atmospheric and oceanic forcing. These buoys were deployed in conjunction with other international programs that form the basis of the developing iAOOS including:

- North Pole Environmental Observatory (http://psc.apl.washington.edu/northpole/)
- Beaufort Gyre Observatory (http://www.whoi.edu/beaufortgyre/)
- DAMOCLES (http://www.damocles-eu.org/)
- International Arctic Buoy Programme (http://iabp.apl.washington.edu/)

Background and data from the IMBs is available at: http://www.crrel.usace.army.mil/sid/IMB/index.htm

APPENDIX

STATE OF THE ARCTIC REPORT: EXECUTIVE SUMMARY

This State of the Arctic Report presents a review of recent data by an international group of scientists who developed a consensus on the information content and reliability. The report highlights data primarily from 2000 to 2005 with a first look at winter 2006, providing an update to some of the records of physical processes discussed in the Arctic Climate Impact Assessment (ACIA 2004, 2005). Of particular note:

- Atmospheric climate patterns are shifting (Figure 1). The late winter/spring pattern for 2000–2005 had new hot spots in northeast Canada and the East Siberian Sea relative to 1980–1999. Late winter 2006, however, shows a return to earlier climate patterns, with warm temperatures in the extended region near Svalbard.

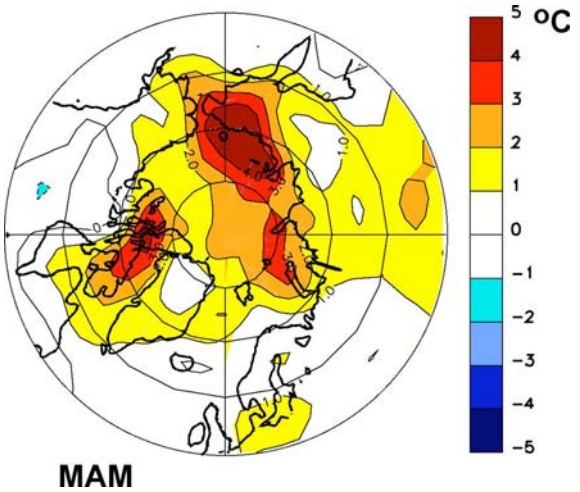


Figure 1. The Arctic system generally shows signs of continued warming, as illustrated in this northern hemisphere map of springtime (March-April-May, or MAM) surface air temperature anomalies for 2000–2005 that differ from earlier temperature patterns in the 20th century. Yellow and red indicate temperatures at least 1°C above average relative to a 1968–1996 base period.

Figure 2. Loss of sea ice and warmer ocean temperatures, highlighted in this report, have favored the pollock fishery in Alaskan waters. (Bryan & Cherry Alexander Photography.)

- Ocean salinity and temperature profiles at the North Pole and in the Beaufort Sea, which changed abruptly in the 1990s, show that conditions since 2000 have relaxed toward the pre-1990 climatology, although 2001–2004 has seen an increase in northward ocean heat transport through Bering Strait (Figure 2), which is thought to impact sea ice loss.

- Sea ice extent continues to decrease. The sea ice extent in September 2005 was the minimum observed in summer during the satellite era (beginning in 1979), marking an unprecedented series of extreme ice extent minima beginning in 2002 (Figure 3). The sea ice extent in March 2006 was also the minimum observed in winter during the satellite era.
- Tundra vegetation greenness increased, primarily due to an increase in the abundance of shrubs. Boreal forest vegetation greenness decreased, possibly due to drought conditions (Figure 4).

Figure 3. The report describes a continued reduction in the extent of summer sea ice cover which has recently benefited ship-based operations in this region. (Photo courtesy of Jeremy Harbeck.)

Figure 4. Observed increases in drought-related conditions in the boreal forests may have contributed to the increase in major wildfires over large parts of northern Alaska during the last two summers. (Photo by Mike McMillan, Spotfire Images.)

- There is increasing interest in the stability of the Greenland ice sheet. The velocity of outlet glaciers increased in 2005 relative to 2000 and 1995, but uncertainty remains with regard to the total mass balance.
- Permafrost temperatures continue to increase. However, data on changes in the active layer thickness (the relatively thin layer of ground between the surface and permafrost that undergoes seasonal freezing and thawing) are less conclusive. While some of the sites show a barely noticeable increasing trend in the thickness of the active layer, most of them do not.
- Globally, 2005 was the warmest year in the instrumental record (beginning in 1880), with the Arctic providing a large contribution toward this increase.

Many of the trends documented in the ACIA are continuing, but some are not. Taken collectively, the observations presented in this report indicate that during 2000–2005 the Arctic system showed signs of continued warming. However, there are a few indications that certain elements may be recovering and returning to recent climatological norms (for example, the central Arctic Ocean and some wind patterns). These mixed tendencies further illustrate the sensitivity and complexity of the Arctic physical system. They underline the importance of maintaining and expanding efforts to observe and better understand this important component of the climate system to provide accurate predictions of its future state.

Observing System Research Studies

D.E.Harrison
NOAA/Pacific Marine Environmental Laboratory, Seattle, WA

1. Project Summary:

This project supports the design, development and evolution of the global ocean observing system for climate. An effective observing system must be built around what is known about the space and time scales and uncertainties of the climate signals of interest, relative to the background oceanic variability. Design and development results are accomplished through a variety of data analysis and modeling studies intended to expand our knowledge about what we know and what we cannot know from the observing system as deployed and the historical data set that has been produced over the decades. The evolution of the observing system is guided through studies of alternative observing strategies and evaluation of the differences between available ocean analysis products (taken as one measure of the uncertainty in these products). Some studies also have been carried out to establish the societal relevance of indices based on accurate, sustained global ocean observations and analyses of these observations.

Finally the Office of Climate Observations and NOAA's ocean and climate observing goals are supported through the PI's activities as Chair of the intergovernmental Ocean Observations Panel for Climate (co-sponsored by the GOOS, GCOS and WCRP) and other national and international sustained ocean observing and science leadership activities. The PI also contributes to the development of international global operational oceanography as a member of the JCOMM Management Committee and work with several of its Program Areas, including the Observation Coordination Group.

No data are collected through this project, so the Ten Climate Monitoring Principles are not relevant to the activities undertaken.

Initial focus has been on SST and subsurface temperature variability since these are agreed to be very important quantities for climate impacts. This work continued during FY06 and was extended to include initial studies of the status of ocean sea ice knowledge. During FY06 significant progress was made on studies based of historical ocean subsurface temperature data base.

2. FY06 Progress:

Summary and Overview

Overall, the work of the group provided a variety of scientific and social impact justifications for continuing the deployment of the planned global climate observing system. Progress continued to be made on defining the space and time scales of observations needed for specific phenomena that must be accurately observed. Some progress also was made on the development of an initial set of ocean climate indices. The Ocean Observations Panel for Climate web site was modified to provide near-real time access to a variety of relevant ocean climate indices (see **http://ioc3.unesco.org/oopc/state_of_the_ocean/index.php**).

Andy Chiodi successfully defended his PhD thesis and continues to work on TMAP research as a JISAO research scientist. Mark Carson successfully defended his MS work. Sean Herring will be leaving during FY07.

The Indian ocean remained a focus of activity, because NOAA plans to continue to extend the tropical mooring array into this ocean in FY07. Indian continental rainfall and its dependence on SST anomalies is one of the primary societal impacts, as almost one billion people depend on the Southwest monsoon's rainfall. Rainfall variability in eastern tropical Africa also is very important to the peoples of that area and work relevant to this region was completed.) Chiodi and Harrison (2007) identifies an important process that contributes to low frequency Indian SST variability relevant to east African rainfall; meridional atmospheric advection of surface water vapor is shown to be much more important than had been thought. Net surface heating due to zonal wind speed variation is not dominant, as has been suggested by other work.

Predicting the termination of El Nino events is another objective of NOAA's seasonal to interannual prediction efforts. Via a series of ocean numerical model studies, the processes responsible for the termination of the 1997-98 and 2002-03 El Nino events have been identified. In each case the mechanism appears to be that proposed by Harrison and Vecchi (1999), in which the coupled interaction between the seasonal meridional cycle of solar insolation and near-equatorial SST anomalies, and the zonal wind anomalies associated with the resulting SST anomalies near the Dateline, is key. Delayed oscillator processes are not necessary to account for the observed oceanic behavior. The state of cold tongue zonal winds at the height of the El Nino determines whether the oceanic response to the zonal wind anomalies will lead to termination of the El Nino in early Spring (as happened in 2002-03), or if the El Nino will continue into late Spring (as happened in 1997-98 and 1982-83). Again, accurate near-equatorial wind and SST knowledge, such as is obtained from the TAO/Triton array, is key to successful prediction.

Work has also continued in the use of TAO/Triton data to test existing models of the equatorial Pacific. It was found previously that the Gent/Cane intermediate model cannot

be reconciled with the observations, when used with the limited vertical resolution that has been adopted so far in model studies using this formulation. A similar result was found using the somewhat more physically complex Gent-Cane "intermediate" model of the tropical ocean. The mooring data have been essential to this study, providing an important result for the relevance of intermediate coupled models for study of El Nino predictability and processes. This work has been accepted for publication.

The importance of high latitude information for US seasonal weather anomaly forecasting has been given a new twist by our discovery that the weather anomalies, particularly over the eastern half of the US and over Alaska during an El Nino winter depend strongly on the sign of the Arctic Oscillation (AO). Further we have found that there is a reasonable statistical basis for Winter AO forecasting, given knowledge of autumn AO conditions. We have communicated this result at national meetings and to L. Uccelini. Accurate knowledge of the AO thus appears key to improved US winter weather forecasts. It may be that improved knowledge of MSLP over the Arctic will lead to improved understanding of the AO and improved means for its seasonal prediction. This work has been accepted for publication.

The importance of having substantially enhanced global coverage of subsurface ocean data has been made clear by the MS thesis work of Mark Carson. In this work the historical ocean data base was examined to identify those grid boxes where there was sufficient data in time to define a statistically significant temperature trend over the period 1950-2000. It was found that even at 100m depth, much less than half the ocean has sufficient data, and was shown that, of the boxes where such data density is found, roughly half of them involve warming trends and half cooling trends. It was not sensible to attempt to estimate global ocean temperature trends. At 300m and 500m much less of the ocean had sufficient data. Runing 20-yr trends also were estimated and it was found that there is lots of decadal time scale trend variability, which makes it clear that it is unwise to extrapolate trends based only on the recent satellite data era (~20years) to longer term trends. This work establishes the importance of additional work to estimate the uncertainty in recently published global ocean temperature trends, and makes very clear the contribution that completing and sustaining the global Argo array of profiling floats will make to important matters like knowledge of subsurface ocean temperature variability and trends. A first paper on this topic has been accepted for publication.

Publications

Harrison, D.E. and A. Chiodi (2007) Westerly Wind Events and Dateline El Nino events. J. Climate (in preparation)

Harrison, D.E. and M. Carson (2007) Is the World Ocean warming, Pt. II? (In preparation)

Chiodi, A.M., and D.E. Harrison (2007): Mechanisms of summertime subtropical Southern Indian Ocean sea surface temperature variability. J. Climate. [to appear]

Harrison, D.E. and M. Carson (2007) Is the World Ocean warming? J. Phys. Oc. (to appear, Carl Wunsch special issue)

Vecchi, G.A. and D.E. Harrison (2006). On the termination of the 1997-98 El Nino: Part I. Mechanisms of oceanic change. J. Climate (in press)

Bennett, A.F, B.S. Chua, H.-E. Ngodock, D.E.Harrison, M.J.McPhaden (2006) Generalized inversion of the Tropical Atmosphere Ocean (TAO) data and the Gent-Cane model of the tropical Pacific. J. Marine Research. 64(1), 1-42

Bond, N.A. and D.E. Harrison (2006) U.S. Winter Weather Anomalies with El Nino and negative Arctic Oscillation: 2002-03 and before. Int'l Journal of Climatology. 26(13), 1821-1841

Vecchi, G.A., and D.E. Harrison (2006): The termination of the 1997–98 El Niño. Part I: Mechanisms of oceanic change. J. Climate, 19(12), 2633–2646. [PDF Version]

Chiodi ,A. and D.E. Harrison (2006). Summertime Subtropical SST Variability. Geophys Res. Lett. 33, L08601, doi: 10.1029/2005GL024524.

Harrison, D.E. (2006): Observing system research studies. In Annual Report on The State of the Ocean and the Ocean Observing System for Climate, Annual Report, Fiscal Year 2005, J.M. Levy (ed.), NOAA/Climate Program Office/Office of Climate Observation, 281–283.

