Ocean Reference Stations and Air-Sea Fluxes

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2. Abstract

This effort has two distinct parts. The first is the Ocean Reference Stations (ORS) project. The goal of the ORS project is to maintain long-term surface moorings with climate-quality observing capabilities as part of the integrated ocean observing system. The emphasis is on accurate observations of surface meteorology, air-sea fluxes, and upper ocean variability in regions of key interest to climate studies and on the use of 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. The second part of the effort is the production of 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 and use of these data to study the heat flux variability on seasonal, annual, interannual, decadal and longer timescales and their relation to global climate change.

3. Project Summary

3.1. Ocean Reference Stations

The goal of this observational project is to maintain long-term surface moorings, known as Ocean Reference Stations, as part of the integrated ocean observing system. Ocean Reference Stations collect long time series of observations of surface meteorology and upper ocean variability in regions of key interest to climate studies. The resulting meteorological and oceanographic observations provide a set of high quality air-sea fluxes of heat, freshwater and momentum as well as upper ocean heat and salt content. The scientific rationale for the collection of these flux products is manifold: 1) to describe the upper ocean variability and the local response to atmospheric forcing; 2) to motivate and guide improvement to atmospheric, oceanic, and coupled models; 3) to calibrate and guide improvement to remote sensing products and capabilities; and 4) to provide anchor points 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 create more accurate global fields.

Three Ocean Reference Stations are being maintained: A site at 20°S, 85°W under the stratus cloud deck off northern Chile (Stratus), the Northwest Tropical Atlantic Station (NTAS) at 15°N, 51°W, and a site north of Hawaii near the Hawaii Ocean Time-series (HOT) site at 22.75°N, 158°W known as the WHOI Hawaii Ocean Time-series Station or WHOTS. Moorings at the Stratus and NTAS sites were initially deployed and serviced annually under NOAA OGP support; these sites have now transitioned to long-term Ocean Reference Stations. WHOTS was established in 2004, in collaboration with investigators that have made shipboard and moored observations in that region in recent years.

The Ocean Reference Stations project is managed under four task areas: 1) Engineering, oversight, and data management, 2) Maintenance of the Stratus site, 3) Maintenance of the NTAS site, and 4) Maintenance of the WHOTS site. Accomplishments in each of the task areas are reported in more detail below.

3.2. Air-Sea Fluxes

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

While improving the quality of each data source is a necessary step toward improving the estimates of surface heat fluxes, this project takes an alternative approach, i.e., to improve the quality of the flux estimates through objectively synthesizing the advantages of the three data sources. The synthesis approach has been applied successfully to generate gridded products of surface vector wind, SST, and precipitation. This project, which is termed "Objectively Analyzed air-sea heat Fluxes (OAFlux)", develops an equivalent global synthesis product for surface heat fluxes by utilizing the methodology developed and experience 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 are produced when satellite data are available. The second objective is to use the data to study the heat flux variability on seasonal, annual, interannual, decadal and longer timescales and their relation to global climate change. The scientific investigation helps to assess the quality and reliability of the dataset in depicting the multi-decade climate record since 1950s and to provide physical insights into the dataset.

4. Scientific Accomplishments

4.1. Ocean References Stations– Engineering Oversight and Data Management

To increase bandwidth over our existing Argos telemetry system, we have implemented an Iridium telemetry system, including mooring controllers and an automated, shore-based decoding and processing system. This modular system allows storage, buffering and transmission of surface meteorology, subsurface data transmitted via inductive link, subsurface data transmitted via acoustic modem, or all three. The system is built around a newly developed Iridium Communication Module (ICM) and a modified ASIMET (Air Sea Interaction Improved METeorology package – developed at WHOI) controller board, and can now be integrated with both a Seabird inductive modem and a Benthos acoustic modem. We continue to add complementary instrumentation to ORS installations to the extent possible. For example, we are now incorporating pCO_2 instrumentation developed by Chris Sabine (NOAA PMEL) on both Stratus and WHOTS buoys. The Stratus buoy is also being used to measure surface waves by collaborating with the National Data Buoy Center (NDBC), who provide hardware and guidance on how to install and operate the wave sensors.

All ORS provide surface meteorology via satellite telemetry. Hourly meteorological data are transmitted via Argos telemetry and made available via an FTP server and a website with download capability. To ensure that ORS surface meteorological data is a truly independent data set that can be used to assess atmospheric and coupled model performance, these data are not

inserted on the GTS. Instead hourly data are placed on and FTP server at WHOI, where they are made available to NCEP and ECMWF, who in return put model data on that FTP site to support ongoing model-observation comparisons. The NTAS ORS has implemented telemetry of subsurface oceanographic (velocity, temperature, salinity) data and that data is also now available in near-real time from the UOP website (http://uop.whoi.edu/projects/NTAS/ntasdata.html). Delayed mode oceanographic (velocity, temperature and salinity) and surface meteorological data (wind speed and direction, air and sea surface temperature, rain, incoming shortwave and longwave, relative humidity, and barometric pressure) are processed and stored on disks attached to our workstations. We maintain a public access archive of historical Upper Ocean Processes (UOP) Group data from mooring deployments http://uopwhoi.edu). The FTP server has near-real time hourly surface meteorology from all ORS. Post-deployment, processed, calibrated, and quality-controlled data from the surface and subsurface are available from the UOP web archive and from OceanSITES.

