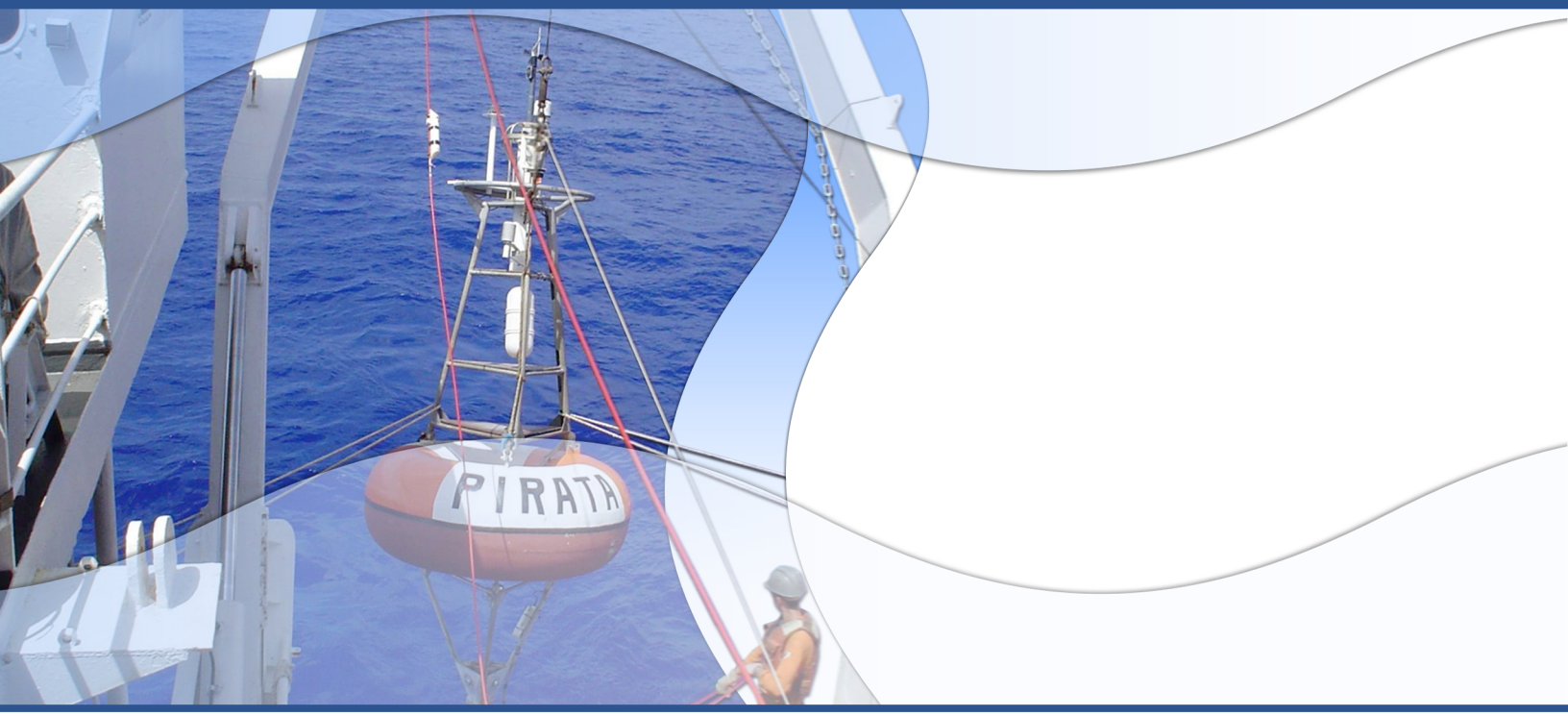


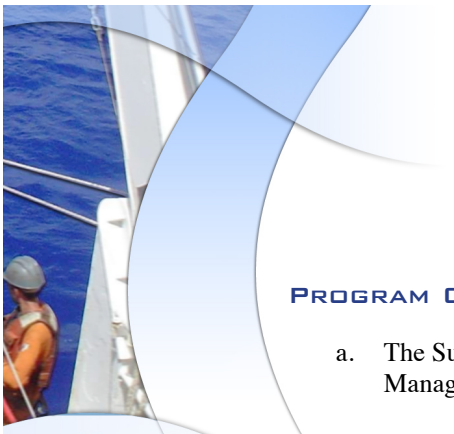
ANNUAL REPORT FY2007

THE OCEAN OBSERVING SYSTEM FOR CLIMATE

National Oceanic and Atmospheric Administration
www.noaa.gov

Office of Climate Observation, Climate Program Office
www.oco.noaa.gov

CHAPTER II



Program Overview FY 2007

a. The Sustained Ocean Observing System for Climate FY 2007 Annual Report System Management

b. FY 2007 OCO Annual Report Chapter 2 Projects and Authors

Tide Gauge Stations

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

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

Drifting Buoys

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

b. Surface Drifter Program

Tropical Moored Buoys

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

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

c. Tropical Atmosphere Ocean (TAO) Array

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. Southern Ocean Modern Observations/Weddell Sea Moorings

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

Ships of Opportunity

a. High Resolution XBT Transects

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

c. Ships of Opportunity

Argo Profiling Floats

a. The Argo Project: Global Observations for Understanding and Prediction of Climate Variability

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 CO2 Measurements aboard the RVIB Palmer and Data Management of the Global VOS Program

c. High-Resolution Ocean and Atmosphere pCO2 Time-Series Measurements

d. Optimal Network Design to Detect Spatial Patterns and Variability of Ocean Carbon Sources and Sinks from Underway Surface pCO2 Measurements

Arctic Ocean Obs System

a. The Arctic Research Program, Fiscal 2007

Product Delivery, Analysis/Reanalysis

a. A Web Site for NCEP's Global Ocean Data Assimilation System for Global Ocean Monitoring, Ocean Monitoring Products, and Data Validation

b. In Situ and Satellite Sea Surface Temperature (SST) Analyses

c. Development of Global Heat and Freshwater Anomaly Analyses

d. Ocean Heat and Freshwater Content Variability Estimates

e. Evaluating the Ocean Observing System: Performance Measurement for Heat Storage.

f. A Fifty-Year Analysis of Global Ocean Surface Heat Flux to Improve the Understanding of the Role of the Ocean in Climate

g. Climate Variability in Ocean Surface Turbulent Fluxes

h. Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses

i. Evaluating the Ocean Observing System: Surface Currents

j. Quarterly Reports on the State of the Ocean: Meridional Heat Transport Variability in the Atlantic Ocean

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

l. Satellite Altimetry

m. Global Carbon Data Management and Synthesis Project

n. Determination of the Information Content in Long-Occupied Voluntary Observing Ship (VOS) Expendable Bathythermograph (XBT) Transects

o. Arctic Ice Thickness: State of the Arctic Report

p. Observing System Research Studies

q. Simulation of the ARGO Observing System

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

Program Overview FY 2007

a. The Sustained Ocean Observing System for Climate FY 2007 Annual Report System Management

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The Sustained Ocean Observing System for Climate
FY 2007 Annual Report
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).