Larkin, N.K., and D.E. Harrison (2005): Global seasonal temperature and precipitation anomalies during El Niño autumn and winter. Geophys. Res. Lett., 32, L16705, doi: 10.1029/2005GL022860. [PDF Version]

Community Service positions

WCRP/GOOS/GCOS Ocean Observations Panel for Climate, Chair
OAR Climate Observing System Council, Chair
US GODAE Steering Team, Co-Chair
US GOOS SC
WCRP/GCOS Atmospheric Observation Panel for Climate
WCRP Working Group on Observations and Analysis
CLIVAR Global Synthesis and Observations Project
JCOMM Management Committee
WCRP Joint Scientific Committee
JISAO Senior Fellow
JIMAR Senior Fellow

Simulation of the ARGO Observing System

I.V. Kamenkovich and E.S. Sarachik

University of Washington, Seattle, WA

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 is rapidly being 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 (GCMs), 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.

Accomplishments

We have (with Drs. Wei Cheng and D.E. Harrison) been looking at the expected performance of the ARGO observing system for the ocean. The main goal of the activities during the FY 2006 was to quantify the effects of oceanic advection on the expected performance of the ARGO system. We analyzed simulation of the ARGO observing system in two models: a global coarse resolution model and a high-resolution model of the North Atlantic. The main objective of the coarse-resolution studies was to quantify effects of the large-scale advection on the expected performance of the ARGO observing system. High-resolution studies addressed the importance of the mesoscale variability.

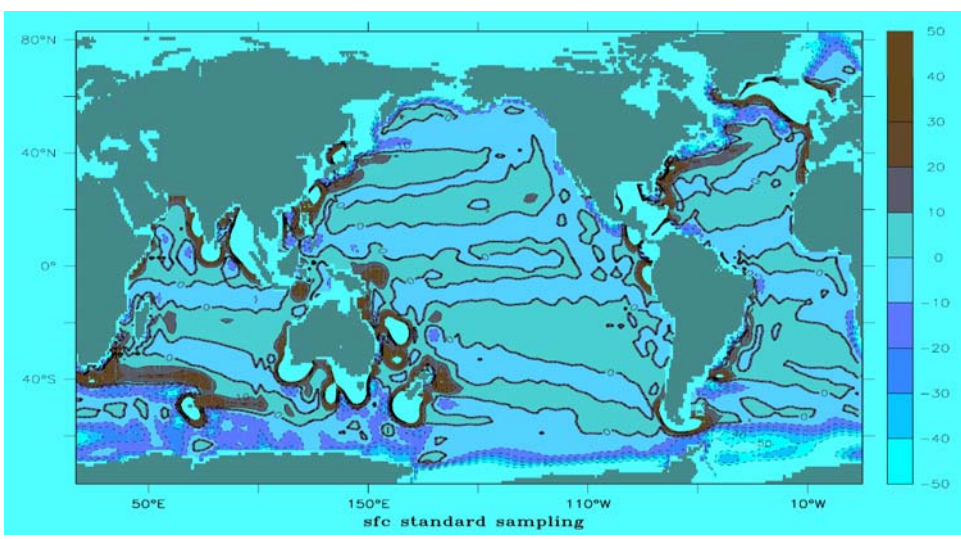
Coarse-resolution studies

We continued studies with a course resolution, 2° in both latitude and longitude, global ocean GCM forced by daily atmospheric fluxes. 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. 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.

We analyzed several oceanic quantities, including the temperature, salinity and depth of the thermocline. In this report, we present the results for the integrated heat content in the upper 750 meters of the ocean. The reconstruction errors, calculated as a difference between the reconstructed and the actual GCM-simulated values, are presented in Figure 1a. To estimate the significance of these errors, we convert them to the heat flux units and compare the results to the magnitudes of the 2003-2005 trend in the 750-meter heat content diagnosed from the real ARGO. The observational data are taken from Lyman et al. (2006), who report a significant (> $50Wm^{-2}$) warming and cooling patterns in North Atlantic, parts of the North Pacific and the Antarctic Circumpolar Current (fig. 1b).

Overall performance of simulated observing system is good, and the reconstructed upper-ocean heat content is very close to the actual GCM-simulated values (fig. 1a). However, there are some significant differences between the reconstructed and actual fields within western boundary systems, such as the Gulf Stream and Kuroshio, and the Antarctic Circumpolar Current (ACC), where the errors exceed the observed 2-year trend (fig. 1b). These reconstruction errors are also noticeably larger than in simulations without float advection (not shown), which demonstrates the role of advection. Since intensity of these swift oceanic currents is underestimated by our coarse-resolution GCM, the deviations of the reconstructed fields from the actual values are expected to be even greater in reality than in our simulation.



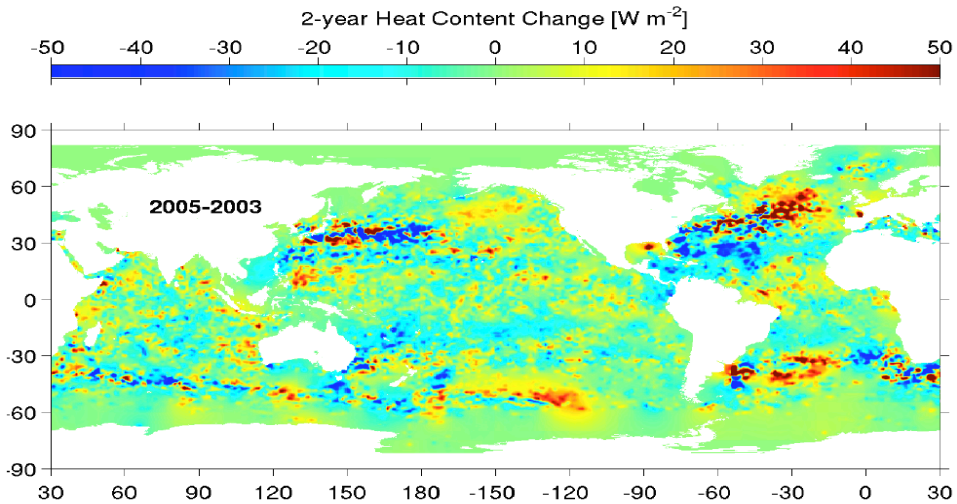


Figure 1 Upper panel: Difference between the reconstructed and GCM-simulated ocean heat content integrated over the upper 750 meters, expressed in flux units (Wm^{-2}); the values are divided by the length of two years to be comparable with the results in Lyman et al. (2006). Lower panel: Figure 2 from Lyman et al. (2006): Map of ocean heat content change ($W\ m^{-2}$) in the upper 750 m from 2003 to 2005.

High-resolution studies in the North Atlantic

Results from the coarse-resolution studies demonstrated sizeable reconstruction errors in the vicinity of fast ocean currents, whose intensity is underestimated by a coarse-resolution model. In addition, the coarse-resolution simulations do not include mesoscale eddies, whose effects can significantly impact the accuracy of the mean-state estimates. To address these issues, we carried our analysis in a regional model of the North Atlantic, whose high resolution permits more accurate simulation the Gulf Stream and mesoscale eddies. The objective is two-fold: (i) to evaluate the expected performance of the ARGO system in the presence of intense oceanic currents; (ii) to analyze the effects of the mesoscale variability on the performance of the ARGO system.

The model has $1/8^o$ resolution in both latitude and longitude and 30 levels in the vertical. The topography is realistic on a coarse $1^o x 1^o$ grid; 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. We perform three simulations in an off-line mode: (i) a standard case; (ii) a case in which the velocity and T/S fields are time-averaged (no eddies); (iii) a case in which the velocity and T/S fluctuations are amplified (amplified eddies).

Preliminary results indicate that at some locations, in particular in the Gulf Stream vicinity and in the subpolar gyre, the errors in the reconstructed upper ocean heat content (fig.2) are at least as large as the observed two-year trend (fig.1b). Increased intensity of the boundary currents in the high resolution model results in larger reconstruction errors; compare figures 1a and 2a,b. Removal of eddies does not have a significant impact on the

size of errors (figs. 2a and 2b). However, if simulated eddies are amplified by a factor of 2.5, which brings the simulated sea-surface height variance closer to the observed values, the errors increase significantly everywhere in the domain (figs 2a,b and 2c).

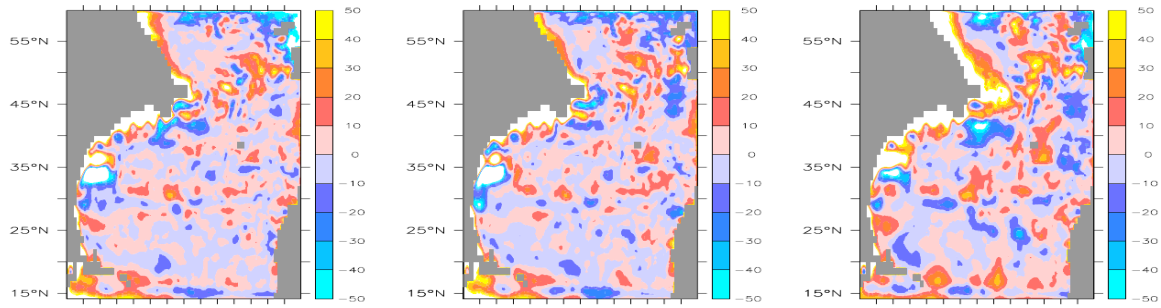


Figure 2 Difference between the reconstructed and GCM-simulated ocean heat content integrated over the upper 750 meters, expressed in flux units (Wm^{-2}): (a) standard case; (b) a case with mesoscale variability removed; (c) a case with mesoscale variability amplified by a factor of 2.5. The errors are comparable to the signal in Lyman et al. (2006) at selected locations; see fig. 1b.

Significance of results

The results clearly demonstrate the importance of oceanic advection in affecting the expected performance of the ARGO observing system. We emphasize the need for additional, dense spatial sampling in the western oceanic boundaries and ACC, as well as in the regions characterized by intense mesoscale variability. It remains unclear, however, whether more frequent sampling can improve performance of the ARGO system (Vecchi and Harrison 2006).

References:

Lyman, J.M., J.K. Willis, and G.C. Johnson, 2006: "Recent cooling of the upper ocean", *Geophys. Res. Lett.*, **33**, L18604, doi:10.1029/2006GL027033

Kamenkovich, I.V., 2005: "The role of daily surface forcing in setting the temperature and mixed layer structure of the Southern Ocean", *J. Geophys. Res.*, **101**, C07006, doi:10.1029/2004JC002610

Vecchi, G.A., and M. Harrison, 2006: "An observing system simulation experiment for the Indian Ocean", *J. Climate*, in press.

10. Data & Assimilation Subsystems:

a. The Observing System Monitoring Center
b. World Ocean Database Project
c. Enhanced Ocean Climate Products from NCEP
d. Ocean Data Assimilation Research at GFDL
e. Ocean Data Management at NCDC
f. U.S. Research Vessel Surface Meteorology Data Assembly Center

The Observing System Monitoring Center

Steven Hankin[1], Kevin J. Kern[2] and Ray ("Ted") Habermann[3]
[1] NOAA Pacific Marine Environmental Laboratory, Seattle, WA
[2] NOAA National Data Buoy Center, Stennis Space Center, MS
[3] NOAA National Geophysical Data Center, Boulder, CO

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.