We have worked with the National Data Buoy Center (NDBC) to exchange WHOI ORS data in a format that can be utilized by standard NDBC processing and display tools. As a result, the three ORS sites are now accessible as stations within the NDBC buoy network (see Stations 32ST0, 41NT0 and 51WH0, at http://www.ndbc.noaa.gov). We also work with the OceanSITES team to develop protocols, policies and data format recommendations, and are presently serving our data in OceanSITES NetCDF format. Talks, white papers, and posters at the OceanObs 09 meeting in Venice in September 2009 included a number of presentations where ORS data were used for examination of the realism of different numerical weather prediction models.

4.2. Ocean Reference Stations – Stratus Ocean Reference Station

The Stratus ORS was originally deployed under a previous grant (from the Pan American Climate Studies) in October 2000. It has been annually serviced (recovered and redeployed) since that time. During the deployments, hourly-averaged surface meteorology is available in near real time via Service ARGOS and the UOP web site. Data are routinely exchanged with ECMWF, NCEP and others to examine numerical weather prediction model performance and examine air-sea fluxes under the stratus clouds. The telemetered meteorological data are also available via the website maintained for this site (http://uop.whoi.edu/projects/Stratus/stratus.html). Internally recorded 1-minute meteorological data as well as the oceanographic data, which are only internally recorded, were downloaded from the recovered instrumentation. Data recovery was good, post-calibrations are being done, and data files have been shared with colleagues. Preliminary cruise reports are filed with the State Department soon after the cruise; final documentation that goes to foreign observers and the State Department includes copies of the underway data and a cruise report.

Field operations this year included taking the lead in the oceanographic component of the VOCALS Rex (VAMOS Ocean Cloud Atmosphere Land System Regional Experiment) on two legs of the *Ronald H. Brown* (Charleston to Arica, Chile; Arica to Arica) in October to December 2008. On the first leg we were deploying the new Stratus mooring and recovering the old mooring, doing calibrations (both pre and post-deployment), using a towed Underway CTD (UCTD) to map the spatial structure of the mesoscale variability in the upper ocean in the region

between the WHOI mooring (20°S, 85°W) and the SHOA DART mooring (20°S, 75°W), data processing, writing cruise reports, preparing mooring hardware and instrumentation for the new deployment and cleaning and assessing the recovered equipment. Data recovery this year was good, post-calibrations are being done, and data files have been shared with colleagues. We also supported on the mooring this year additional sensors, microstructure instruments, in support of work by Tom Farrar (WHOI) and Chris Zappa (LDEO); this was further supported by deploying for them a ship-based Vertical Microstructure Profiler.

On the Stratus 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. During the deployment, high data rate (up to 1 sample per minute) data are stored in each instrument. The internally recorded data goes through processing, has calibration information applied, and is subject to preliminary analyses before being made publicly available on our website. Hourly surface meteorological data are being shared with OceanSITES (http://www.oceansites.org), with the Chilean Navy (SHOA), with CLIVAR modelers interested in the Stratus region, with VAMOS investigators in the U.S. and in South America, and with Peter Glecker at PCMDI for use in the SURFA project. Once per minute as well as hourly surface meteorological time series are provided to VOCALS PIs and others (including Sandra Yuter, Chris Bretherton, Meghan Cronin) after recovery. Data have also been made available to the satellite community (including NASA-Langley, JPL, NCEP/NCDC and SEAFLUX). The oceanographic data are being used by Weller to investigate air-sea coupling and upper ocean variability under the stratus deck.

The Stratus cruises serve the wider scientific community by providing a platform on which to study the regional ocean. Researchers who participated in collaborative research or benefited from shared ship time in FY2009 have come from many institutions: NOAA Earth System Research Laboratory, Servicio Hydrografico y Oceanografico de la Armada (SHOA, Chile), Lamont-Doherty Earth Observatory, the NOAA National Data Buoy Center, University of Miami, University of Hawaii, University of California at San Diego, Brookdale School, Bigelow Laboratory for Ocean Sciences, UK Met Office, University of Washington, Scripps Institution of Oceanography, the Argo float program, the NOAA surface drifter program, and IMARPE (Institute of Marine Research, Peru). Ten Argo floats and 20 surface drifters, were deployed during the cruise. During the transit from Rodman, Panama, sampling was done Ecuadorian and Peruvian waters in collaboration with these countries. A teacher from NOAA's Teachers-at-Sea program (Dave Grant) participated in Leg 2 of the cruise.

In collaboration with participants from SHOA, we recovered and redeployed the Chilean Navy tsunami warning buoy at 20°S, 75°W. WHOI meteorological sensors on the surface buoy were serviced, and WHOI ocean sensors on the mooring line of the surface buoy were also serviced. This part of a growing partnership between the ORS project and SHOA.

In the context of VOCALS and in the context of examining atmospheric and coupled model performance in areas of persistent marine stratus clouds, the Stratus ORS is providing essential, climate-quality observations to improve understanding and modeling of the processes at work in stratus cloud regimes. Stratus data is used in the collaborative SURFA project where operational

model centers and operators of long time series sites such as the ORS exchange data and foster ongoing model validation and verification studies in support of improving these models. Figure 1 shows a summary comparison of Stratus ORS buoy net shortwave radiation against that from ECMWF and NCEP.