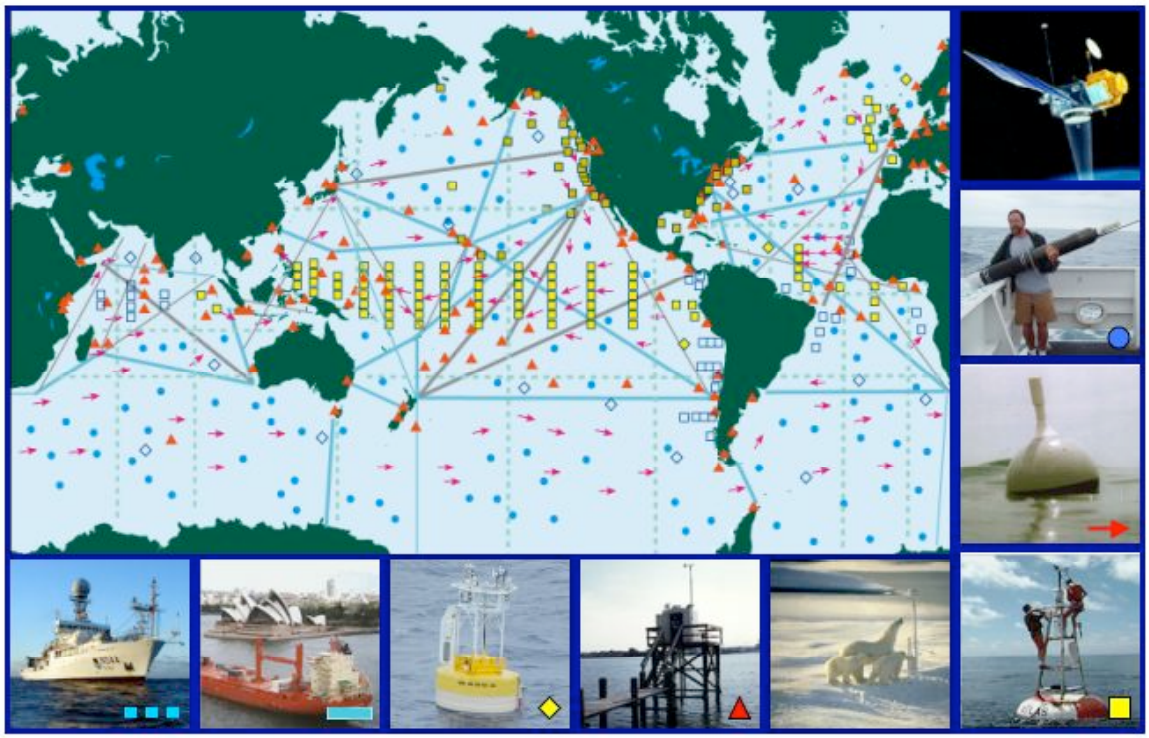

Figure 1. The Networks that make up the Sustained Ocean Observing System for Climate are (from lower left to upper right): Dedicated Ships, Ships of Opportunity, Ocean Reference Stations, Tide Gauge Stations, Arctic Observing Systems, Tropical Moored Buoys, Surface Drifting Buoys, Argo Profiling Floats,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

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.

Responsible Institutions

The "Networks" are managed by 22 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), CIFAR (University of Alaska), NCDC, NODC, NGDC, CO-OPS, OMAO, NDBC, NCEP, FSU (Florida State University), LSA, and CLS America. The contributions of these centers of expertise are summarized by the project managers in their individual reports.

Across the NOAA centers and partner institutions there are 49 Federal employees and 119 non-Federal employees working to implement the system. Within the OCO project office there are six Federal employees and one 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. OMAO ship operations are necessary for supporting the ocean observing system. NESDIS continuous satellite missions are needed to provide 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 the 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 59% 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 JCOMM. These specific GCOS-92 actions now provide an excellent roadmap to guide observing system work plans. GCOS-92 is accessible via link from the OCO web site: www.oco.noaa.gov -- click on "Reports & Products." The work supported by OCO is directed toward implementation of this international plan and the projects are being implemented in accordance with the GCOS Ten Climate Monitoring Principles. The OCO supported projects contributed nearly half of the total international effort in 2007.

FY 2007 Accomplishments

The international global ocean climate observing system overall advanced from 56% complete in 2006 to 59% complete in 2007. Of the 7723 *in situ* platforms maintained globally, 3860 were supported by NOAA. The annual reports of the Project Managers detail the specific advancements of the individual networks.

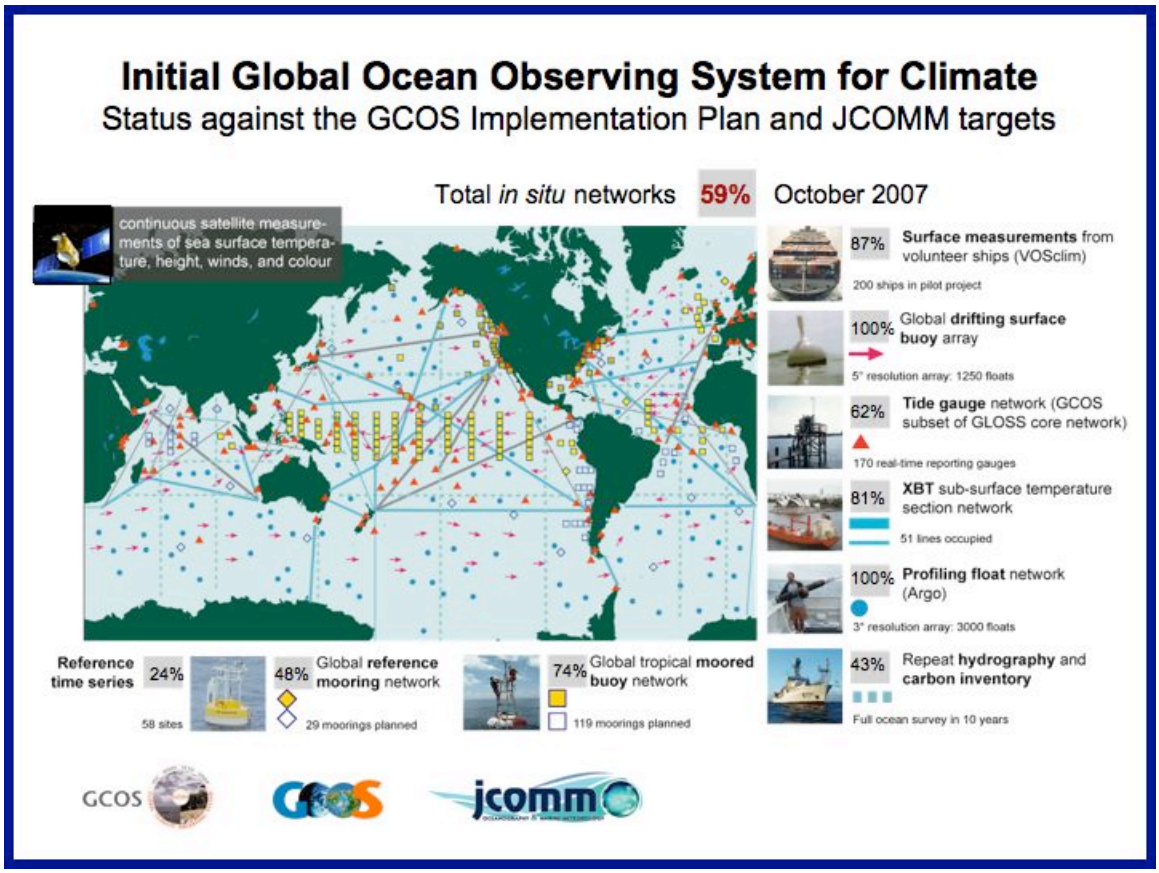

Figure 2: A schematic of the initial composite ocean observing system, including the current status against the targets of JCOMM and the GCOS Implementation Plan (GCOS-92).