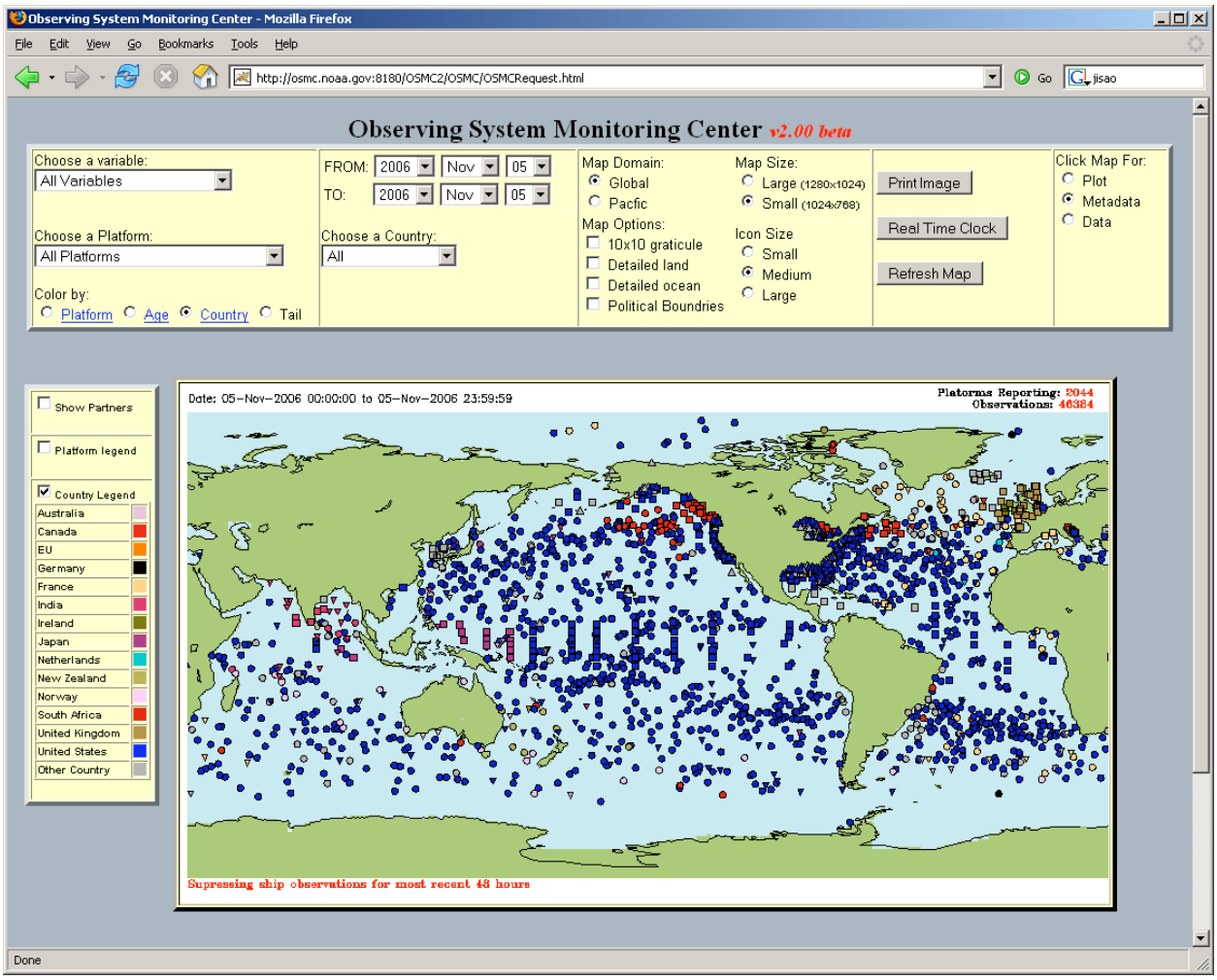


Figure 1. Screen snapshot of OSMC interface

The OSMC system displays the current and historical status of the globally distributed surface meteorological and oceanographic *in situ* ocean observing system (Figures 1, 2). It provides dynamically generated maps to visualize the coverage of observations. 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.

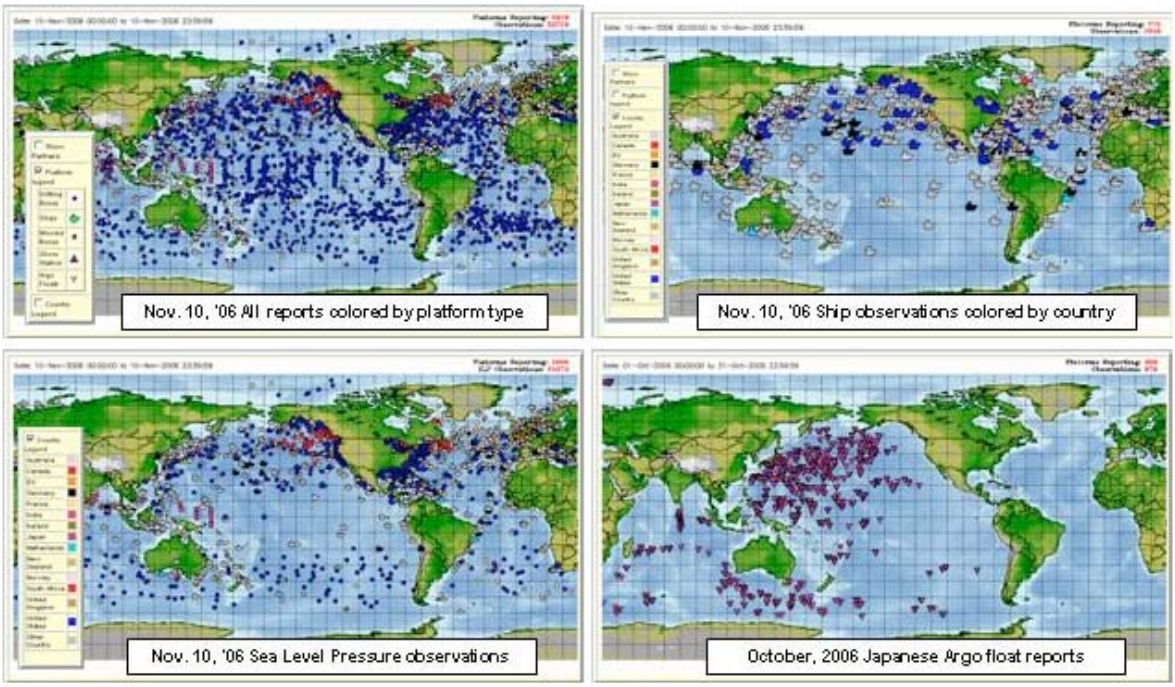


Figure 2. Sample OSMC maps

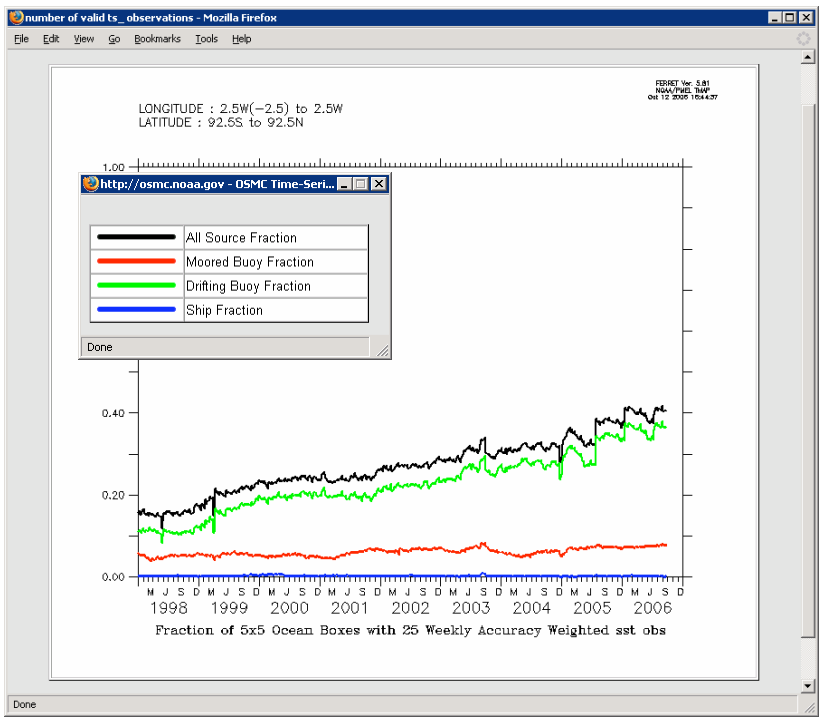
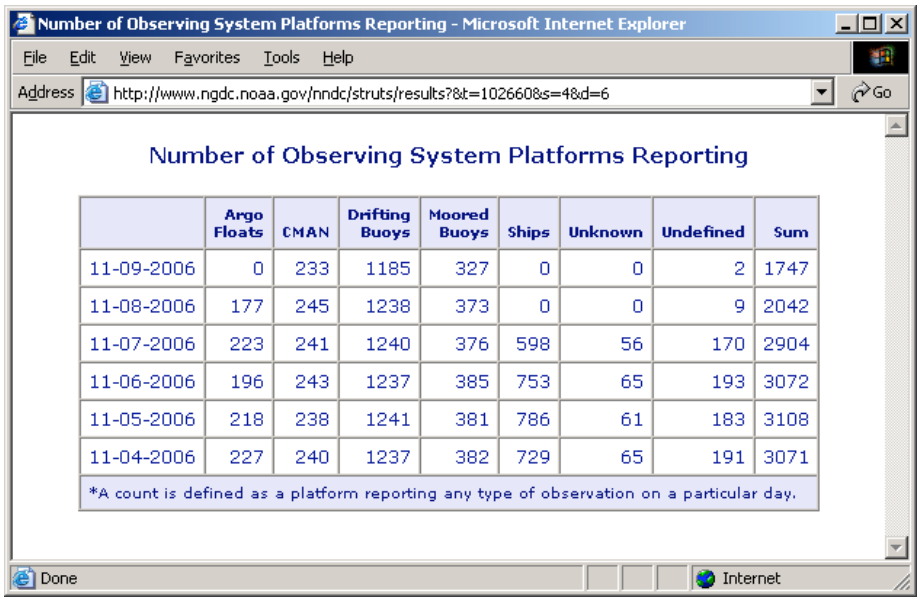


Figure 3. Progress in implementation of the ocean observing system

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 5) and via ESRI ArcIMS® tools (Figure 6).



Number of Observing System Platforms Reporting - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Address http://www.ngdc.noaa.gov/nndc/struts/results?&t=102660&s=4&d=6 Go

Number of Observing System Platforms Reporting

	Argo Floats	CMAN	Drifting Buoys	Moored Buoys	Ships	Unknown	Undefined	Sum
11-09-2006	0	233	1185	327	0	0	2	1747
11-08-2006	177	245	1238	373	0	0	9	2042
11-07-2006	223	241	1240	376	598	56	170	2904
11-06-2006	196	243	1237	385	753	65	193	3072
11-05-2006	218	238	1241	381	786	61	183	3108
11-04-2006	227	240	1237	382	729	65	191	3071

*A count is defined as a platform reporting any type of observation on a particular day.

Done Internet

Figure 4. One of many OSMC table-style summaries

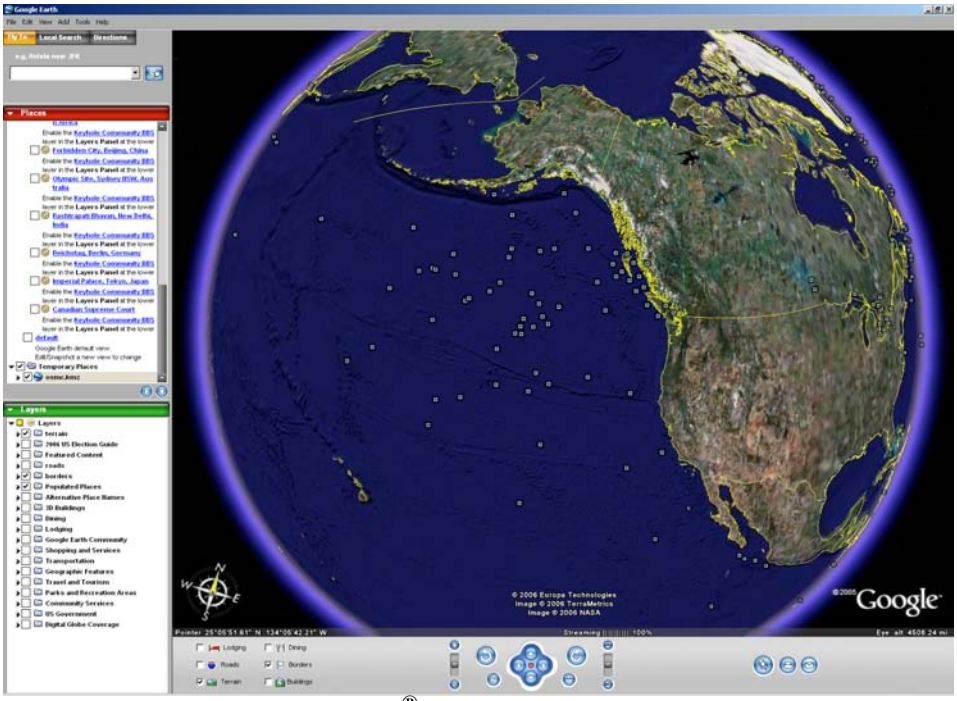


Figure 5. Google Earth® viewer showing ocean observations

As the system is further developed analysis capabilities will be added through collaborations with the Climate Observing System Council (COSC), that will assess the adequacy of the observations to compute critical ocean state fields, such as sea surface temperature. A limited capability to project drifter locations into the future will be added, so that we may anticipate gaps in the observing system and better deploy resources.

The OSMC system is available on-line at http://www.osmc.noaa.gov (note that at the time of this writing a new home page is under construction). It is provided as a resource to other NOAA centers, national research partners, and international partners.