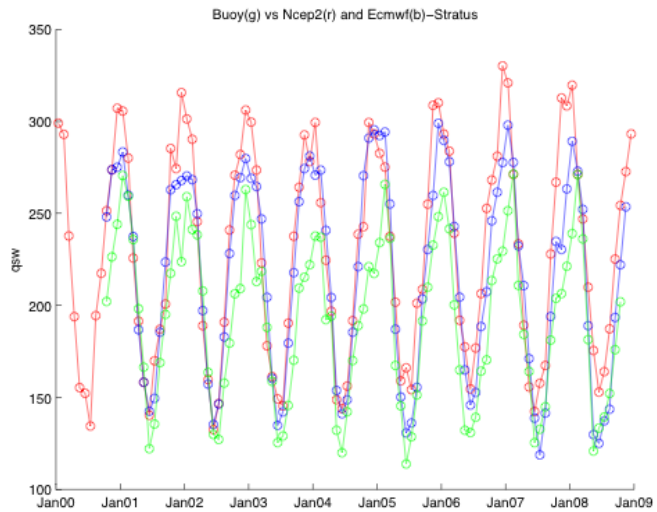

Figure 1. Monthly mean net shortwave from the Stratus buoy (green), ECMWF (blue), and NCEP (red). Note how the models are challenged to get shortwave radiation correct and how, during the spring-summer, the two models can differ by up to 100 W m^{-2}.

4.3. Ocean References Stations – NTAS Ocean Reference Station

The NTAS ORS was originally deployed in 2001 and has been annually serviced (recovered and redeployed) since that time. NTAS surface meteorological data are archived on the UOP web site (http://uop.whoi.edu/projects/NTAS/ntas.htm) and also available in near real time from the NDBC web server (Station 41NT0, http://www.ndbc.noaa.gov). Data are exchanged with ECMWF and NCEP, and they in turn provide operational model output at the grid point nearest the buoy. NTAS data are also available through OceanSITES and are shared with the Baseline Surface Radiation Network (BSRN) and the GEWEX (Global Energy and Water Cycle Experiment) Radiation Panel.

The NTAS mooring service cruise was conducted on the NOAA Ship *Ronald Brown* during the period 17 June to 4 July 2009 in order to retrieve the existing mooring (NTAS-8) and replace it with a new mooring (NTAS-9). In preparation for this cruise, three ASIMET systems were calibrated and tested, and two systems, comprised of the best performing sensors, were prepared for deployment. The NTAS-9 mooring was deployed on 29 June 2009 and the NTAS-8 mooring was recovered on 1 July. The period between deployment and recovery was dedicated to a comparison of the two buoy systems, with the shipboard system as an independent benchmark. Data return from NTAS-8 was good, with all meteorological sensors showing complete records except for precipitation and wind direction. One precipitation sensor failed after 59 days (17%

data return) and the vane follower of one wind system failed after 54 days (16%). Since the second system had a complete precipitation and wind records, no data will be missing in the final (combined) data set. New this year was the deployment of an internally recording GPS system, providing accurate buoy position that will be useful in analysis of observed currents.

The 2009 NTAS cruise represented the third year of collaboration with the Meridional Overturning Variability Experiment (MOVE). The MOVE effort involved servicing (recovery and redeployment) of three subsurface mooring sites and servicing (data collection and/or retrieval and replacement) of five Pressure/Inverted Echo Sounders (PIES).

The NTAS-9 mooring represented the third year of development for real-time telemetry of subsurface data. Engineering work undertaken as part of the WHOI VOS project resulted in a 3rd generation telemetry system, including an Iridium communication controller, Seabird SIM interface, and Benthos acoustic modem interface. Using these new electronics along with hardware developed for NTAS-7, the mooring was outfitted with a system for both inductive and acoustic telemetry of underwater instruments. A series of problems were encountered during preparation and testing of the acoustic communication system, and the final deployment represented a sub-optimal installation. Still, the results have been excellent to date, with the NTAS-9 mooring transmitting subsurface data from both inductive and acoustic subsystems via Iridium during the first three months of operation (Fig. 2).

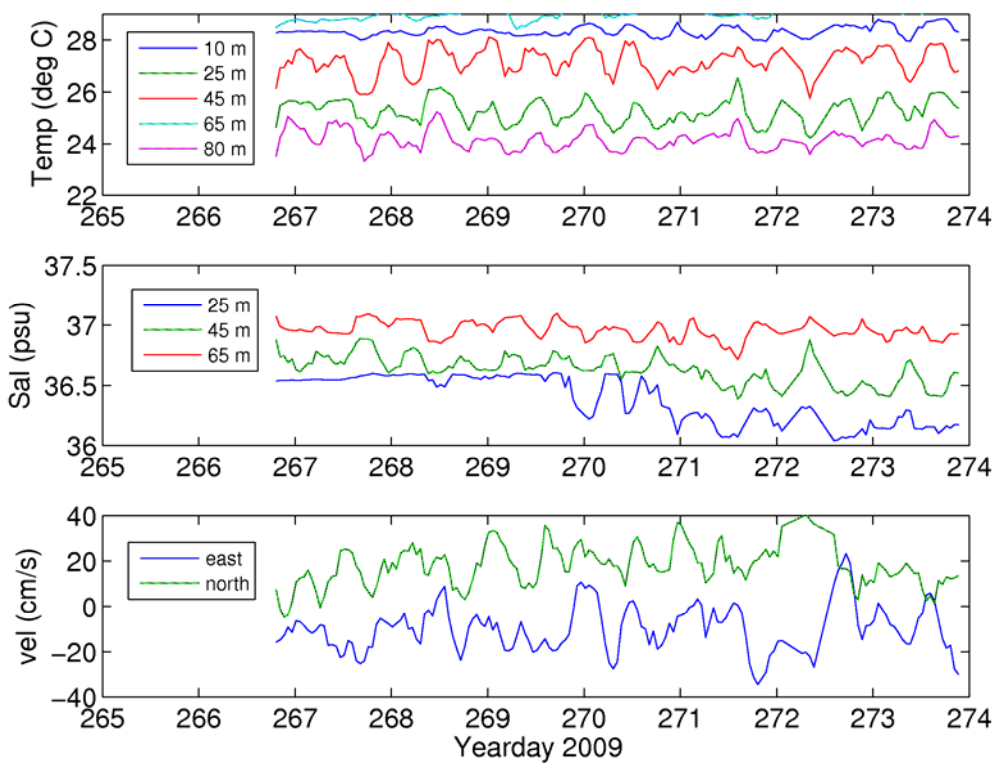

Figure 2. Subsurface temperature (10-80 m), salinity (25-65 m) and velocity (12.5 m) data from the NTAS-9 Ocean Reference Station for the period 24-30 Sep 2009. These data are made

available via an inductive telemetry subsystem passed through an Iridium satellite. An acoustic telemetry system provides velocity profile data (not shown).