The OCO program was reviewed 5-7 June 2007 in Silver Spring. The Fifth Annual System Review brought together 78 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. External review of the program was provided by the Climate Observing System Council (COSC).

The project office was relocated temporarily to the NOAA SSMC campus in November 2006 while the Wayne Avenue facilities were being refurbished and expanded to house other national ocean programs. In July 2007, the project office was re-established at 1100 Wayne Avenue in the expanded facilities and is now co-located with the NOAA IOOS Program office and the National Office for Integrated and Sustained Ocean Observations (Ocean.US).

Global Ocean Observing System Budget Allocation ($K)						
Network	**FY 02**	**FY 03**	**FY 04**	**FY 05**	**FY 06**	**FY 07**
Tide Gauge Stations	670	710	970	1196	1177	1196
Drifting Buoys	1699	2077	2769	3130	3427	3130
Tropical Moored Buoys	3175	3175	3625	4360	3094	3288
Ships of Opportunity	1960	1903	2487	2907	2776	2804
Argo Profiling Floats	6978	9706	9811	9491	9758	9796
Ocean Reference Stations	1983	2357	3271	3244	4205	5336
Ocean Carbon Networks	1478	2204	2875	3521	3482	3167
Arctic Ocean Observing Network	1937	4659	3988	5325	5237	3995
Dedicated Ship Time	0	626	523	92	542	482
Data & Assimilation Subsystems	2099	1803	3012	2826	1779	1993
Product Deliver, Analysis/Reanalysis	578	638	896	1982	2048	2580
Institutional Infrastructure	626	653	1269	1356	711	1344
Global Systems Total Expenditure	**23183**	**30511**	**35496**	**39430**	**38236**	**39111**
Funding Distribution						
NOAA						15923
External						20213
Business						1320
Community Support (workshops, panels, JCOMM, CLIVAR, GOOS)						1655
Total						**39111**
Income Budget Lines						
OAR Laboratories & Cooperative Institutes				5613	5389	5389
OAR Climate & Global Change Program				4886	4619	4619
OAR Climate Observations & Services				28575	24556	25603
NWS TAO/PIRATA					2695	2959
Other (one-time supplemental funding)				356	977	541
Total Income				**39430**	**38236**	**39111**

Table 1: System Funding Record

FY 2007 OCO Annual Report
Chapter 2 Projects and Authors

Project	Authors	Web Site
Tide Gauge Stations		
1. Global Sea Level Observations	Mark A. Merrifield	http://uhslc.soest.hawaii.edu 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	Rick Lumpkin, Silvia Garzoli	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. Development of a Next Generation Platform and Instrumentation for Continuous Ocean Observations (PICO)	Christian Meinig	http://www.pmel.noaa.gov/pico/ http://www.rdinstruments.com/dvs.html http://www.pmel.noaa.gov/stnP/data.html
3. Tropical Atmosphere Ocean (TAO) Array	Landry Bernard, Michael McPhaaden	http://www.tao.noaa.gov/ http://www.pmel.noaa.gov/tao/
Ocean Reference Stations		
1. Ocean Reference Stations	Robert A. Weller, Albert J. Plueddemann	http://www.oceansites.org/ http://uop.whoi.edu/projects/Stratus/stratus.htm http://uop.whoi.edu/projects/NTAS/ntas.htm http://uop.whoi.edu/projects/WHOTS/whots.htm http://www.pmel.noaa.gov/co2/moorings/hot /hot_main.htm.
2. Western Boundary Time Series in the Atlantic Ocean	M. Baringer, C. Meinen, and S. Garzoli	http://www.aoml.noaa.gov/phod/wbts/ http://www.aoml.noaa.gov/phod/floridacurrent/
3. Flux Mooring for the North Pacific's	Meghan F. Cronin, Christian	http://www.pmel.noaa.gov/keo/ http://www.pmel.noaa.gov/keo/

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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/ http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/ http://www.pmel.noaa.gov/stnP/
4. Southern Ocean Modern Observations/ Weddell Sea Moorings	Arnold L. Gordon, Bruce Huber	
5. Monitoring the Indonesian Throughflow in Makassar Strait	Arnold L. Gordon, R. Dwi Susanto	
6. Meridional Overturning Variability Experiment	Uwe Send	
7. Integrated Boundary Current Observations in the Global Climate System	Uwe Send, Russ Davis, Daniel Rudnick, Peter Niiler, Bruce Cornuelle, Dean Roemmich	
8. High Resolution Climate Data From Research and Volunteer Observing Ships	Chris. 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/cruises/ 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://pacrain.evac.ou.edu/ http://sparce.evac.ou.edu/ http://srdc.evac.ou.edu http://www.pi-gcos.org/ http://pacrain.evac.ou.edu/pacusers.html http://pacrain.evac.ou.edu/changes.html
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/xbt.php http://www.aoml.noaa.gov/phod/trinanes/SEAS/ http://seas.amverseas.noaa.gov/seas/
2. Ships of Opportunity	Robert A. Weller, Albert J. Plueddemann	http://kuvasz.whoi.edu/vos http://frodo.whoi.edu

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Chapter 2 Projects and Authors

1. The Argo Project -	Dean H. Roemmich, Russ E. Davis, Stephen C. Riser, W. Brechner Owens, Silvia L. Garzoli, Gregory C. Johnson	http://www.argo.ucsd.edu http://argo.jcommops.org http://www.usgodae.org/ http://www.ifremer.fr/coriolis/cdc/argo.htm http://www.argo.ucsd.edu/FrBibliography.html
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 C. Johnson, Molly Baringer, John Bullister, Calvin W. Mordy, Jia-Zhong Zhang	http://www.pmel.noaa.gov/co2/co2-home.html http://www.aoml.noaa.gov/ocd/gcc/co2research/index.html http://www.carboncyclescience.gov 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/rvbrown_data2006.php http://www.pmel.noaa.gov/co2/uwpco2 http://www.aoml.noaa.gov/ocd/gcc/explorer_realtime.php http://www.bios.edu/Labs/co2lab/vos.html 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	http://www.ldeo.columbia.edu/res/pi/CO2/ http://www.bios.edu/Labs/co2lab/vos.html http://www.oceansites.org
4. High-Resolution Ocean And Atmosphere pCO_2Time-Series Measurements	Christopher L. Sabine, Francisco Chavez, Nicholas R. Bates	http://www.pmel.noaa.gov/co2/moorings/ http://www.oceansites.org/
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	
Arctic Ocean Observing System		
1. The Arctic Research Program, Fiscal 2006	John.Calder, Kathleen Crane, Jacqueline	www.arctic.noaa.gov