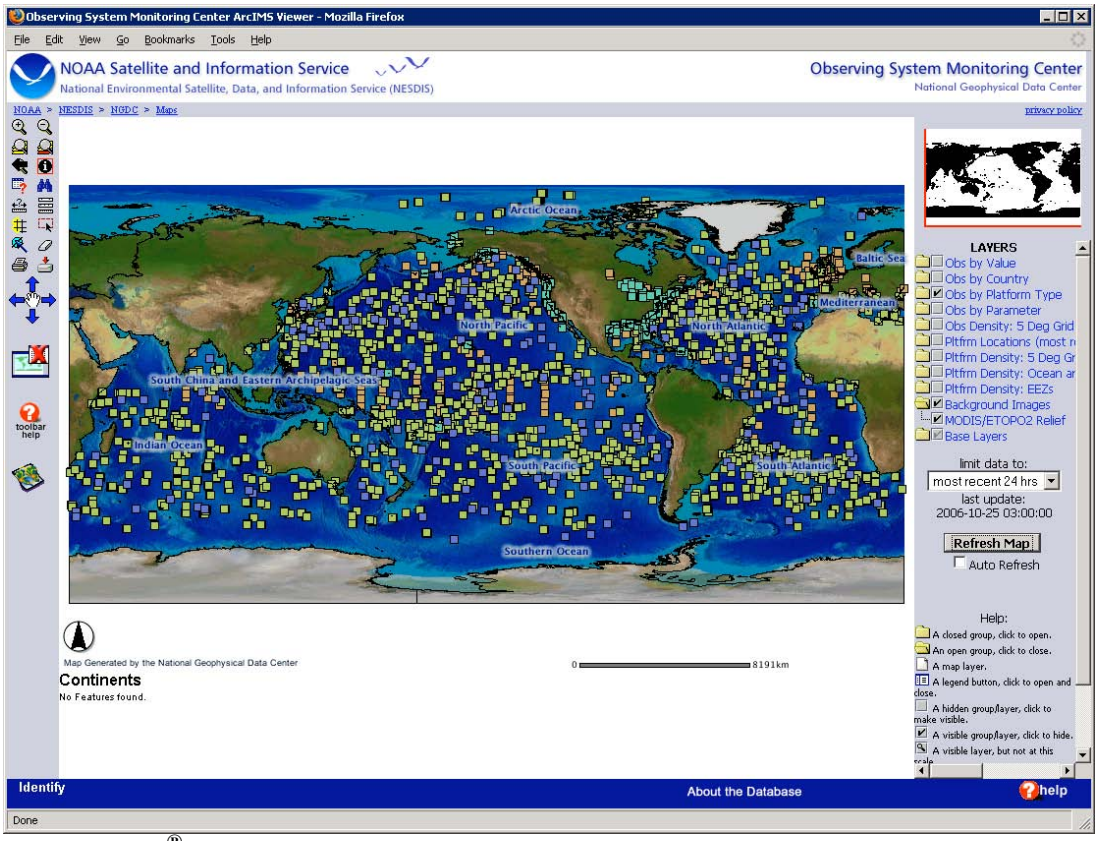


Figure 6 ArcIMS® viewer showing observations taken during the last 5 days, colored by platform type

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 consulting and development services on the use of data bases and GIS interfaces.

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.

FY2006 Progress

The following milestones track the progress made on OSMC during fiscal year 2006.

All (PMEL, NDBC, NGDC)

- Presented an OSMC overview at the NOAA Climate Observation Program 4th Annual System Review in Silver Spring (May 10-12, 2006). Solicited feedback from the Climate Observing System Council (COSC).

- Held OSMC technical meeting June 13,14 2006 at PMEL, Seattle

PMEL Accomplishments

- Developed v2.00 OSMC system for individual observations offering
    - Selection of observations based upon parameter, platform type, country, and date
    - Map outputs with tailored platform type icons and color control by country, time since observation, and platform type. Option to show drifter tails.
    - Improved readability and content to drill down functionality (metadata reports)
    - Configurable map size to address different desktop and laptop screen resolutions
    - Uses local connection to OSMC Oracle database maintained at NDBC
    - Higher performance and easier maintenance by using the new LAS version 7
    - Added a status bar to inform user that product was being generated.
    - Added user-selectable legend information on left side of map overview.
    - Added icons representing contributing organizations.
    - Improved reporting when region requested by user contains no observations.
    - Feedback to inform user that ship observations were being delayed by 48 hours.
    - Full list of platforms to the platform menu. Those not available are grayed out).

- New and continued analysis capabilities
    - Installed an independent v1.00 alpha system for OSMC analysis at NDBC utilizing summarized, gridded data for performance
    - Animations and time series graphics showing growth in the Observing System.
    - Static images showing monthly status of observing system

- Support for the Adopt-a-Drifter web site including numerous enhancements on request.
    - Adopt-a-Drifter provides educational opportunities through the Teacher at Sea program. It accesses the OSMC through a highly simplified user interface suitable for grade school students
    - Transferred responsibility for routine maintenance to Todd Pearce at OCO HQ.

- Performance
    - Major enhancements to performance, in part due to incorporation of improved SQL queries developed by partners (e.g. drifter tails query optimized by returning only a single location per day)

- **Not completed**:
    - New OSMC home page

        - Draft version remains to be made public. Transferred responsibility for this draft to Todd Pearce at OCO to ensure that it is consistent with the "corporate look and feel" of other OCO pages.
    - Tide gauges
        - Tide gauges were added to the UI as a new platform type. Further addition of tide gauges to the OSMC has been postponed pending a redesign of the OSMC database schema (currently underway).
    - "Last reported" maps
        - A "most recent report" option has been prototypes, but release has been delayed to correct database inconsistencies.

NDBC Accomplishments

- Continued to update the OSMC Oracle database and NetCDF files with data from the following sources:
    - GODAE T-File
    - WMO Allocation table (Country info)
    - WMO Pub 47 data (meta-data)
    - JCOMOPS floats (meta-data)
    - NDBC Website (meta-data)

- New data sources added
    - Tsunami DART observations. Actual data is available via a URL link.
    - NOS Tide Gauge stations. Actual data is available via a URL link.
    - The main Ocean Reference sites of interest to the Climate Office. Additional sites will be added during FY07.

- Proposed a replacement data source for the GODAE T-Files using the NDBC GTS feed via the NWSTG.

- Database technical enhancements
    - Implemented a 48 delay for ship data to address security concerns.
    - Working to finalize the database scheme redesign incorporating improvements recommended by NGDC.
    - Upgraded the OSMC Oracle database from Standard Edition to Enterprise Edition. Also configured database tuning.
    - Performed several reconciliations between the OSMC float information and the JCOMMOPS web graphic. Currently the two systems are reporting similar numbers for the GTS floats.
    - Performed OSMC server upgrades and security patches as required.

NGDC Accomplishments

- Research strategies to improve database performance
    - Continued to enhance prototype parameter/value database design.

- Demonstrated ability to use spatial object in prototype database design through spatial queries against U.S. Exclusive Economic Zones and World Ocean / Sea Names, and five-degree cells.
- Results of these queries are displayed on the map viewers and as chained text views that support drill-down through nested regions.

- Work with partners to implement improvements as determined through research
  - Participated with NDBC in the database design white paper.
  - Implemented scripts for transforming the content of the original OSMC database tables into the prototype design. This includes extracting data from XML fields and migrating that data into the mainstream design.
  - Tested these scripts on an on-going basis by running them daily at NGDC. The resulting database has been used for the ArcIMS and Google Earth viewers.
  - Will provide these scripts to our partners at NDBC to help them in the operational database design evolution.

- Explore further application of COTS internet mapping tools (ESRI ArcIMS)
  - Added observation density layers for EEZs, Oceans and Seas, and five-degree grid cells to map, with access to table views of data to the ArcIMS viewers.
  - Implemented many of the data access features of the ArcIMS viewer using the Google Earth Viewer. The Google Earth implementation includes links to report on observations for selected platform.

- Access to recent OSMC data using Open Geospatial Consortium web services
  - Demonstrated access to OSMC map layers using OGC WMS requests.

- Create text/table output capabilities supporting a variety of queries and reports
  - Have implemented tabular summary views of the OSMC database including: Number of observations / type / day; Number of observations / country / type / day; Number of observations / EEZ Region / type / day; Platforms / EEZ Region / day; Number of observations / 5 degree tile; Observations / Platform; Number of observations / Ocean or Sea / type / day; Platforms / Ocean or Sea / day; Platform / type / day

- Database integrity checks
  - NGDC did an extensive comparison of platforms in the OSMC database and the NOSA database, including NOSA DART, NWLON, BOY, and MAN stations, as well as presence on the Tides and Currents web page. The results of these comparisons were provided to NDBC in a spreadsheet to help understand the overlaps and differences between various observing systems

World Ocean Database Project

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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 33 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 4400 times during the past 24 years.

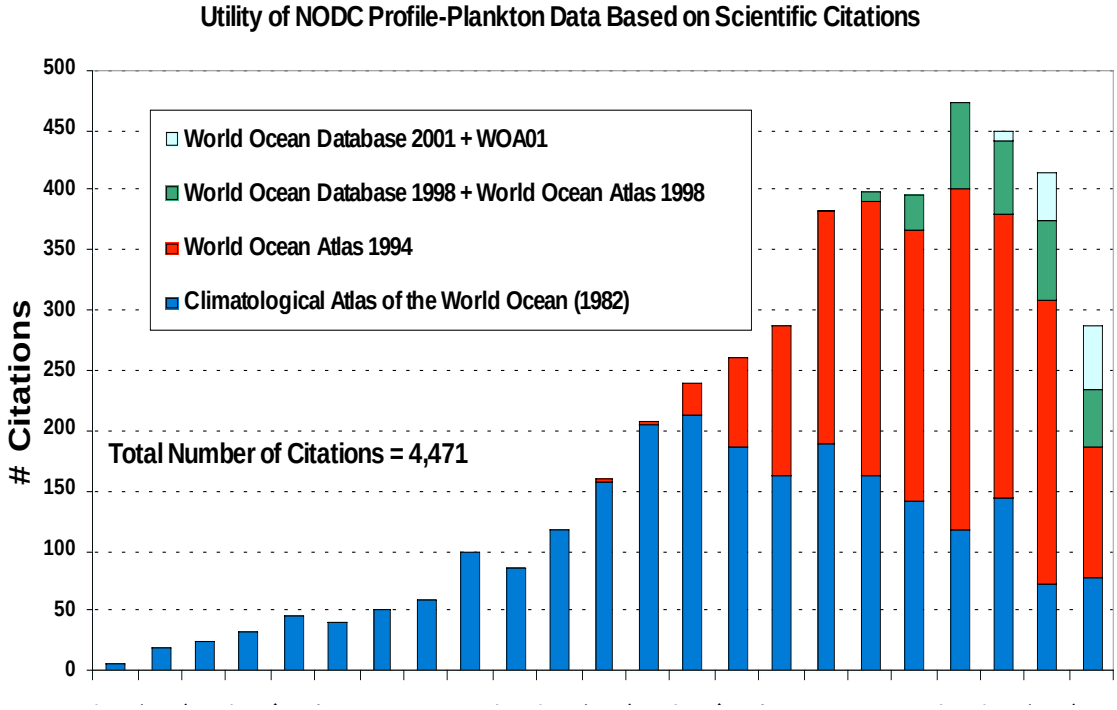

Figure 1. Time series of the number of citations as a function of year for NODC profile databases and products based on those databases.

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 shoes that more than 1 billion ocean profiles have been downloaded during the past three years alone.

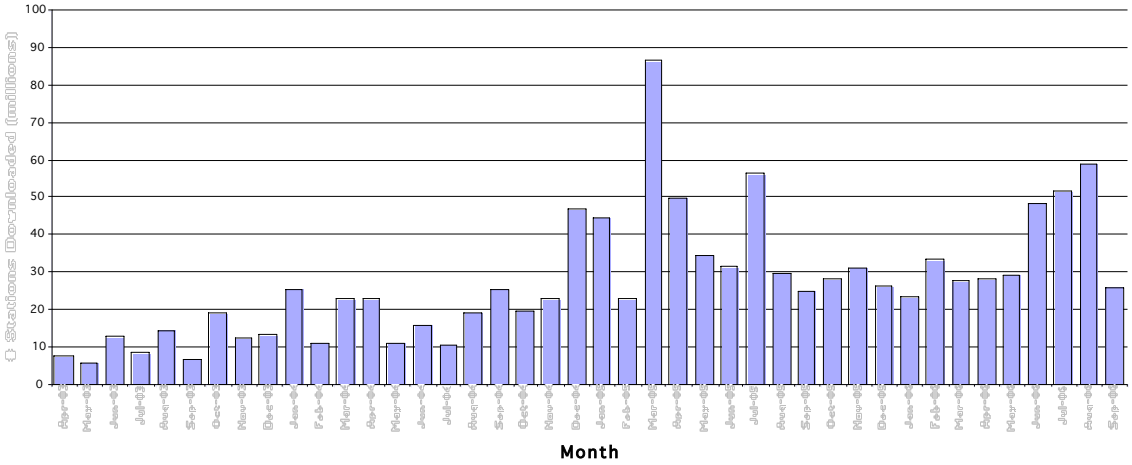

Figure 2. Number of casts in the World Ocean Database downloaded as a function of time.

Accomplishments

We published *World Ocean Database 2005* (WOD05) in FY06. WOD05 contains approximately 900,000 historical as well as modern temperature profiles not previously available. In addition there are many additional profiles for all the other variables included in WOD05 such as salinity, oxygen , nutrients etc. For the first time tracer data are included in the WOD series.