4.4. Ocean Reference Stations – WHOTS Ocean Reference Station

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). The primary intent of the WHOI Hawaii Ocean Time-series 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. The WHOTS ORS was originally deployed in 2004 and has been annually serviced (recovered and redeployed) since that time.

WHOTS surface meteorological data are archived on the UOP web site (http://uop.whoi.edu/projects/WHOTS/whots.htm) and also available in near real time from the NDBC web server. Data are exchanged with ECMWF and NCEP, and they in turn provide operational model output at the grid point nearest the buoy. WHOTS data are also available through OceanSITES and are shared with the Baseline Surface Radiation Network (BSRN) and the GEWEX (Global Energy and Water Cycle Experiment) Radiation Panel. Subsurface oceanographic sensors on the mooring are being provided through cooperation with Roger Lukas (U. Hawaii; funded by the National Science Foundation). In cooperation with C. Sabine (PMEL), and with the assistance of D. Sadler (U. Hawaii), a pCO2 system was incorporated in the WHOTS-6 buoy. Incorporation of CO2 measurements on the WHOTS buoy provides continuation of the time series begun in 2004 from the MOSEAN buoy.

The WHOTS mooring service cruise was conducted on the R/V *Kilo Moana* during the period 9 to 17 July 2009 in order to retrieve the existing mooring (WHOTS-5) and replace it with a new mooring (WHOTS-6). In preparation for this cruise, three ASIMET systems were calibrated and tested, and two systems, comprised of the best performing sensors, were prepared for deployment. The WHOTS-6 mooring was deployed on 10 July and the WHOTS-5 mooring was recovered on 15 July. The period between deployment and recovery was dedicated to a multi-investigator, multi-system meteorological sensor intercomparison. Sensors and systems included those from the R/V *Kilo Moana*, NOAA ESRL/PSD, WHOI AutoIMET, WHOTS-5, and WHOTS-6. A NOAA Teacher at Sea and Teacher in the Lab participated in the cruise and assisted with the mooring work and meteorological comparison study. Preliminary analysis by Frank Bradley of CSIRO (who also participated in the cruise) confirmed the overall high accuracy of the ORS systems, pointed to specific problems with shortwave radiation calibrations on the WHOTS-5 buoy, and provided many other insights about sensor performance on ships and buoys (Fig. 3). Data return from WHOTS-5 was very good, with all meteorological sensors showing complete, high quality records except for wind. We had difficulty with compass biases on both systems due the installation method (rectified for WHOTS-6) and one wind sensor was physically damaged (lost prop), failing after 201 days (49% data return). Since the second wind sensor had a complete record, no data will be missing in the final (combined) data set.

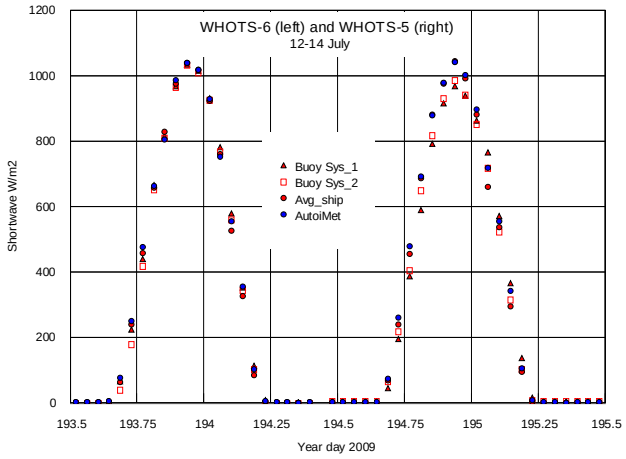

Figure 3. Hourly average shortwave radiation from two meteorological systems on the R/V Kilo Moana and two WHOTS ORS buoys during the WHOTS-6 mooring turnaround cruise intercomparison period. A two day interval is shown during which the ship moved from adjacent to the WHOTS-6 buoy (yearday 193.5 to 194.5) to adjacent to the WHOTS-5 buoy (yearday 194.5 to 196.5). All four independent systems show close agreement during the first day, verifying the calibration of the WHOTS-6 system. The two buoys are notably lower than the shipboard systems on the second day, confirming the need for calibration adjustments on the WHOTS-5 system.

4.5. Ocean Reference Stations – Highlights, Impacts, and Challenges

The NOAA Climate Observation Program seeks to deliver continuous records and analyses of SST and surface currents, of ocean heat content and transport, of the air-sea exchanges of heat, freshwater, and momentum and of carbon uptake and content. The Ocean Reference Stations have been highly successful at meeting these objectives. The Stratus ORS site was successfully serviced, initiating the ninth year of continuous operation. The NTAS ORS site was successfully serviced, initiating the ninth year of continuous operation. The WHOTS ORS site was successfully serviced, initiating the sixth year of continuous operation. The Stratus and WHOTS ORS are collecting pCO2 data in addition to surface meteorology and air-sea fluxes of heat, freshwater, and momentum. Stratus is also collecting surface wave data. The NTAS ORS is delivering surface meteorology and upper-ocean properties in near-real time via Iridium telemetry. The WHOTS ORS mooring service cruise was used as an opportunity for an extensive meteorological data intercomparison, and has resulted in improved air-sea flux accuracy from ORS and a better understanding of instrument performance.