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	Grebmeier, M. Zhdanov, A. Ostrovskiy, Jackie Richter-Menge, James Overland, Igor Polyakov, Ignatius Rigor, Taneil Uttal, Tom Weingartner and Terry Whitledge	
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.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php http://www.ncdc.noaa.gov/oa/climate/research/sst/sst.html http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/
3. Development of Global Heat and Freshwater Anomaly Analyses	Gregory C. Johnson, John M. Lyman, Josh K. Willis	http://oceans.pmel.noaa.gov/
4. Ocean Heat and Freshwater Content Variability Estimates	Sydney Levitus	
5. Evaluating the Ocean Observing System: Performance Measurement for Heat Storage	Claudia Schmid, Gustavo Goni	http://www.aoml.noaa/gov/phod/soto/
6. A Fifty-Year Analysis of Global Ocean Surface Heat Flux	Lisan Yu and Robert A. Weller	http://oaflux.whoi.edu
7. Climate Variability in Ocean Surface Turbulent Fluxes	Mark A. Bourassa, Shawn R. Smith, Eric Chassignet	http://www.coaps.fsu.edu/RVSMDC/FSUFluxes/ http://www.coaps.fsu.edu/RVSMDC/SAC/index.shtml
8. Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses	Pingping Xie, John Janowiak, Phillip Arkin	http://www.cpc.ncep.noaa.gov/products/global_precip/html/web.shtml
9. 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
10. Quarterly reports on the state of the ocean:	Molly Baringer, Silvia Garzoli,	http://www.aoml.noaa.gov/phod/soto/mht/index.php

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10. 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
11. 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/
12. Satellite Altimetry	Laury Miller	http://ibis.grdl.noaa.gov/SAT/
13. Global Carbon Data Management and Synthesis Project	Christopher L. Sabine, Richard A. Feely, Steve Hankin, Rik Wanninkhof, Tsung-Hung Peng, Alex Kozyr, Robert Key, Frank Millero, Andrew Dickson	http://cdiac3.ornl.gov/waves http://cdiac.esd.ornl.gov/oceans/global_pco2.html http://mercury.ornl.gov/ocean http://cdiac.ornl.gov/oceans/CARINA/Carinal_inv.html http://cdiac.ornl.gov/oceans/PICES/PICES_table.html
14. Determination of the information content in long-occupied Voluntary Observing Ship (VOS) Expendable Bathythermograph (XBT) transects	Robert L. Molinari, Gustavo Goni,	
15. 16. Arctic Ice Thickness: State of the Arctic Report	Jacqueline A. Richter-Menge, Jim Overland, Andrey Proshutinsky, Vladimir Romanovsky	http://www.arctic.noaa.gov/reportcard/ http://psc.apl.washington.edu/northpole/ http://www.whoi.edu/beaufortgyre/ http://www.damocles-eu.org/ http://iabp.apl.washington.edu/ http://www.crrel.usace.army.mil/sid/IMB/index.htm
16. Observing System Research Studies	D.E.Harrison	
17. Simulation of the ARGO Observing System	I.V. Kamenkovich, E. S. Sarachik	
Data and Assimilation		
1. Observing System Monitoring Center (OSMC)	Steven Hankin, Kevin J. Kern, Ted Habermann	http://www.osmc.noaa.gov http://osmc.noaa.gov/OSMC
2. World Ocean Database Project	Sydney Levitus	
3. Enhanced Ocean Climate Products	Stephen J. Lord	

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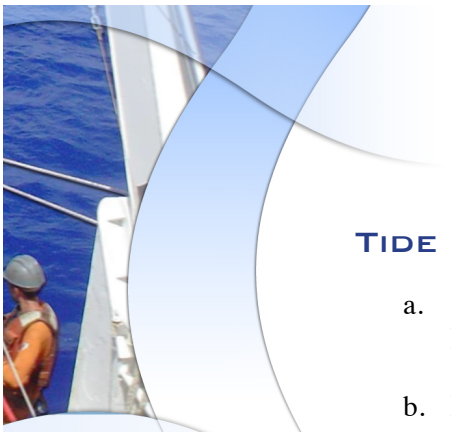
Chapter 2 Projects and Authors

4. Ocean Data Assimilation Research at GFDL	Tony Rosati, Brian Gross	
5. Ocean Data Management at NCDC	Huai-Min Zhang	http://www.ncdc.noaa.gov/oa/rsad/blendedseawinds.html http://www7.ncdc.noaa.gov/CDO/CDOMarineSelect.jsp http://www.ncdc.noaa.gov/oa/climate/vosclim/vosclim.html
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://samos.coaps.fsu.edu/html/data_availability.php



Tide Gauge Stations

a. Global Sea Level Observation 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
Honolulu, Hawaii

PROJECT SUMMARY

The University of Hawaii Sea Level Center (UHSLC) collects, processes, analyzes, and distributes tide gauge data from around the world in support of climate and oceanographic research. The UHSLC focuses on the collection of high frequency measurements that are available in near-real time usually via the Global Telecommunications System (GTS). The center complements the Permanent Service for Mean Sea Level (PSMSL), which is the primary archive for historic monthly-averaged time series of sea level. Data are provided to the UHSLC from ~ 450 stations maintained by 65 international agencies. In addition, the UHSLC directly assists host countries in the maintenance and operation of 59 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, WOCE, GODAE and CLIVAR.

ACCOMPLISHMENTS

Tide Gauge Operations

The UHSLC assists with the operation and maintenance of 59 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 to 6 minute averaged data; however, we are in the process of switching all stations over to 5 to 15 minute transmissions of 1 to 3 minute averages, with even higher rates at major tsunami generation zones. Of the 59 UHSLC stations, 46 contribute to the GLOSS Core network, and 32 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 repair and upgrade components and to ensure the proper operation of the station, to trouble-shoot problems as they arise in coordination with local operators, and to quality assess the datasets.