Publications and Reports

Boyer, T. P., J. I. Antonov, H. Garcia, D. R. Johnson, R. A. Locarnini, A. V. Mishonov, M. T. Pitcher, O. K. Baranova, and I. Smolyar, 2006: World Ocean Database 2005, Chapter 1: Introduction, NOAA Atlas NESDIS 60, Ed. S. Levitus, U.S. Gov. Printing Office, Wash., D.C. , 182 pp., DVD.

Johnson, D. R., T, P. Boyer, H. E. Garcia, R. A. Locarnini, A. V. Mishonov, M. T. Pitcher, O. K. Baranova, J. I. Antonov, I. V. Smolyar, 2006: World Ocean Database 2005 Documentation. National Oceanographic Data Center Internal Report 18, Silver Spring, MD, 164 pp.

Enhanced Ocean Climate Products from NCEP

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Project Summary

The impact of new observational data sets on the current operational GODAS was examined through a series of data assimilation experiments. Use of ARGO salinity data dramatically improved the equatorial current structure and removed major climatological biases. Altimetry data was prepared for operational use and will be implemented in 2007. Two evolutionary improvements into NCEP's 3DVAR GODAS were developed and tested. Extension of the analysis to 2200 m (from 750 m) dramatically reduced the temperature bias in GODAS analyses. Preliminary work with MOMv4 was completed in preparation for making it the basis of new versions of the GODAS and the CFS.

1.0 Progress in FY06

The work in FY06 focused on three areas. First, we examined the impact of new observational data sets on the current operational GODAS and prepared for the operational use of altimetry data, second, we developed two evolutionary improvements into our 3DVAR assimilation system, and third, we completed preliminary work with MOMv4 in preparation for making it the basis of new versions of the GODAS and the CFS.

1.1 New observational data sets for GODAS

All work has been completed to make the assimilation of Jason-1 altimetry part of the operational GODAS. NCEP is currently installing the next generation of its IBM super computers and changes to the operational suite are on hold. When the computer upgrade is complete after the first of the year, the assimilation of altimetry will become operational. In the meantime, the new GODAS is run daily in an operational-like mode and has functioned without fault since June. Because the new version of GODAS continues to assimilate profile data, any loss of altimetry data, such as has occurred recently, does not cause GODAS to fail.

Our experimentation with the assimilation of Argo salinity data in place of the synthetic salinity data that is used in the operational GODAS has produced an interesting and surprising result. Mean biases in the equatorial surface currents have been an ongoing problem in GODAS and in its predecessor, the Pacific Ocean data assimilation system. In the GODAS, this has taken the form of a westward bias in the far western Pacific and an eastward bias in most of the central Pacific. To test the impact of Argo salinity, we have conducted an experiment in which we assimilated only Argo and XBT profile data. Observed Argo salinity profiles were paired with the Argo temperature profiles and synthetic salinity profiles with the XBTs. In this experiment no TAO mooring data were assimilated so as to allow the Argo salinity profiles to dominate in the tropical Pacific.

When we compared the equatorial currents in this experiment for the year 2005 with ADCP observations the results were unambiguous: the mean current biases of the standard GODAS were gone and even the complex vertical structure of the currents in the western Pacific were well reproduced. The message appears clear: to get the surface currents right, you first have to get the upper ocean salinity right. The challenge now is to try to improve our method of computing synthetic salinity to take advantage of this result in the years prior to the Argo era. This will be one of our tasks for FY07.

The altimetry and Argo salinity work are described in more detail in Behringer (2007).

1.2 Improvements to the 3DVAR assimilation system

The operational 3DVAR assimilation system is univariate in temperature and salinity. As part of the FY06 work plan we developed a version of GODAS that is multivariate in the *U* and *V* components of velocity. It was motivated by recent published reports that suggested that a multivariate scheme provides a better representation of ocean currents through a balancing geostrophic relationship. After some tuning of the method to deal with the fact that geostrophy breaks down at the equator and the fact that near-equatorial currents are not strictly linear, we ran a multivariate experiment for the years 2000-2005. The results of the experiment showed much improved surface currents in the tropical Pacific as compared to those in the operational GODAS. The improvement, however, was not as impressive as in the case where Argo salinity data were assimilated (see 1.1 above).

Another, simpler improvement to the operational 3DVAR assimilation system was also tested in FY06. The standard GODAS assimilates data only in the upper 750 meters and we wanted to test the effect of extending the assimilation much deeper, to 2200 meters. The idea was to take full advantage of the deeper Argo profiles. We also wanted to see whether we could extend the deep assimilation backward in time by using deep temperature climatology in the years prior to the availability of Argo. We did a deep assimilation run extending from 1979 through 2005. The results of that experiment were satisfying. In the standard GODAS at 1200 meters on the equator there is a steady drift over time toward warmer temperatures in the Indian and Pacific Oceans and toward colder temperatures in the Atlantic Ocean. In the GODAS experiment with deep assimilation, the temperature drifts in the Indian and Pacific Oceans have been eliminated and the cold drift in the Atlantic Ocean has been replaced by a long-term warming trend. Comparison of the GODAS results with independent CTD sections in the Atlantic Ocean, shows that the deep assimilation both removes a deep temperature bias in the standard GODAS and correctly captures the long term trend.

The multivariate and deep assimilation modifications to the 3DVAR system are described in more detail in Behringer (2007).

1.3 Preparation of MOMv4 for new versions of GODAS and CFS

We have completed a fully global configuration of MOMv4 that will be used in the next versions of the GODAS and the CFS. It has been spun-up as a forced model and we have gained some understanding of its performance. Incorporating it into the new versions of GODAS and CFS will be part of the work for FY07.

Reference

Behringer, David W., 2007: The Global Ocean Data Assimilation System (GODAS) at NCEP. *Eleventh Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface, AMS 87th Annual Meeting, H.B. Gonzalez Convention Center, San Antonio, Texas, 12pp.* (a PDF version is available from http://ams.confex.com/ams/87ANNUAL/techprogram/programexpanded_393.htm)

Ocean Data Assimilation Research at GFDL

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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.

Accomplishments

1. Development of Coupled Data Assimilation System using GFDL's coupled climate model (CM2)

   An ensemble filtering coupled data assimilation system using the GFDL's coupled climate model has been developed and tested, for the purpose of climate detection and SI forecasts. This system also serves as a test bed for understanding the predictability of larger time scale variability, such as NAO, AMI and THC etc. Currently, the system can be configured for either/both atmospheric and oceanic data assimilations (ADA/ODA). The corrected variables for the atmosphere include temperature, moisture, wind and surface pressure, and the corrected variables for the ocean include temperature, salinity, currents and wind stress. Other assimilation components (land/ice etc.) can feasibly be added if observations are applicable.

2. Climate Detection

   A series of assimilation experiments have be done within a perfect model framework for climate detection:
   - An ODA experiment based on the 20th-century ocean observing network (XBTs, CTD...) shows that the ODA process in the CDA system is able to detect the signals of climate changes in ocean heat content, only

assimilating the observed ocean temperature into the ocean state variables in the coupled model.

- An ODA experiment based on the 21st-century ocean observing network (Argo) shows that the assimilation of ocean temperature and salinity is able to reconstruct the large time scale thermohaline structures at middle and high latitudes. In particular, the decadal trend of the North Atlantic (NA) meridional overturning circulation (MOC) has been retrieved very well.
- A CDA (ADA+ODA) experiment based on the 20th-century ocean observing network and the atmospheric `reanalysis' data shows the fully-coupled assimilation improves significantly the estimate of ocean climate with a systematic error due to the lack of salinity source information. Particularly, the interannual variability of the NA MOC is retrieved very well due to the correction of the sea-surface forcings from the ADA.
- A CDA (ADA+ODA) experiment based on the 21th-century ocean observing network and the atmospheric `reanalysis' data shows the fully-coupled assimilation utilizing both the ocean temperature and salinity observations retrieves the ocean thermohaline structures very precisely. Particularly, both the interannual variability and decadal trend of the NA MOC is reconstructed with a high accuracy since the CDA system builds up a correct thermohaline structure by ODA and correct sea-surface forcings by ADA.

3. Impact of CDA's initialization of coupled model on SI forecasts

   Based on the ODA, ADA and CDA products described above, a series of ENSO forecast experiments is on going for understanding the model's sensitivity to the coupled initial conditions. These sensitivity studies help improve the predictability of SI variability described by the coupled numerical system so as to improve the forecast skills eventually.

Publications

Zhang, S., M. J. Harrison, A. T. Wittenberg, A. Rosati, J. L. Anderson, and V. Balaji, 2005: Initialization of an ENSO Forecast System using a parallelized ensemble filter. *Monthly Weather Review*, **133(11)**, 3176-3201.

Zhang, S., M. J. Harrison, A. Rosati, and A. Wittenberg, 2006: Coupled ensemble data assimilation for Global Oceanic Climate Studies, Part I: System design and evaluation. *Monthly Weather Review*, in press.

Zhang, S., A. Rosati, and M. J. Harrison, 2006: Detection of multi-decadal ocean capability within a coupled ensemble data assimilation system. JGR Oceans, submitted.

The output from ODA experiments is available at
http://nomads/nomads/forms/assimilation.html

Ocean Data Management at NCDC

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1. PROJECT SUMMARY

There are two elements covered by this project. The first one is to develop a sea surface wind product. The second is to improve access to the surface marine archive of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS).

Objectives: The two objectives for this project are:

1) To develop and improve a globally gridded blended high resolution sea surface wind product from multiple satellites from several US agencies and to make this research product operational.
2) To provide access to ICOADS data, for the full period of record (1854-present), via NCDC's Climate Data Online (CDO) system. Also, to provide access via NCDC's Geographic Information System (GIS) services.

Both projects support NOAA/NCDC Goal 2 - provide the highest feasible data quality and information. They also support NCDC Goal 3 activities #6) - U. S. Integrated Earth Observation System (USEOS) and #7) - Global Earth Observation System of Systems (GEOSS). Additionally, they support cross NOAA-NASA-DoD activities.

2. FY 2006 ACCOMPLISHMENTS

1) Blended High Resolution Global Sea Winds

Present Global Ocean Observing System (GOOS) consists of multiple platforms and instruments. 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, blending of them together is necessary 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). Thus an effort to produce globally gridded high resolution products for the sea surface wind speed has been started at NCDC. (Separate high resolution blended products for sea surface temperature are also being produced at NCDC and partially funded by NOAA/CPO/OCO.)

We first assessed the feasibility of producing gridded products for various resolutions from all available wind speed observations. Given the dense satellite data coverage, in-situ data play minor role in the blended products to reduce random and sampling errors and to increase resolutions, thus were not considered so far. However, in-situ data play an essential role to

correct systematic satellite biases, and they will be used in the future in this regard for improvement.

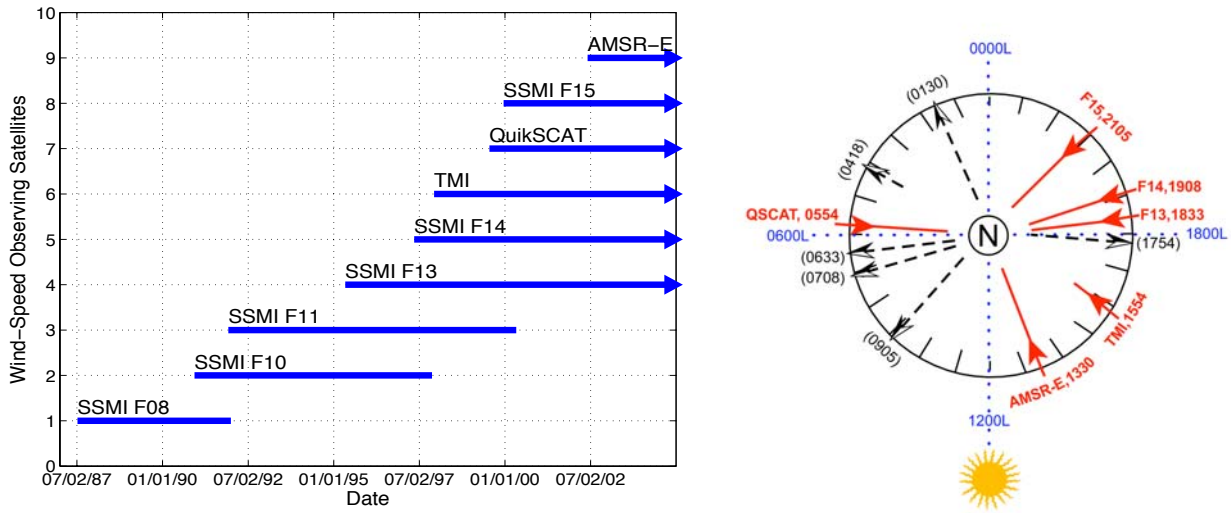

Figure 1 a) Timeline of the long-term US sea surface wind speed observing satellites (left panel); and b) Typical satellite tracks since mid 2002 (right panel). This is a simplified view from the North Pole in Local Solar Time. Red/solid lines represent ascending tracks; black/dashed lines represent descending tracks.