The ORS surface meteorological and air-sea flux time series identify the failing of present weather and climate models and are used to improve research and operational models. By quantifying upper ocean velocity and temperature/salinity the ORS provide the tools to examine the change in upper ocean heat content and the extent to which a one-dimensional budget (local atmospheric forcing and vertical mixing in the upper ocean) holds. In the case of the Stratus ORS the findings from that site have lead to an observational and ocean model focus on the role of eddies in upper ocean heat and freshwater budgets. Thus, the ORS go far to not only improve

our understanding of the dynamics that maintain SST and upper ocean heat content but also to motivate improvements to predictive weather and climate models.

Challenges to the ORS program are logistical and budgetary. Problems with the NOAA Ship RH Brown have lead to delays in cruises and to the need to use charter vessels. Delays lead to loss of data and degradation of data quality when instruments remain in the water longer than planned. Labor and materials costs increases erode the capability to do the work when support is level funded. At the same time level funding greatly limits our ability to add additional sensors, such as the Sabine PCO2 system and the NDBC surface wave hardware to the ORS. Funding restrictions also limits our ability to put data out in real time. Although we have developed Iridium transmission capability, we are limited by cost from using this ability to provide a greater volume of data in real time. The value of sustained time series ORS was strongly substantiated at the Venice Ocean Observations 09 meeting, and we plan to support additional ORS as part of the international effort to meet the goal to have a global ORS network. This plan, however, requires new funding to the Climate Observation Program.

The long-term goals of this work are to improve in-situ observations of marine boundary layer meteorology and air-sea fluxes in order to improve understanding and prediction of the earth's climate.

4.6. Air-Sea Fluxes – OA Flux Analysis

A nearly 50-year (1958-present) analysis of global surface latent and sensible heat fluxes with monthly and daily resolutions has been released and are 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.

The OAFlux project develops global analysis of ocean evaporation, air-sea latent and sensible heat fluxes, and related surface meteorological variables from 1958 onward on 1-degree resolution, with monthly datasets available for the entire analysis period and daily datasets from 1985 onward (Fig.4).

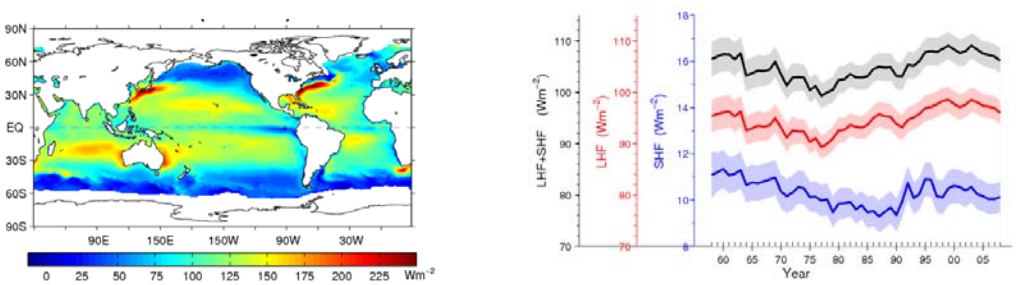

Figure 4 (top) Climatology of global latent and sensible heat fluxes produced by OAFlux. (bottom) Variability of yearly-mean global averages of latent hear flux (red line), sensible heat

flux (blue line), and latent plus sensible heat fluxes (black line). The shaded area on both sides of the line represents the lower and upper bounds of the error bars.

The OAFlux products are constructed not from a single data source, but from an optimal blending of a total of 22 daily input fields originating from three NWP reanalyses (ERA40, MCEP1, NCEP2) and multiple satellite platforms (AVHRR, SSM/I, QuikSCAT, AMSR-E). These optimally estimated daily surface meteorological fields were then input into the COARE bulk flux algorithm 3.0 to compute daily flux fields. Methodology, strategy, and procedure of the synthesis were detailed in a technical report (Yu et al. 2008). Comparison with 107 buoy time series shows that the mean OAFlux-buoy difference is of 1.0 Wm^{-2} and the mean OAFlux-buoy difference in absolute measure is of 7.4 Wm^{-2}. Based on the buoy comparisons, error estimation for daily global flux field was derived through post analysis (Fig.5).

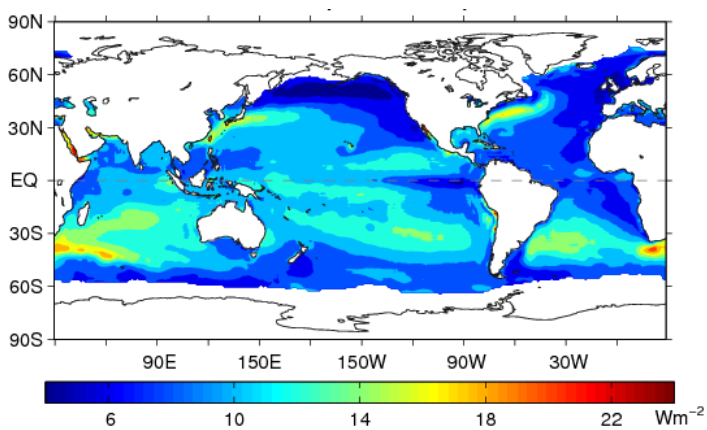

Figure. 5. Estimated errors for latent plus sensible heat fluxes.