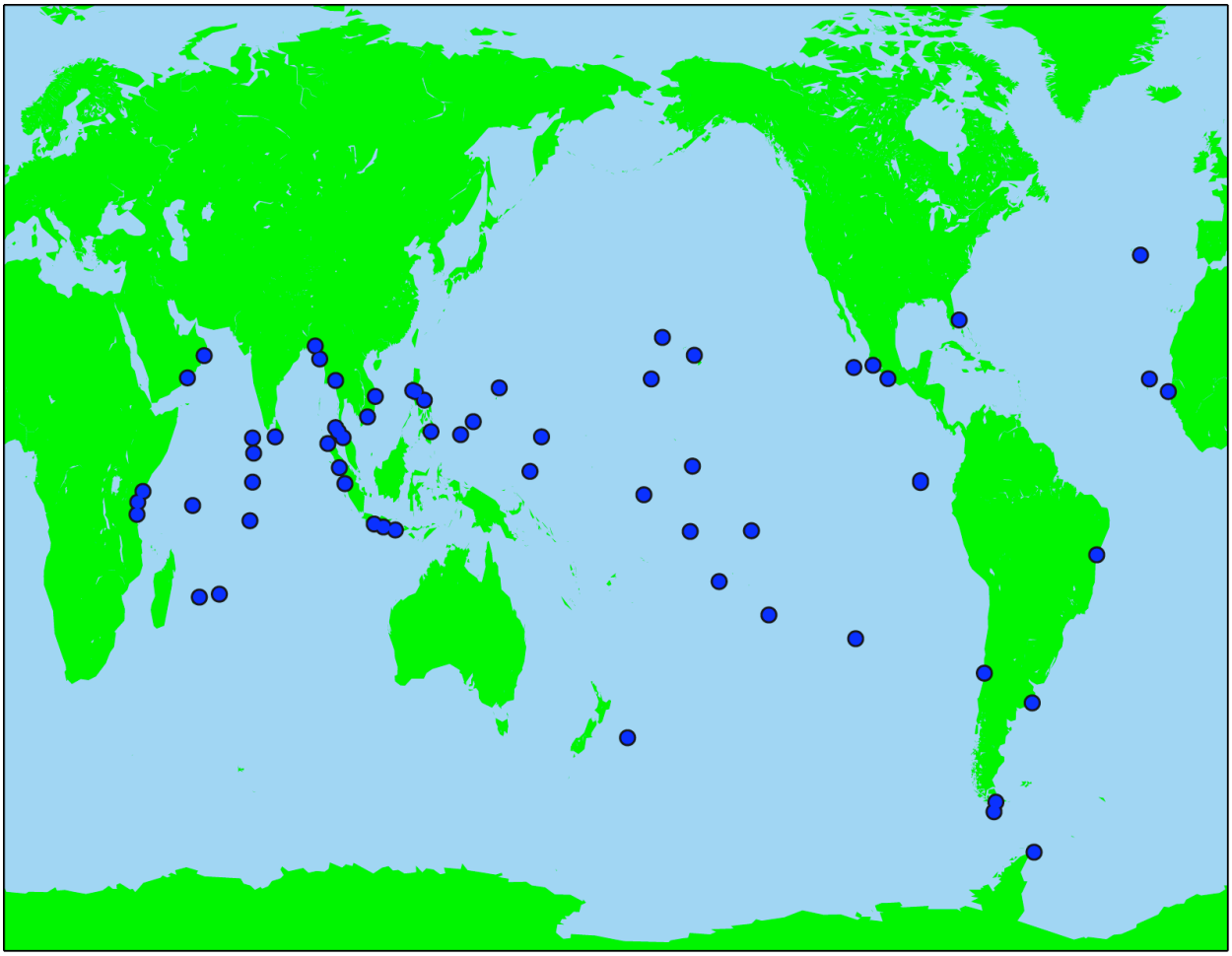


Figure 1. Tide gauge stations operated and maintained with assistance from the UHSLC.

New station installations and upgrades of existing OCO stations during November 2006 through October 2007 are listed in Table 1. Five stations involved substantial financial support from co-sponsoring agencies (the Intergovernmental Oceanographic Commission, IOC; the Asian Disaster Preparedness Center, ADPC). 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**
Christmas Island	Kiribati	2006/11	
Sibolga	Indonesia	2007/02	
Cilacap	Indonesia	2007/02	
Prigi	Indonesia	2007/02	
Saipan	N. Marianas Is.	2007/02	
Subic Bay	Philippines	2007/02	ADPC
Davao	Philippines	2007/02	
Kanton	Kiribati	2007/03	
Acapulco	Mexico	2007/05	
Manzanillo	Mexico	2007/05	
Tern Island	USA	2007/05	
Moulmein	Myanmar	2007/06	IOC
Chittagong	Bangladesh	2007/06	IOC
Penhryn	Cook Islands	2007/08	
Rikitea	Fr. Polynesia	2007/09	
Papeete	Fr. Polynesia	2007/09	
Malakal	Palau	2007/09	
Yap	Fed. Micronesia	2007/09	
Nuku Hiva	Fr. Polynesia	2007/09	
Qui Nhon	Vietnam	2007/10	ADPC
Vung Tau	Vietnam	2007/10	ADPC
Dakar	Senegal	2007/10	
Palmeira	Cape Verde	2007/10	

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 11,460 station-years, including 6,870 station-years at 232 GLOSS sites. The 2007 submission of the JASL data to the World Data Center-A for

Oceanography included 161 series that contained measurements through the year 2005, and 49 series through 2006.

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 217 stations, 176 of which are located at GLOSS sites, and 119 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 170 stations in the GCOS network into full operational mode, which means having all stations report high quality data in near-real time, with the majority of stations having 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 17 new GCOS stations into the near-real time data stream, so that 60% of the network is at that capability (72% are at Fast Delivery status or better). We estimate that 77 of the GCOS stations have nearby (< 10 km) GPS or DORIS for datum control. Immediate implementation plans for the GCOS network are described in the FY2008 work plan.

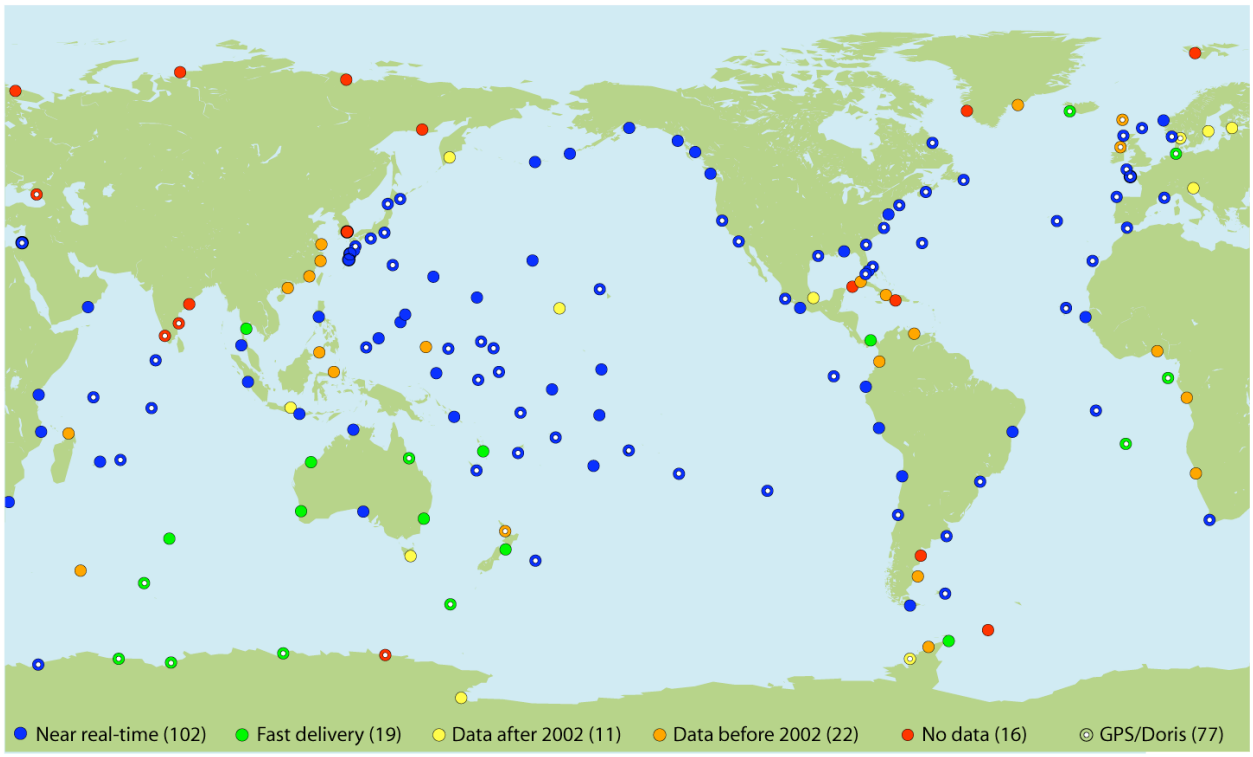


Figure 2. Summary of GCOS station data availability at UHSLC as of November 2007. The data must be sampled at one hour period or shorter. "Near real-time" are typically received within 1 hour, "Fast delivery" within 4-6 weeks.

Research Highlights

Research during FY07 focused on annual reporting of sea level, extreme events, and sea level rise estimates.

The seasonality of extreme sea level events has been quantified and related to tidal and storm forcings. At a surprising number of stations, annual extremes are determined primarily by higher than normal spring tides occurring at the equinoxes or the solstices. Maps of the amplitude and phase of extreme springs tides has been published for a global set of tide gauges. A paper is in press as part of the Aha Hulikoa workshop proceedings.