Sea surface wind speed observing satellite number has been increased from one in late 1987 to more than six since June 2002 (Figure. 1). These satellites are operated by NOAA, NASA and DOD. Detailed assessment (Table 1; Zhang et al. 2006) showed that for a global spatial grid of 0.25º, blended products with temporal resolutions of 6-, 12- and 24-hours have become feasible since mid 2002, mid 1995 and January 1991, respectively (Table 1). The corresponding feasible times can be farther extended back to the beginning of 2000 and 1991 and late 1987 when the minimum spatial coverage was reduced to 65%, 70% and 75%, respectively.

Table 1. Typical percentages of the global 0.25º oceanic boxes between 65ºS – 65ºN in which there are data coverage 75% of the time or better for the specified time resolutions (1st column) and as functions of time (indicated by the top row). The whole time period is classified into six stages corresponding to the typical number of available satellites. The time periods with ≥ 90% spatial coverage and ≥75% temporal coverage are highlighted by shading.

Time period & satellites / Time resolution	JUL1987→ I F08	JAN1991→ II F10, F11	JUN1995→ III F10, F11, F13	JAN1998→ IV F11,F13, F14 TMI	JAN2000→ V F13, F14, F15 TMI, QSCAT	JUN2002→ VI F13, F14, F15 TMI, QSCAT AMSR-E
6-hourly	12	26	42	56	66	91
12-hourly	27	72	97	99	100	100
Daily	75	100	100	100	100	100

From the above statistics and for an initially uniform blending for the whole sea wind satellite era (July 1987 – present), a 12-hourly time window was chosen for the first blended

product. Sub-sampling aliases may still be large in the early few years but data are abundant for the later years (Table 1). Taking the advantage the latter year's dense sampling, blended data were generated 4 times a day at 00, 06, 12 and 18Z. To avoid heavy smoothing for instantaneous product, a Gaussian-like weighting in both time and space was used (Zeng and Levy 1995). The 6-hourly 0.25º gridded data and data production details are available at http://www.ncdc.noaa.gov/oa/rsad/blendedseawinds.html. Products of daily and monthly are also available and are simple averages of the 6-hourly data, and operationally updated each quarter.

To make the data available to a wider user community, they are served in multiple data formats, including the netCDF that can be served through inter-operable data servers for different levels of users. For example, through an "One-NOAA" approach and to provide streamlined services across different NOAA Goal Teams (Ecosystem and Climate) and Line Offices (NESDIS and NMFS), NCDC and the Environmental Research Division (ERD) of NMFS Southwest Fisheries Science Center started a pilot project for inter-operable data analysis and visualization and web services. This collaborative project leverages the products and resources at NCDC and ERD to provide value-added services. Through the distributed access and inter-operable data server at NCDC, ERD can acquire the NCDC data "on-the-fly" by web browsing, sub-setting, visualization and disseminating to users in user-preferred formats (images, text or binary data, etc.); shown in Figure 2 is in a global image. The "Live Access Severs" are available at both ERD and NCDC: http://las.pfeg.noaa.gov/las6_5/servlets/dataset?catitem=20; http://nomads.ncdc.noaa.gov:8085/las/servlets/dataset?catitem=731.

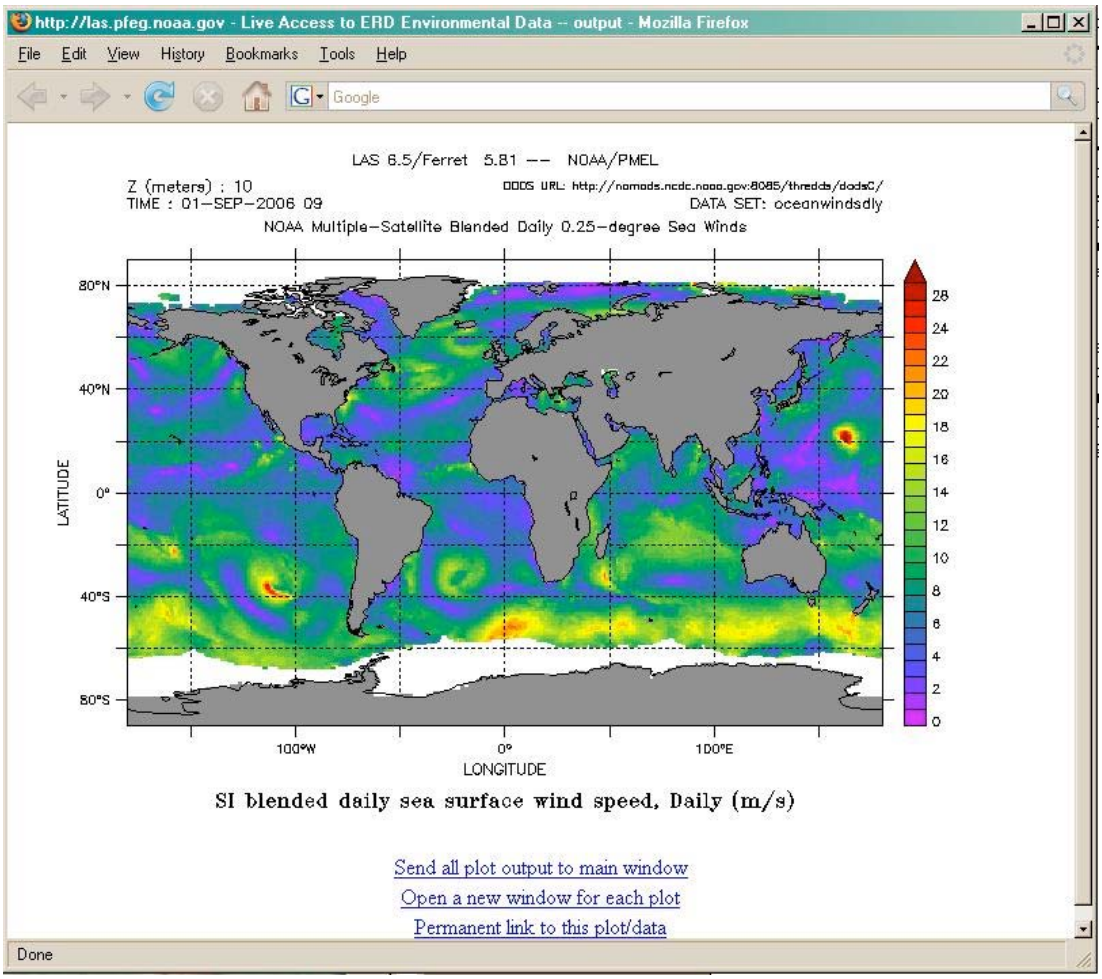

Figure 2 An example of blended global sea winds on 1 September 2006, with a typhoon in the west Pacific Ocean clearly shown. The data reside on an inter-operable data server at NCDC in Asheville, NC, and were acquired and displayed "on-the-fly" by the "Live Access Server" (LAS) at the fisheries lab in Monterey, CA.

2) ICOADS Data Access

During FY06, data access accomplishments focused on four main areas:

a) Marine data consists of several "raw" formats including WMO Ships' Synoptic Code (FM 13-X); Coastal-Marine Automated Network (C-MAN FM12); Drifting Buoy (FM18). All formats are converted to ICOADS, archived, and made available to the web based online system ("Climate Data Online" - CDO) for public access.

b) The relational data model (in Oracle) was completed, to allow for easy retrieval of the data via CDO. This also includes the keys and indices needed within Oracle, to support fully automated retrieval processes. Then, the data were "pulled" from the NCDC digital archive and loaded into the relational database. Also, online data are updated monthly with the latest available data for the current year.

c) Initially, 2005-2006 data were placed online for public access. (Note that the data are available free of charge to all customers/users.) Data prior to 2005 will be made available online

in the near future, after some additional quality control is applied. Customers are now able to retrieve the ICOADS marine data online, rather than placing orders for off-line delivery as done in the past.

d) The CDO software development was completed, to allow customers to request their desired data via latitude/longitude area, ship/buoy ID, and time period. Also, the CDO system provides several data format options, such as the "common marine format" used for many years. The CDO development team worked extensively with NCDC's Customer Services Branch to ensure user requirements fully met.

3. PUBLICATIONS/REPORTS

Zhang, H.-M., J.J. Bates, and R.W. Reynolds, 2006: Assessment of composite global sampling: sea surface wind speed. *Geophysical Research Letters*, 33, L17714, doi:10.1029/2006GL027086, Vol. 33 (17).

Zhang, H.-M., J.J. Bates, and R.W. Reynolds, 2006: Global 0.25° gridded 6-hourly and daily sea surface winds from multiple satellites. *Flux News, Newsletter of the WCRP Working Group on Surface Fluxes*, Issue 2, 17-18 (Also available online: ftp://ftp.etl.noaa.gov/user/cfairall/wcrp_wgsf/newsletter/vol2_fluxnews_07_06.pdf and ftp://ftp.ncdc.noaa.gov/pub/data/papers/2006rrjbhmzfluxfree.pdf)

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Zhang, H.-M., R.W. Reynolds, and J.J. Bates, 2006: Blended and gridded high resolution global sea surface wind speed and climatology from multiple satellites: 1987 - present. *86th AMS Annual Meeting, 29 January - 2 February 2006, Atlanta, Georgia, combined preprints* [CD-ROM], American Meteorological Society, Boston, MA, (14 SAT P2.23), 7p. (Online: ftp://ftp.ncdc.noaa.gov/pub/data/papers/200686amsp2.23hzfree.pdf)

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WMO/TD-No. 1036/WCRP-112 (2000), *Final Report of the Joint WCRP/SCOR Working Group on Air-Sea Fluxes (SCOR Working Group 110): Intercomparison and Validation of Ocean-Atmosphere Energy Flux Fields*, 303pp+xvi.

Zeng, L., and G. Levy (1995), Space and time aliasing structure in monthly mean polar-orbiting satellite data, *J. Geophys. Res.*, *100 (No. D3)*, 5133-5142.

Zhang, H.-M., J.J. Bates, and R.W. Reynolds, 2006: Assessment of composite global sampling: sea surface wind speed. *Geophysical Research Letters*, 33, L17714, doi:10.1029/2006GL027086, Vol. 33 (17).

U.S. Research Vessel Surface Meteorology Data Assembly Center

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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 they 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 which are distributed with a delay of several weeks. All quality-evaluated research vessel data at the DAC 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.

Accomplishments

Over the past year our efforts have focused on the continued development of the SAMOS Initiative. We wrapped up a successful data exchange pilot project with WHOI and now are receiving routine data transmissions from the *Knorr* and *Atlantis* while they are at sea. We continued to expand our SAMOS data quality evaluation system and have improved access to both preliminary data files and metadata on our web pages. Throughout the year DAC personnel have been actively promoting the SAMOS Initiative through meetings and working groups, and in May 2006 the DAC coordinated the 1st Joint SAMOS/GOSUD Workshop in Boulder, Colorado (with supplemental funding from a one-off add task from NOAA/OCO). Finally, we continued our delayed mode data processing for NOAA vessels and have actively recruited additional vessels to participate in SAMOS.

Deliverables for FY 2006 included:

1. Recruiting additional vessels to provide daily data transfers to the SAMOS DAC through collaboration with UNOLS, USCG, NOAA, etc.
2. Establishing, where possible, data transfers from international vessels through collaboration with GOSUD and international research vessel operators.
3. Continuing daily and delayed mode quality processing and distribution of meteorological data from select NOAA vessels and vessels recruited to SAMOS
4. Evaluating and improving data ingest and quality control system based on FY 2005 experience.
5. Expanding data and metadata distribution, including collaboration with national archive centers.
6. Compare R/V observations to global reanalysis products and to independent marine platforms (e.g., tropical moorings).
7. Produce a one or more written reports from the 1st Joint GOSUD/SAMOS Workshop (from one-off FY 2006 add task).

The following accomplishments address the deliverables. Also noted are impediments to achieving the deliverables.

Vessel recruitment [Deliverable 1]

Recruitment of additional vessels to participate in the SAMOS Initiative has been an ongoing, albeit slow, process. The project manager (Smith) attended the annual UNOLS RVTEC meeting in Oregon in November 2005 and had good conversations with several vessel operators. Most expressed interest in participating, but initiating new data transfers is still difficult in these times of tight operational budgets for research vessels. In spring 2006 a plan was established with NOAA OMAO to use a new fisheries vessel, the *Bigelow*, as a pilot vessel to establish SAMOS data transfers from NOAA vessels. Most NOAA vessels are equipped with the scientific computing system (SCS) software and the latest version of SCS will be installed on the *Bigelow*. The new SCS will facilitate SAMOS data transfers and once tested can then be spread to other vessels in the NOAA fleet. Due to problems with the *Bigelow* at the shipyard, early tests of data transmissions from NOAA vessels were conducted in August 2006 with data from the *Miller Freeman*. In addition to the NOAA vessels, a dialog is underway with several other UNOLS operators to bring additional vessels into the SAMOS Initiative.