The OAFlux evaporation production provides the climate community the needed component in studying global water cycle. Precipitation estimates from 1979 to present are available from two groups, the NASA GPCP (Global Precipitation Climatology Project) and NOAA CMAP (CPC Merged Analysis of Precipitation by Xie and Arkin). Effort in the past year has made to link the OAFlux evaporation with precipitation, and to analyze and understand changes in global water cycle. The OAFlux evaporation shows that global evaporation has been increasing steadily since the early 1980s (Fig. 6) , and the increase is consistent with the increase in GPCP precipitation. As evaporation drives precipitation, the coherent increase in evaporation and precipitation suggests an acceleration of global hydrological cycle under global warming.

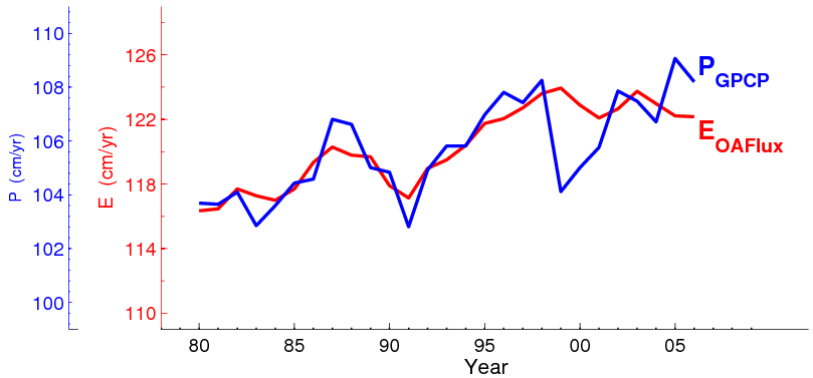

Figure 6. Yearly-mean time series of global-averaged ocean evaporation from OAFlux (red), precipitation from GPCP (blue).

4.7. Air-Sea Fluxes – OA Flux Analyses Highlights and Challenges

The highlights of the work have been: 1) Established OAFlux analysis of ocean evaporation, air-sea latent and sensible heat fluxes, and related surface meteorological variables from 1958 to present. 2) Linking OAFlux evaporation product to precipitation product suggested an acceleration of global water cycle in past decades.

The project investigates variability of air-sea heat exchanges on seasonal, annual, interannual, decadal and longer timescales and its relation to global climate change. The project aims at understanding climate variability and change to enhance society's ability to plan and respond. Funding limitations have forced a focus on the production of the OA Flux fields and restricted investigation of the spatial and temporal variability in these fields and thus of the oceans role in climate.

5. Education and Outreach

ORS cruises are often conducted with participation from the NOAA Teacher at Sea (TAS) program. The October-November 2009 Stratus cruise was to have two TAS on board; that cruise was delayed due to problems with the NOAA Ship Ronald H. Brown. Participation in the October-November 2009 cruise had also been made available to a graduate student from CIRA, the NOAA Cooperative Institute at Colorado State University and to a graduate student at the University of Concepcion, Concepcion, Chile. The cruise to the stratus region in late calendar 2008 was part of the large international, cooperative VOCALS (VAMOS Ocean Cloud Atmosphere Land Study) that received considerable publicity. The second leg of the Brown cruise, in November-December 2008, did have a TAS on board. Legs 1 and 2 of VOCALS each included more than 20 scientists, including postdocs and students.

Weller: Weller made the following presentation: Geo V Plenary, Bucharest (Weller, RA OceanSITES and the NSF OOI), AMS Annual Meeting (Weller, RA and CW Fairall Surface meteorology and air-sea fluxes under the stratus clouds off northern Chile), VOCALS workshop

(Weller, RA Surface fluxes and ocean variability in the VOCALS region), and at the PAROS Innovative Ocean Observing Workshop (Weller, RA Three-dimensional observations in the upper ocean).

Weller has served as:

Director, Cooperative Institute for Climate and Ocean Research (CICOR)
Chair, Physical Oceanography Dept, starting July 1, 2006
OAO Advisory Committee
Member CLIVAR VAMOS VOCALS Science Working Group
Member, UNESCO/IOC Ocean Observations Panel for Climate (OOPC).
Member, GEOSS Capacity Building Panel
Member, GEOSS Science and Technology Advisory Panel
Member, NRC Committee on NPOESS and Climate, ended in 2008
Discipline Expert, Group on Earth Observations (GEO)
Discipline Expert, Interagency Working Group on Earth Observations (IWGEO)
NOAA: Climate Observing System Council, Climate Working Group
Co-chair, International Time Series Science Team (OceanSITES)
Chair, UCAR Membership Committee
CNO/SecNav Chair in Oceanography
External Review Panel, GERG, Texas A&M

Weller attended:

December 2008 – CINAR planning meeting, Newark
January 2009 - POGO (Partnership Ocean Global Observations) in Concepcion, Chile
February – Chair, NRC committee meeting, Washington DC
February – external review of GERG at Texas A&M
March – planning meeting at NDBC
March – NOAA Cooperative Institute Director's Annual Meeting, Silver Spring
April – NOAA Climate Observing System Council Meeting, Silver Spring, MD
April – Chair, NRC committee meeting, Washington DC
May – GEOSS workshop on sustained ocean observations, Bremen, Germany
May – Oceans 09, Bremen, Germany
May – Chair, NRC committee meeting, Washington DC
July – Planning meeting for OceanObs 09, Paris
July – PAROS Innovative Ocean Observing Workshop, Seattle
July – Vocals workshop, Seattle
July – VOCALS SWG, Seattle
August - Chair, NRC committee meeting, Washington DC
Sept - OceanSITES meeting, Venice
Sept- OceanObs 09, Venice