Estimates of globally averaged sea level from the GCOS or GLOSS networks are subject to errors associated with sparse spatial coverage, varying tide gauge record lengths, and unresolved vertical land motion at each station. An assessment of these errors has been made by comparing estimates from the tide gauge network with more complete averages from altimeter observations and SODA-POP model simulations. Even with simple spatial averaging strategies, the GCOS network does reasonably well in reproducing global sea level variability when the majority of the network is in operation. The results degrade as the number of available stations within latitude bands decreases going back in time, particularly in the southern hemisphere. The impact of land motion corrections on the global sea level estimates is assessed using vertical rates derived from continuous GPS measurements. The error analysis is used to assess global sea level rise trends obtained from the GCOS network and comparisons are made with rates derived from altimetry

and other recent tide gauge based studies. This work was presented at the Ocean Topography Group meeting in Hobart and a manuscript is in preparation.

We are developing a global reference frame for determining vertical land motion at tide gauge locations. This work is now in its final phase, with Michael Bevis at the Ohio State University performing the global analyses of GPS time series. We intend to have maps of land rates at all available GCOS and GLOSS stations by the end of the coming year.

We took part in the third OCO contribution to the BAMS State of the Climate report, describing sea level patterns during 2006, and an update of global sea level rise estimates (Merrifield et al., 2007).

Conferences, Meetings, Expert Panels, and Working Groups

- January 2007 – ICG/IOTWS WG Chairs Steering Group Meeting, Perth 2007.
- February 2007- NOAA IOTWS Project meeting, ITPT meeting, Washington DC.
- March 2007 - Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System (ICG/IOTWS-IV), Mombassa , Kenya.
- April 2007 – PTWS Officers meeting, Honolulu, Hawaii.
- June 2007 – GLOSS Group of Experts meeting, Paris, France.
- September 2007 - ICG/IOTWS WG2 intersessional meeting, Jakarta, Indonesia
- September 2007 - The 22nd meeting of the Intergovernmental Coordination Group of the Pacific Tsunami Warning System (ICG/PTWS-XXII), Guayaquil, Ecuador
- October 2007 – NOAA PRIDE investigators meeting, Honolulu, Hawaii

PUBLICATIONS AND REPORTS

Brooks, B. A., M. Merrifield, J. Foster, C. L. Werner, F. Gomez, M. Bevis, S. Gill, Space geodetic determination of spatial variability in relative sea level change, Los Angeles basin, *Geophys. Res. Lett.*, 34, L01611, doi:10.1029/2006GL028171, 2007.

Merrifield, M**.,** G.T. Mitchum**,** S. Gill and P. Woodworth, Sea Level *in* State of the Climate in 2006, Arguez, A., ed., *Bull. Amer. Met. Soc.*, **88**, S1-S135, doi:10.1175/bams-88-6-929Mitchum, G.T., R., 2007.

Merrifield, M. A., Y. L. Firing, and J. J. Marra, Annual climatologies of extreme water levels, Aha Hulikoa workshop proceedings, in press, 2007.

Mitchum, G., S. Nerem, M.A. Merrifield and R. Gehrels, 20th Century Sea Level Change Estimates From Tide Gauges and Altimeters, Cambridge University Press (reviewed book chapter), in press, 2007.

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

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:

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

An third task, to develop and implement a routine annual sea level analysis reporting capability that meets the requirements of the Climate Observation Program, is described in the Product Delivery, Analysis/Reanalyis section of 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.

Tide Station Network

Task 1: Upgrade NWLON Remote 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.

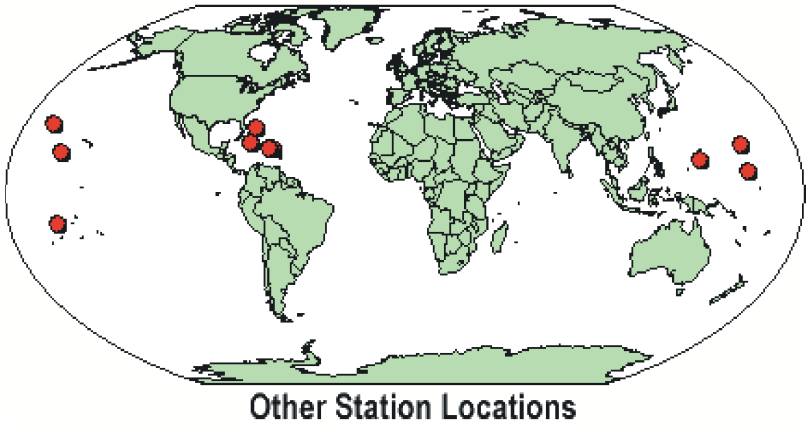


Figure 1. Ocean Island NWLON Station Map

Although operation of all of the long term NWLON and GLOSS stations is important, the NOAA NWLON Ocean Island stations are being upgraded first with this funding to ensure their continuous operation (NOS program funding and budget initiatives will be used for operation of the coastal stations). These targeted funds are being used for travel costs and for upgrade to backup systems. The upgrades include high accuracy acoustic or paroscientifc pressure sensors and redundant Data Collection Platforms (DCP's) with equal capability to the existing primary systems. The station operations will also be enhanced with GPS connections to geodetic networks 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	StationUpgraded
Guam	Yes	2007
Kwajalein	Yes	2007
Pago Pago	Yes	yes
Wake	No	yes

Midway	No	yes
Adak	No	
Bermuda	Yes	2008 planned
San Juan. PR	Yes	
Magueyes Island, PR	No	
Charlotte Amalie, VI	No	
St Croix, VI	Yes	

Task 2: Satellite Altimeter Mission Support

Support for the TOPEX/Poseidon satellite altimeter mission began with installation of an acoustic system and a digibub system on Platform Harvest in 1993 (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". This station continues to support the Jason Altimeter Missions.

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

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

FY2007 ACCOMPLISHMENTS

Task 1:

Maintenance and upgrade of the ocean island NWLON stations continued. Redundancy upgrades were installed at Kwajalein and Guam in FY 2007. 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 Kwajalein, which now includes redundant equipment.

Task 2:

Operation and maintenance of the Platform Harvest station (see Figure 3) continued the past year. Coordination of activities continues with JPL. The redundant DCP that was previously inactive was repaired and two DCP's are now operational. JPL continues to provide reports on the status of the verification project at Platform Harvest. The tide station has been reporting at intermittent intervals since 1993 and near continuous data since 2002 when the OCO funded an upgrade (Figure 4).