Daily processing of Knorr and Atlantis data [Deliverable 3]

The DAC completed development of the preliminary processing of SAMOS observations received via daily email messages from participating research vessels. Currently two vessels, the *Knorr* and *Atlantis*, have automated their transmission of daily data messages (which include all one minute average observations for the day) to the DAC. The data messages are generated on each vessel by scripts developed by WHOI. Once the data file arrives at the DAC (as an attachment to an email), the data are unpacked, verified that they conform to the format and parameters expected for the individual vessel, and finally 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 web and ftp (see below). 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). Strict version control is used to track individual data files received from their original email attachment to the preliminary netCDF files posted for users.

The expanded spatial coverage of data received, processed, and on-line from the *Knorr* and *Atlantis* is shown in Figure 1 for FY 2005 and 2006. In FY 2005, the Knorr and Atlantis provided approximately 300,000 individual one minute marine reports. Their contributions doubled to ~600,000 reports in FY 2006, in part due to the inception of SAMOS data transfers in the middle of FY 2005. The quality of the preliminary data for both vessels was good with on average less than 5% of the individual data values being flagged as suspect. The majority of the suspect observations were shortwave radiation values below zero. These unrealistic values often occur because the shortwave sensor is not sensitive to low values and can report negative values at night. Several minor problems with the underway sensors (e.g., an RH sensor that had drifted and was recording anomalously high values) were noted by the DAC analyst and were reported to WHOI. These near-real time reports resulted in rapid repair of problems and a continuous stream of high quality observations.

Continue delayed-mode evaluation of NOAA ship data [Deliverable 3]

The DAC continues to evaluate the quality of the meteorological observations collected by the NOAA vessels *Ronald Brown* and *Ka'Imimoana*. Over the past year the DAC has received and processed *Ronald Brown* observations for the periods May 2004 – March 2005 (Rolph and Smith 2005) and July 2005 – November 2005 (Rolph and Smith 2006). We continue to see improvements in the quality of the meteorological observations from the *Ronald Brown* and these data make up an extensive (1999-2005) data set for a wide array of satellite and model validation studies. In September 2006 we received the underway data from the Ronald Brown covering the period 17 February – 11 September 2006. The data for the *Ka'Imimoana* tend to arrive in multiple data formats which complicates their conversion for quality processing. We recently converted observations for September 2004 - December 2005 and have completed the visual quality evaluation. The quality report and data files for this period of Ka'Imimoana data will be posted on-line shortly. We continue to receive and process additional data for the *Ka'Imimoana* on a regular basis.

Delayed-mode SAMOS processing [Deliverable 4]

The initial processing of SAMOS observations is completed in near-real time (see 1 above). Due to data logging problems on the ship or communication drop-outs, 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 can be fragmented and may arrive as multiple files attached to an 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 and visual data quality evaluation and is then released as a "research-quality" SAMOS data file for the particular observation day.

Over the past six months, the code to merge multiple files has been developed, tested, and is now operational. The merge program is designed to eliminate duplicate records from the files being merged. Duplicates are eliminated based on a series of rules that take into account the automated quality control applied to the preliminary data files. The merge process is fully automated and the merged files are tracked within the file tracking data base. Currently the merge occurs 10 calendar days after the observation day (when the preliminary data should arrive at the DAC). Using the file tracking database, the analyst can easily reference the original file pieces that were merged to create a single data file for each observation day. Once merged, a summary of the data quality flags on the new file is produced and stored in the database. Developing the delayed-mode processing has been slowed by the heavy demands on our computer programmers (from multiple projects) but we anticipate completion of the codes for visual data quality inspection of the merged files late in 2006.

Public access to observations and metadata [Deliverables 1, 3, 5 and 7]

A web presence for SAMOS has been completed and is accessible at: http://samos.coaps.fsu.edu/. The pages provide information on the SAMOS Initiative as a whole, provides links to relevant literature, and access to past SAMOS workshops (including the 1st Joint GOSUD/SAMOS Workshop). Through these pages, the DAC provides access to the preliminary quality controlled data for the *Knorr* and *Atlantis*. A metadata portal allows users to access ship- and parameter-specific metadata along with digital photos and schematics of participating vessels. Both the metadata portal and data access are user searchable. Criteria include searches by vessel and the observation dates. The web site also provides access to desired SAMOS parameters, accuracy requirements, and training materials. In September 2006 an extensive ship recruiting section was added to the SAMOS web page that includes necessary metadata forms and data specifications for vessels interested in contributing to the SAMOS Initiative.

Liaison activities [Deliverables 2 and 7]

The SAMOS DAC serves as the international coordination office for the 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. As a result, Smith and Bourassa have presented at numerous conferences and workshops (see below).

Foremost among the liaison activities was the coordination of the 1st Joint 1st Joint Global Ocean Surface Underway Data (GOSUD)/Shipboard Automated Meteorological and Oceanographic System (SAMOS) Workshop held in Boulder, CO on 2-4 May 2006. In response to an FY 2006 Add Task, NOAA supported the travel, logistics, and venue for the workshop through the UCAR Joint Office for Science Support (JOSS). The SAMOS DAC supported all planning of the scientific program, pre- and post-meeting documentation, and the workshop web page

(http://www.coaps.fsu.edu/RVSMDC/marine_workshop3/). The workshop focused on establishing collaboration between GOSUD and SAMOS and addressing the need of the research and operational community for high-quality underway oceanographic and meteorological observations from ships. The SAMOS initiative is working to improve access to calibrated, quality-controlled, surface marine meteorological data collected in-situ by automated instrumentation on research vessels (primarily) and merchant ships. GOSUD focuses on the collection, quality evaluation, and distribution of near surface ocean parameters (salinity and sea temperature) from vessels.

The workshop organizing committee (Shawn Smith, Robert Keeley, Thierry Delcroix, Mark Bourassa, and Christopher Fairall) brought together representatives from the scientific and operational marine observational communities. Participants from the U.S. government represented NOAA (ESRL, AOML, NDBC, NODC, OMAO), the Army Cold Regions Laboratory, and the U.S. Coast Guard. The U. S. university community was represented by the Woods Hole Oceanographic Institution, the Scripps Institution of Oceanography, the University of Miami, University of Alaska, Oregon State University, the National Center for Atmospheric Research, and the Florida State University. A significant international presence included representatives from the CSIRO (Australia); CNRS, IRD, IFREMER, and Mercator Ocean (France and New Caledonia); Environment Canada and MEDS (Canada); Tokai University and JAMSTEC (Japan); and the NOC (UK). Finally, the private sector was represented by Raytheon Polar Services, ADA Technologies, Earth and Space Research, and the International Sea Keepers Society.

The workshop was organized in three sessions: (1) parallel SAMOS and GOSUD technical working group meetings, (2) invited talks and posters focusing on applications of SAMOS and GOSUD observations and potential collaborations between marine observing programs, and (3) a plenary discussion encompassing sessions (1) and (2). A primary discussion topic was the scientific user needs for high-quality, automated, near-surface ocean and atmosphere measurements to achieve objectives ranging from satellite calibration and validation, ocean data assimilation, polar studies, air-sea flux estimation, and improving analyses of waves, precipitation, and radiation. The quantification and reduction of measurement bias and uncertainty was also addressed. The SAMOS and GOSUD working groups addressed both issues internal to each program as well as future interaction between SAMOS, GOSUD, and other international marine observing programs. The result of the workshop was a series of action items, recommendations, and reports (Smith 2006, Smith et al. 2006).

Additional collaborative activities are promoted by the SAMOS DAC. Colleagues at NOAA/ESRL/PSD and WHOI are working to develop a portable seagoing air-sea flux standard instrument suite. This system will be deployed on UNOLS and other research vessels to assess the accuracy of the SAMOS installations on those vessels. Once deployed recommendations for improving SAMOS on individual vessels can be made. The SAMOS DAC continues to promote the development of training materials for marine technicians and scientists planning to make meteorological measurements at sea. The first achievement of the training effort will be the Fall 2006 publication of a “Guide to making climate quality meteorological and flux measurements at sea”. Lead authors of the guide are Frank Bradley (CSIRO, Australia) and Chris Fairall (NOAA/ESRL/PSD) and the guide has been a collaborative effort of the SAMOS initiative and

the WCRP Working Group on Surface Fluxes. A new collaboration with the National Oceanography Centre (UK) and NOAA/ESRL will allow the SAMOS Initiative to undertake a program of computational fluid dynamics (CFD) modeling of research vessels. The primary focus of the CFD modeling is to identify the accelerations/decelerations of the wind flow over the vessel structure, allowing sensors to be moved to the "best" possible exposure on the vessel. The program will evaluate existing techniques and new methods to model the maximum number of vessels for the lowest cost. Finally, Smith has joined the Baseline Surface Radiation Network (BSRN) Ocean Working Group to expand the role of the SAMOS Initiative in resolving questions related to radiation measurements at sea.

SAMOS vs. bridge data comparisons [Deliverable 6]

A preliminary comparison was completed between marine meteorological observations that currently are available in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and those collected by automated science instrument systems on a dozen research vessels (R/Vs). Research vessels are typically equipped with both an automated science instrument system and a set of independent sensors used by the bridge crew for routine weather reports. The routine bridge reports are the typical source of observations in ICOADS and tend to be reported at one, three, or six hourly intervals. Hourly observations, derived from one-minute interval science system data, are used to evaluate the ICOADS reports from each R/V.

For this experiment, comparison data come from a dozen R/Vs that participated in the World Ocean Circulation Experiment. The comparison reveals large differences in temporal coverage provided by the bridge and science reporting systems on R/Vs. For the vessels examined, a large fraction of the bridge observations do not routinely appear in ICOADS (Figure 2). Using standard statistical techniques, differences in atmospheric pressure, sea and air temperature, humidity, and true wind direction and speed are examined. In some cases, large differences exist between bridge and science observations on individual vessels (Figure 3). Using available metadata (e.g., instrument heights, varying data sources in ICOADS, etc.) we will next consider possible causes for observed differences between the bridge and science observations and their impact on turbulent air-sea fluxes.

Publications and Reports

Refereed

Smith, S. R., 2006: Collaboration between Shipboard Oceanic and Atmospheric Programs. *EOS, Trans Amer. Geophys. Union*, **87**, 463, 466.

Gould, W. J and S. R. Smith, 2006: Research vessels: Underutilized assets for climate observations. *EOS, Trans Amer. Geophys. Union*, **87**, 214-215.

Technical reports

Rolph, J. J., and S. R. Smith, 2006: *Ron Brown IMET data quality control report: July 2005 – November 2005*. RVSMDC report 06-02, Center for Ocean-Atmospheric Prediction Studies, Florida State University, Tallahassee, Florida, 32306-2840, USA, 15 pp.

Smith, S. R., R. Keeley, and T. Delcroix, 2006: Report of the 1st Joint GOSUD/SAMOS Workshop. UCAR Joint Office for Science Support, Boulder, CO, USA, 63 pp. [Available from COAPS, The Florida State University, Tallahassee, FL 32306-2840].

Conference proceedings/presentations

Bourassa, M. A., 2006: Uncertainty in monthly surface wind fields from in situ observations. *1st Joint GOSUD/SAMOS Workshop*, 3-5 May 2006, Boulder, CO.

Bourassa, M. A., and P. J. Hughes, 2006: Hybrid surface turbulent fluxes model. *3rd SEAFLUX Workshop*, 3 March 2006, Tallahassee, FL.

Bourassa, M. A., 2005: New insights into how wind influences stress, and resulting implications to equivalent neutral winds and wind retrieval, *Ocean Vector Wind Science Team Meeting*, March, Seattle, WA.

Bourassa, M. A., 2005: On the important differences between earth-relative winds and equivalent neutral winds. *Scatterometer High Wind Model Function Meeting*, July, Pasadena, CA.

Bourassa, M. A., 2005: Wave Influences on Surface Turbulent Fluxes. *2nd International Workshop on Advances in the Use of Historical Marine Climate Data (MARCDAT-II)*, 17-20 October 2005, Exeter, U.K, 14.

Smith, S. R., 2006: Progress of the Shipboard Automated Meteorological and Oceanographic System (SAMOS) initiative. *Short Abstract*, *Climate Observation Program 4th Annual System Review*, Silver Spring, MD, USA, NOAA (in press).

Smith, S. R., 2006: A Comparison of SAMOS and Bridge Observations on Research Vessels, *1st Joint GOSUD/SAMOS Workshop*, 3-5 May 2006, Boulder, CO.