Plueddemann: Dr. Plueddemann routinely presents research results at national and international scientific meetings. He also presents many science and technology talks each year suitable for a general audience, for example to incoming graduate students, program officers, visiting officials, industry representatives and journalists. He routinely reviews research papers and proposals and

has served as Associate Editor for Reviews of Geophysics and the Journal of Atmospheric and Oceanic Technology. He served on the advisory committee for the New England Center for Ocean Sciences Education Excellence (COSEE), and has participated in COSEE-sponsored workshops on scientific communication and ocean literacy. He has participated in the Cambridge Science Festival. He has sponsored student interns, as well as NOAA Teacher at Sea and Teacher in the Lab participants on research cruises. He has advised or co-advised 4 postdoctoral scholars, 1 Ph.D. student, 1 M.S. student, 3 guest students, 8 Summer Student Fellows and 1 Undergraduate Research Fellow.

Interactions with NOAA

Office of Climate Observation: Presentations at Annual System reviews, 2003–2009.

Atlantic Oceanographic and Meteorological Laboratory: Discussions with Dr. Baringer regarding meteorological instrumentation on ships running Atlantic VOS/XBT lines.

Pacific Marine Environmental Laboratory: Cooperation with Dr. Sabine to deploy pCO2 sensors on WHOTS ORS buoy.

Earth System Research Laboratory: Cooperation with Drs. Fairall and Pezoa on field intercomparisons of meteorological data and determination of sensor accuracy.

National Data Buoy Center: Cooperation with Dr. D. Conlee on deployment of radiation sensors on NDBC buoys; discussions with Dr. Teng on deployment of NDBC surface wave packages on ORS buoys; ongoing discussions about passing Atlantic ORS data to NHC/TPC.

National Hurricane Center – Tropical Prediction Center: Discussions with Eric Blake, Tropical Analysis and Forecast Branch, about making Atlantic ORS data available.

Education and Outreach Activities (2001-2009)

Member, WHOI Advisory Committee on Computing: 1997-2001
Associate Editor, Reviews of Geophysics 1997-2001
Associate Editor, Journal of Atmospheric and Oceanic Technology 1999-2002
Guest Editor, IEEE Journal of Oceanic Engineering 2001
Member, NSF Physical Oceanography review panel, November 2002
Advisor, Summer Fellow Aaron Donohoe 2002
Sponsor/Advisor, Guest Student Andrea Taschetto 2002
Guest lecturer on Air-Sea Fluxes in “Introduction to Physical Oceanography” class, 2002-2004
Co-Advisor (with W. Jenkins), Postdoc Burkard Baschek 2003-2005
Core-Team member, WHOI Messaging and Website Strategy Project 2003
Committee member, PhD student Gregory Gerbi, 2005-2008
Member, NE-COSEE Science Advisory Group 2004 – 2007
Participant, Ocean Literacy Online Workshop 2004–2005
Participant, Roundtable Discussion on Ocean Exploration, U-Mass Dartmouth, January 2004
Participant, NE-COSEE Telling Your Story Workshop, January 2004

Presenter, U.S. ambassador to Barbados visit to NOAA ship Ronald H Brown
(resulting article in Barbados Advocate newspaper, March 2005)
Presenter, Barrow Arctic Science Consortium Outreach series, August, 2005
Committee member, PhD student Katie Silverthorne, 2006-
Participant, Integrated Collaborative Education online workshop for IPY, 2006
Presenter, NTAS-2006 "Expedition Reports" from ship to third grade class in North Falmouth
Advisor, Summer Fellow Tess Brandon, 2007
Co-Advisor (with J. Trowbridge), Postdoc Tobias Kukulka, 2007-2009
Sponsor, JOI/CORE science interns on NTAS-2007 cruise, resulting in Mission 15-51 website
Presenter, Knight Science Journalism Fellows, October 2007
Panelist, Atlantic Canada-New England Business Forum, November 2007
Presenter, Chicago Museum of Science and Industry representatives, December 2007
Presenter, Olin College SCOPE program, September 2008
Presenter, WHOI Ocean Science Journalism Fellows, January 2009
Participant, Strategic Communication online seminar, January 2009
Participant, COSEE-NOW Telling Your Story workshop, January 2009
Exhibitor, Cambridge Science Festival, April 2009
Advisor, Postdoc Emily Shroyer, 2009-

Reviewer: Journal of Physical Oceanography, Journal of Geophysical Research, Deep-Sea Research, Journal of Marine Research, Limnology and Oceanography, Geophysical Research Letters, Reviews of Geophysics, Journal of Atmospheric and Oceanic Technology, IEEE Journal of Oceanic Engineering, Nature.

The following public presentations were presented as part of the Flux Analysis project:

September 2008: "Role of the ocean in variability of seasonal evaporation and long-term changes in global water cycle". Oral presentation given at the NOAA Climate Observation Division 5th Annual System Review. Silver Spring, Maryland.

November 2008: "Introducing the WHOI OAFlux Global Analysis of 0.25° Ocean Vector Wind (1987 – present)". Oral presentation given at the NASA OVWST meeting. Seattle, WA. Invited.

December 2008: "Trends in ocean evaporation, precipitation, and surface salinity". Poster presentation at the AGU Fall meeting. San Francisco, CA.