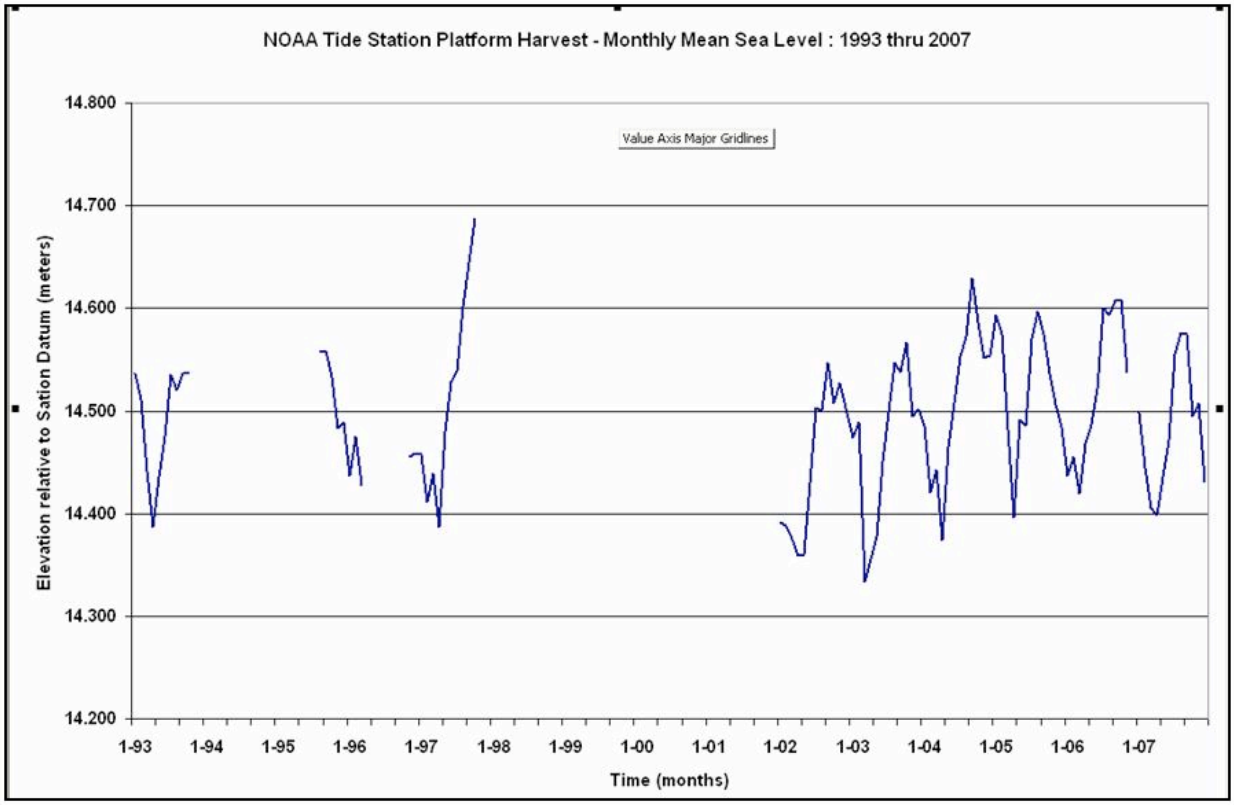


Figure 4. Platform Harvest Calibration Site – Observed Monthly MSL from the Tide Station from 1993 thru 2007.

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

Drifting Buoys

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

b. Surface Drifter Program

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

Peter Niiler
The Scripps Institution of Oceanography, La Jolla, CA

1. Project Summary

1.1) *Rationale*:

The principal scientific questions of the role of the ocean in climate change are how well can we describe or model the present climate of ocean circulation and how well can these descriptions or models predict the evolution of future climates. A principal climate index of oceans is sea surface temperature (SST) whose evolution is both forced by the atmosphere and is the cause of atmospheric climate change. A global array of drifters provides the operational instrumental data sets for describing ocean surface circulation and SST evolution. These data are also 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 designed, manufactured and deployed by the Global Drifter Program have proven to be reliable, autonomous platforms for obtaining climate and operational weather data from the global oceans.

1.2) *Objectives of the Global Drifter Program*:

The "Global Drifter Program" (*GDP*) is the principal international component of the Joint Commission of Marine Measurements (JCOMM) *"Global Surface Drifting Buoy Array"*. It is a "Scientific Project" of the Data Buoy Cooperation Panel (DBCP) of World Meteorological Organization (WMO)/International Ocean Commission (IOC). It is a near-operational ocean-observing network that, through the ARGOS satellite system and the Global Telecommunication System (GTS), returns real time data on ocean near-surface currents, SST and 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 a near-operational, near-real time data stream of drifter position, SST, and sea level pressure. GTS compatible data on winds, T(z) and SSS are also provided on operational basis when these sensors are mounted on the drifters.

2) Observe the 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 0.5º resolution (Figure 1)

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

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

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

1.3 *Required Drifter Observations and Status of Global Array*

The 'required' global drifter array size by JCOMM is based on the need to maintain 1250 platforms that return instrumental observations of daily average SST (+/- 0.1^0C) over the global ocean at a 5º resolution, or the spatial scale of the error covariance function of the

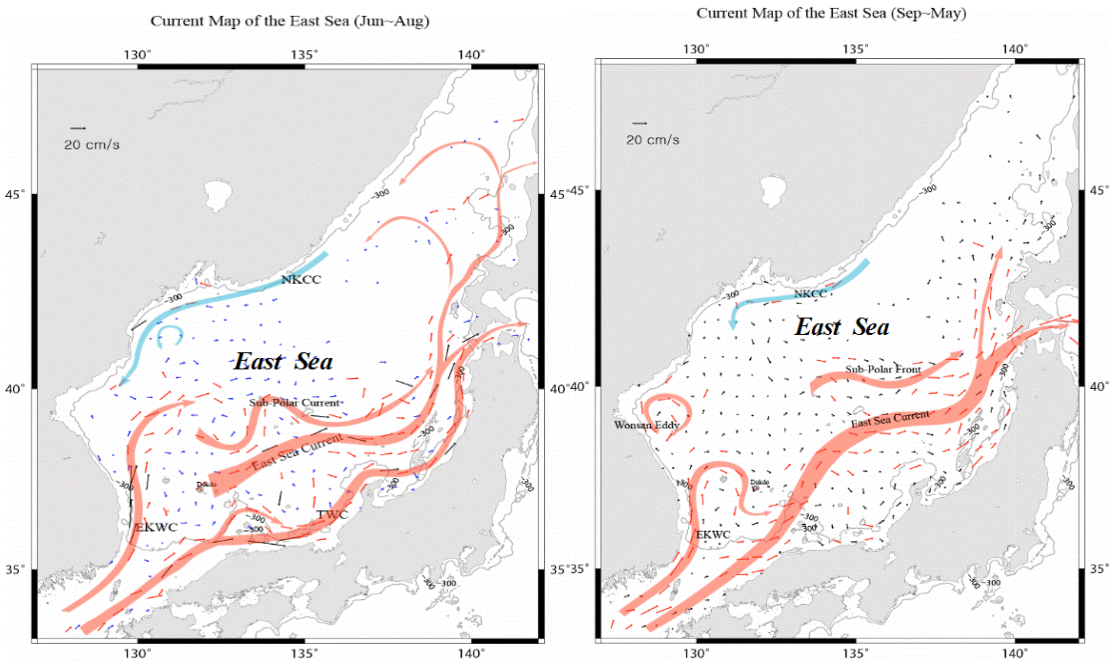


Figure 1. The East Sea seasonal mean surface current patterns in June-August (left panel) and September-May (right panel) derived from 310 drifters deployed in the period 1996-2006 within the ONR/NOAA/Korean joint study of seasonal circulation in the East Sea. Black arrows are for mean currents > 20cm/sec, red arrows are for mean currents >10 cm/sec and < 20 cm/sec and blue arrows are for mean currents < 10 cm/sec.