Smith, S. F., 2006: High quality R/V observations for air-sea flux analysis. *3rd SEAFLUX Workshop*, 3 March 2006, Tallahassee, FL.

Smith, S. R., S. D. Woodruff, and S. Worley, 2005: Marine climatology from research vessels. Abstracts from *2nd International Workshop on Advances in the Use of Historical Marine Climate Data (MARCDAT-II)*, 17-20 October 2005, Exeter, UK, 43.

Smith, S. R., 2005: Progress of the shipboard automated meteorological and oceanographic system (SAMOS) initiative. Abstracts from *2nd International Workshop on Advances in the Use of Historical Marine Climate Data (MARCDAT-II)*, 17-20 October 2005, Exeter, UK, 48.

Smith, S. R., 2005: Show and tell: Shipboard Automated Meteorological and Oceanographic System (SAMOS). *UNOLS Research Vessel Technical Enhancement Committee (RVTEC) Annual Meeting*, 8-10 November 2005, Corvalis, OR.

Figures

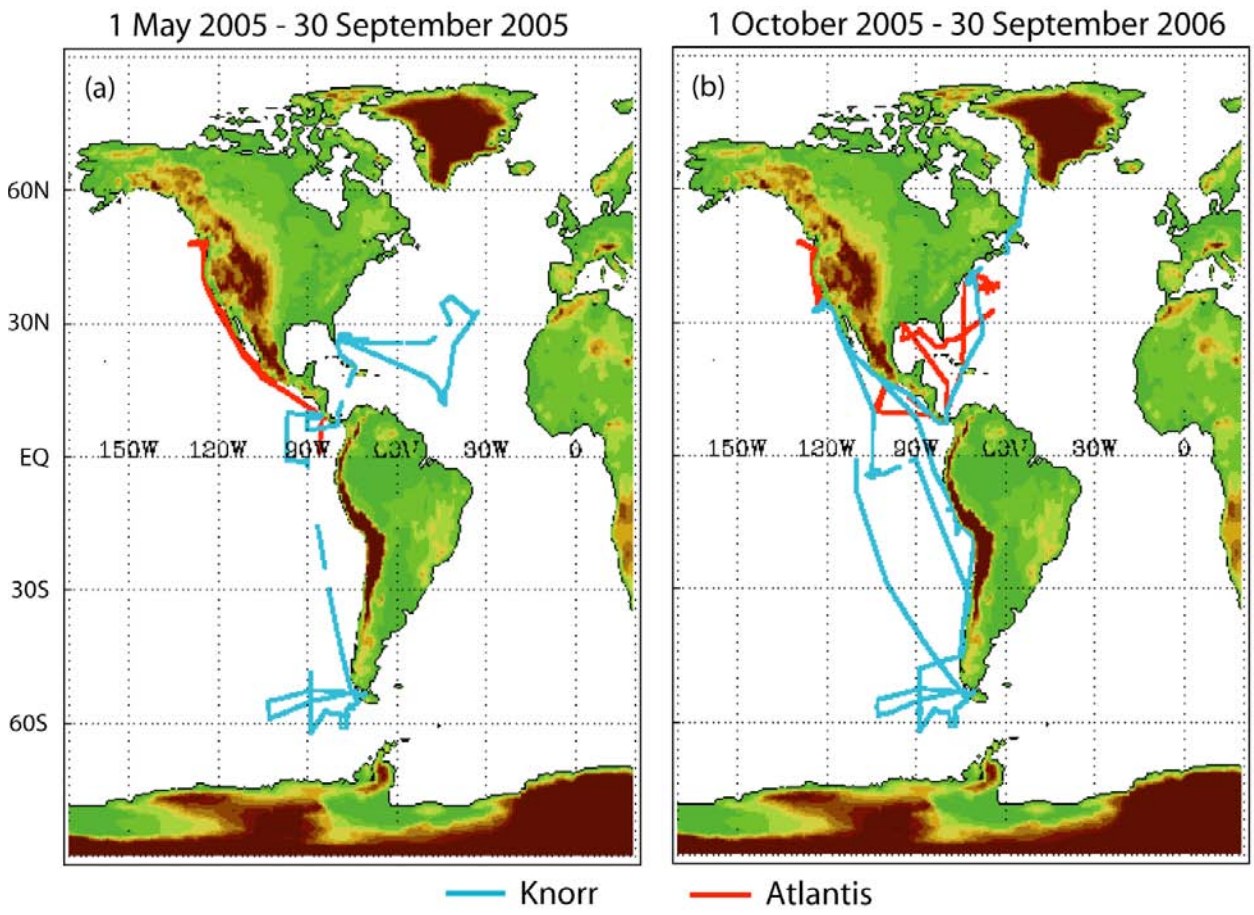

Figure 1. Cruise tracks for the *Knorr* and *Atlantis* for which SAMOS data were received, processed, and distributed by the DAC. The period of record is (a) 1 May 2005 through 30 September 2005 and (b) 1 October 2005 through 30 September 2006.

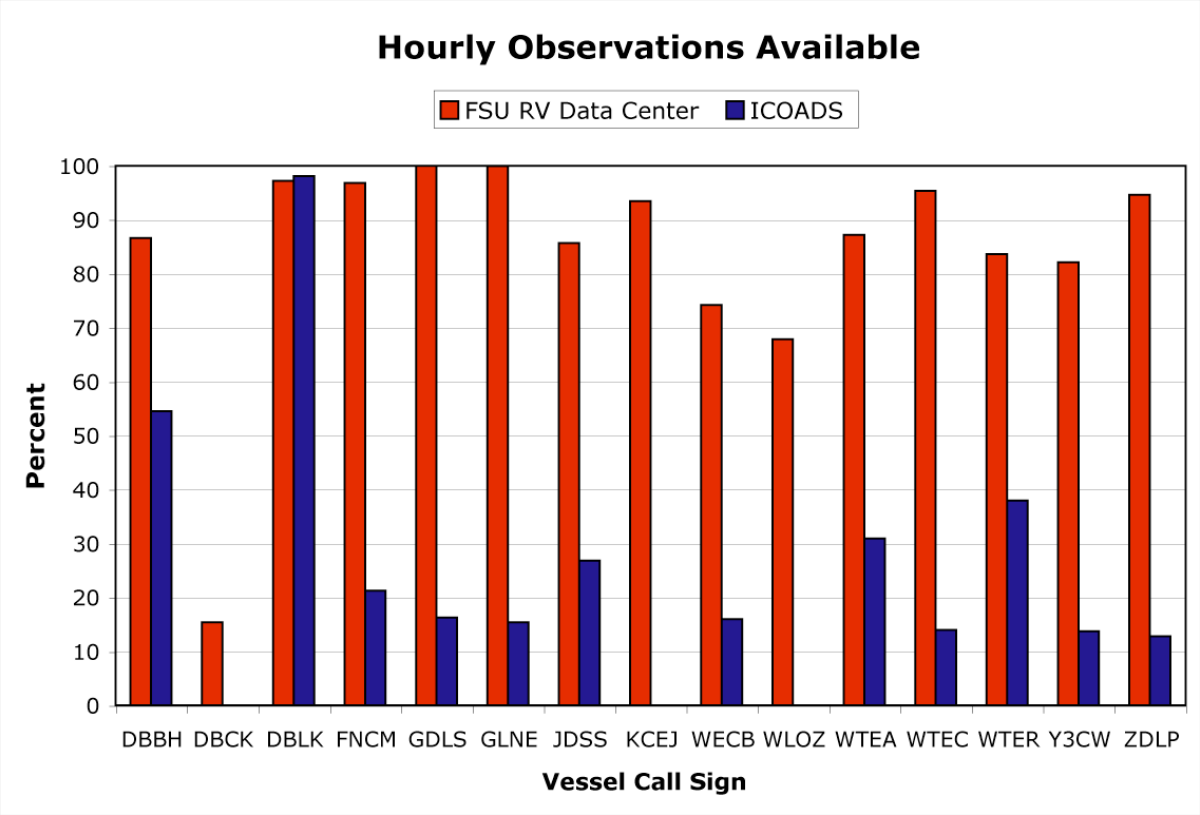

Figure 2: Percentage of hourly marine reports available during 90 WOCE cruises from the ICOADS (bridge) and FSU R/V data center. Vessels evaluated include the *Meteor* (DBBH), *Heincke* (DBCK), *Polarstern* (DBLK), *L'Atalante* (FNCM), *Charles Darwin* (GDLS), *Discovery* (GLNE), *Hakuho Maru* (JDSS), *Knorr* (KCEJ), *Melville* (WECB), *Maurice Ewing* (WLOZ), *Discoverer* (WTEA), *Ronald Brown* (WTEC), *Malcolm Baldrige* (WTER), *A. von Humboldt* (Y3CW); and the *James C. Ross* (ZDLP).

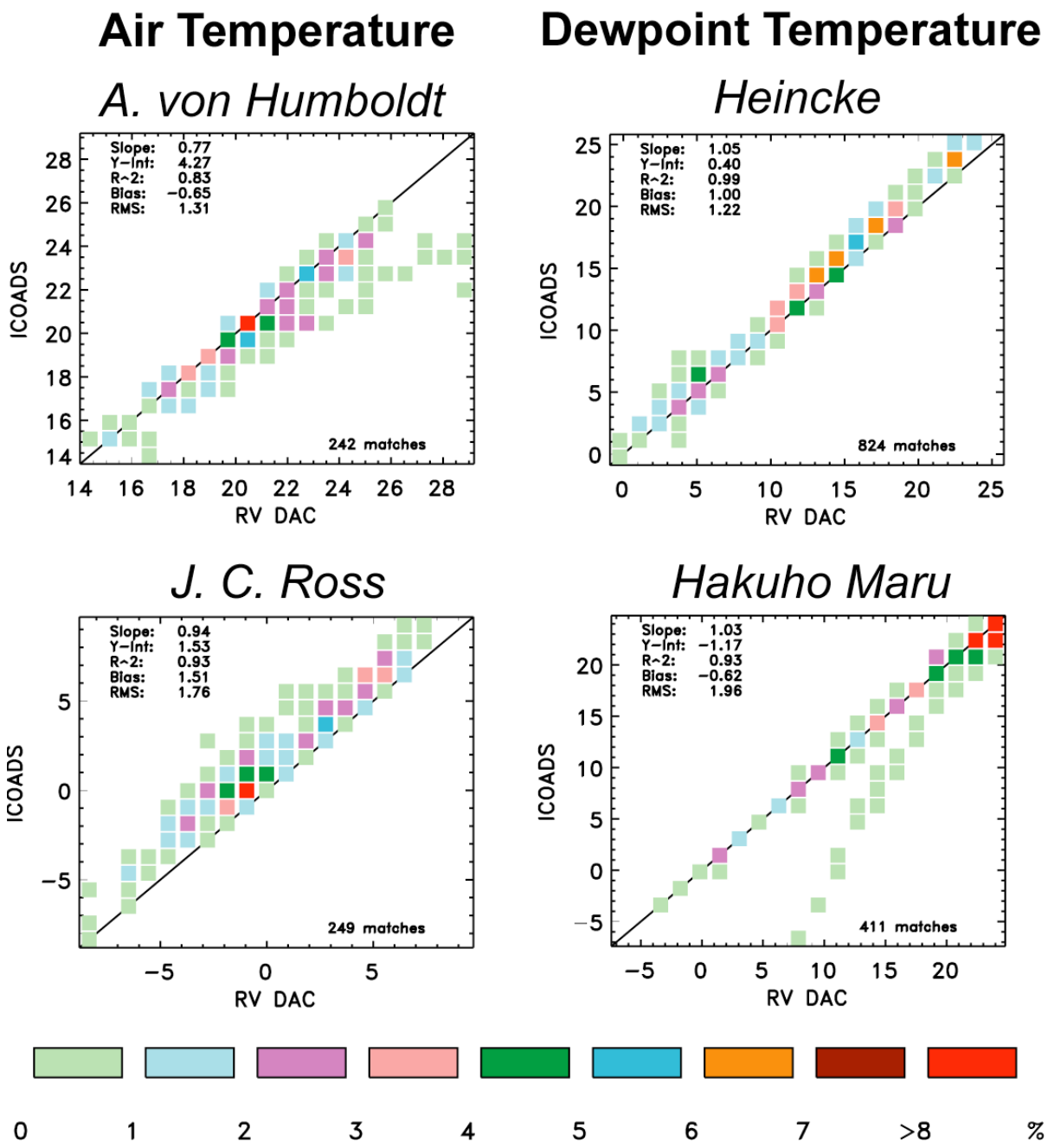

Figure 3: Comparison histograms for unadjusted air (left) and dewpoint (right) temperature (˚C). Histograms represent the percentage of one-to-one matches that fall within each bin on the graph (similar to a scatter plot). Each graph is divided into 20 equal bins on the x and y axis. Percentages are calculated relative to the number of matches for each variable (lower right on each plot). Plots are labeled with the vessel that provided the observations.