December 2008: "Do ocean salinity observations support a changing global water cycle?" Oral presentation at the AGU Fall meeting. San Francisco, CA. Invited.

January 2009: "Climate Variability of air-sea heat, evaporation, and wind developed by OAFlux". Oral presentation given at the AMS annual meeting. Phoenix, AZ.

June 2009: "Air-sea interaction in the Bay of Bengal". Oral presentation at the Indian Ocean Panel meeting. Reunion. Invited.

July 2009: “Indian Ocean’s involvement in making Cyclone Nargis”. WHOI PO seminar.

August 2009: “Scatterometer and evaporation: past, present, and future connection”. Oral presentation given at the NASA-NOAA workshop on Scatterometry and Climate. Arlington, Virginia. Invited.

6. Publications and Reports

6.1. Publications by Principal Investigators

Colbo, K. and R.A. Weller, 2009. The accuracy of the IMET sensor package in the subtropics. *J. Atmos Oceanic Tech.*, 26, 1867-1890.

Ghate, V. P., B.A. Albrecht, C.W. Fairall, R.A. Weller, 2009. Climatology of surface meterology, surface fluxes, cloud fraction and radiative forcing over south-east Pacific from buoy observations. *J. Climate*, accepted.

Joyce, T., Y-O. Kwon, and L. Yu, 2009: On the Relationship between Synoptic Wintertime Atmospheric Variability and Path Shifts in the Gulf Stream and the Kuroshio Extension. *J. Climate.* 22, 3177-3192.

McPhaden, M. J., G. R. Foltz, T. Lee, V.S.N. Murty, M. Ravichandran, G. A. Vecchi, J. Vialard, J. D. Wiggert, and L. Yu, 2009: Ocean-atmosphere interactions during Cyclone Nargis. *EOS Trans.*, Americ. Geophys. Union, 90(7), 53-60.

McPhaden, M. J., G. Meyers, K. Ando, Y. Masumoto, V. S. N. Murty, M. Ravichandran, F. Syamsudin, J. Vialard, L. Yu, W. Yu, 2009: RAMA: The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. *Bull. Ameri. Meteor. Soc.* 90, 459-480.

Schulz, E. W. and R. A. Weller, 2009. Verification of Numerical Weather Prediction Marine Meteorology using Moorings: An OCEANSITES Application. Additional contribution to Ocean Obs 09.

Vialard, J., J-P. Duvel, M. McPhaden, P. Bouruet-Aubertot, B. Ward, E. Key, D. Bourras, R. Weller, P. Minnett, A. Weill, C. Cassou, L. Eymard, T. Fristedt, C. Basdevant, Y. Dandoneau, O. Duteil, T. Izumo, C. de Boyer Montégut, S. Masson, 2009, Cirene: Air Sea Interactions in the Seychelles-Chagos thermocline ridge region, *Bull. Am. Met. Soc.*, 90, 45-61.

Yu, L., 2009: Sea surface exchanges of momentum, heat, and freshwater determined by satellite remote sensing. Encyclopedia of Ocean Sciences, In: J. Steele, S. Thorpe, and K. Turekian (eds.), Encyclopedia of Ocean Sciences, First Online Update, Academic Press, London, UK, http://www.elsevierdirect.com/brochures/oceansciences/index.html.

Yu, L., and R. A. Weller, 2009: Global ocean heat fluxes.[in "State of the Climate in 2008"]. *Bull. Amer. Meteor. Soc.*, 90, S1-S196.

Yu, L., 2009: On surface salinity skin effect under evaporation conditions and implications for remote sensing of ocean salinity. J. Phys. Oceanogr. In press.

6.2. Other Relevant Publications

Bouchard, P., J. Lord, N. Galbraith, G. Allsup, S. Whelan, A. Plueddemann and R. Weller, 2008. "Inductive telemetry for UOP Ocean Reference Station Moorings", ONR/MTS Buoy Workshop, 4-6 March 2008, Bay St. Louis, MS.

Cronin, M. et al, 2009: Monitoring Ocean-Atmosphere Interactions in Western Boundary Current Extension; submitted to OceanObs09

Fairall et al, 2009: Observations to Quantify Air-Sea Fluxes and Their Role in Climate Variability and Predictability; submitted to OceanObs09

Hood, M. et al, 2009: Global Ocean Ship-based Hydrographic Investigations Project (GO-SHIP); submitted to OceanObs09.

Send, U. R. A. Weller, et al, 2009: OceanSITES; submitted to OceanObs 09.

Plueddemann, A., F. Bahr, L. Yu and R. Weller, 2008. "Observed and Modeled Longwave Radiation in the North Pacific During 2004", NOAA Office of Climate Observation Annual System Review, Silver Spring, MD, 3-5 Sept 2008.

Upper Ocean Processes Group, 2007. "Inductive telemetry for UOP Ocean Reference Station Moorings", UOP Tech Note, December 2007, contributed by A. Plueddemann, J. Lord, G. Allsup and N. Galbraith. http://uop.whoi.edu/techdocs/technotes.html

Whelan, S.P., A. Plueddemann, R. Lukas, J. Lord, P. Lethaby, J. Snyder, J. Smith, F. Bahr, N. Galbraith, and C. Sabine, 2008: WHOI Hawaii Ocean Timeseries Station (WHOTS): WHOTS-4 2007 Mooring Turnaround Cruise Report. *Technical Report, WHOI-2008-4*, UOP 2008-02, 120 pages.

Whelan, S. et al, 2009: Stratus 9/VOCALS ninth setting of the Stratus Ocean Reference Station & VOCALS Regional Experiment, WHOI-2009-03, *Technical Report.*