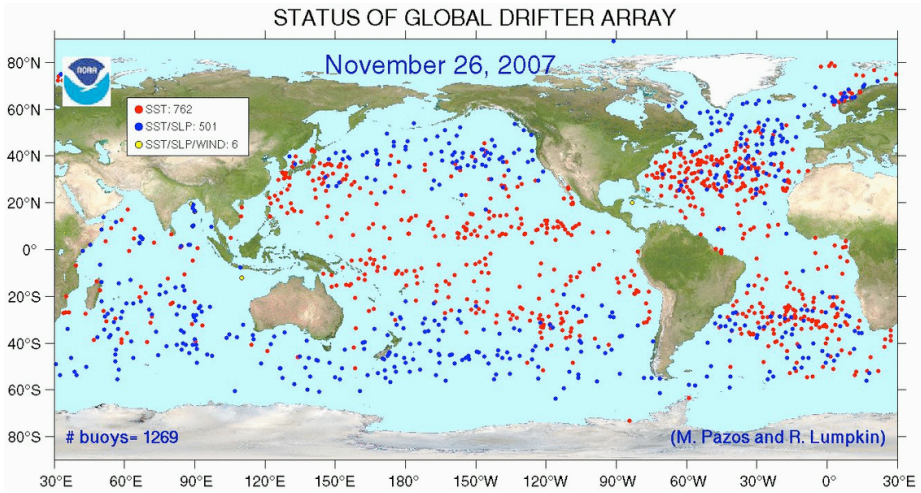


Figure 2. Status of the Global Drifter array on 26 November 2007. Special scientific programs have increased the density of drifters in the North and South Atlantic basins.

operational NOAA satellite infrared SST sensors. The 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 (Fig. 2). Surface pressure sensors are supported by regional meteorological agencies based on regional needs. The number of drifters in the array is composed of the NOAA supported *GDP*, research principal investigator enhancements who have requested their data to be included in the *GDP* real-time data base and international partners

On 26 November 2006, 1269 drifters were reporting to GTS and to the Atlantic Oceanographic and Meteorological Laboratory (AOML) *Drifter Data Center* (Figure 2). In FY'07, the NOAA Climate Observations Program funded to JIMO (920) and AOML (80) sufficient numbers of SVP drifters, and with the contributions of drifters (100-120) from other national and international sources, the array was maintained from late 2005 to present date at the desired level (Fig.3). In 2008 the efforts will continue to adjust the array spatial density with the desired the surface of the ice-free ocean at 5º resolutions.

The international science bodies, such as JCOMM, request that the drifter array provide instrumental observations of SST and the operational meteorological agencies desire to obtain atmospheric pressure observations from as many drifters as possible. To this latter end, the DBCP (October'06) requested these meteorological agencies begin to provide funds to attach a barometer to every SVP drifter. By November 2007, over 500 drifters provide barometer sensor data on to GTS. For the past 20 years, most drifters in research program have been justified on the basis of velocity observations, where 99% of reviewed scientific research papers make principal use of drifter velocity observations (viz: http://www.aoml.noaa.gov/phod/dac/drifter_bibliography.html). In early December 2007, the CLIVAR Velocity Working Group will consider the requirements of climate research for global velocity observations.

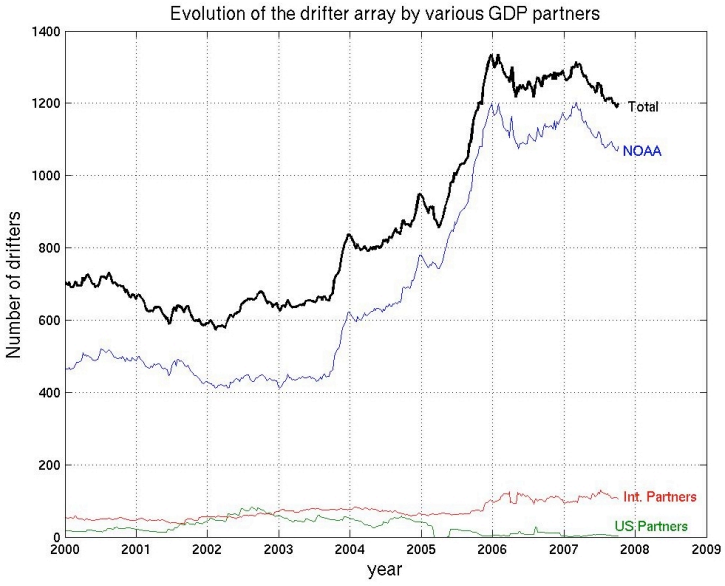


Figure 3. The evolution of the GDP drifter array as reported on GTS.

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 of this proposal, Peter Niiler, assumes the responsibility for the coordination between the following entities:

• US manufacturers in private industry (*Technocean, Inc.* of Cape Coral, FL*; Clearwater, Inc*. of Watertown, MA*; Pacific Gyre, Inc.* of 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). As reflected in the FY'08 budget, small increases (2.85%) for SVP-Mini drifter construction costs over FY'06 budget were allocated in FY'07. This represents the second year of a small adjustment.

• 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'07 and proposes the activities for FY'08.

2. FY'07 Progress

In FY'07 NOAA Grants office funding of the *GDP* through JIMO occurred in the last week of September 2007. The designated date for the start of the FY'08 funding of GDP is 1 July '08, but as has been the case in the past five years, we do not anticipate that the NOAA Grants Office is capable of meeting that date. This is a report of what was accomplished with both the FY'06 and FY'07 funding during the period of October 2006 - November 2007:

2.1) *Summary of Drifter Acquisitions and Technology: With the FY'06 funds 940 drifters with SST sensors were built and were delivered to AOML for deployment. With the FY'07 funds, 920 drifters were ordered in October 2007 and are now being delivered to AOML for deployment. In August 2007, all 12 drifters deployed into category 4 Hurricane Dean worked well (4 were SVP-W wind drifters and 8 were SVP-W-T(z) wind and thermistor chain drifters). All 20 air deployable drifters ordered in '06 were delivered to Keesler*

AFB for deployment for the 2007 hurricane season. Because only one hurricane was sampled in 2007, there now are 36 SVP-W-T(z) and 16 Minimet drifters at Keesler AFB fully rigged for air-deployment. When in June 2008 an additional 8 SVP-W-T(z) and 12 SVP-W drifters will be delivered to Keesler AFB, there will be 72 hurricane drifters available for the '08 Hurricane season.

With the FY'07 funds:

a) A total of 650 SVP-Mini drifters and 270 SVP-B barometer 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 12 SVP-W wind-drifters and 8 SVP-W-T(z) wind and thermistor chain drifters, fully rigged for air deployment, were ordered from Pacific Gyre, Inc. All 20 units will be delivered the 53rd Air Force Reserve "Hurricane Hunter Squadron" at Keesler AFB before June 1, 2008. Dr. Rick Lumpkin at AOML are , working closely with the National Hurricane Center at AOML, organizes the deployment of what will now be 72 hurricane drifters in the 2008 hurricane season.
c) In October 2007, 5 refurbished SVP drifters with salinity sensors were deployed in off the coast of South America in the Amazon plume by the French oceanographers.

In FY'07 JIMO purchased 920 drifters and AOML purchased 147 drifters, for total NOAA contribution of 1167 drifters to the JCOMM *"Global Surface Drifting Buoy Array".*

2.2) Enhanced Data Sets and Publications: Between October 2006 and December 2007, there were 17 requests for enhanced drifter velocity data sets. Dr. Yoo Yin Kim who works under the direction of P. Niiler as a Senior Statistician prepared and distributed these data. The drifter peer-reviewed publication list was upgraded in December 2006: (http://www.aoml.noaa.gov/phod/dac/drifter_bibliography.html).

2.3) Meetings and Lectures: The following personnel participated in the GDP presented lectures or attended the following organization meetings:

• DBCP-XXIII, October 15-20, 2007 Jeju, Korea: "Observations of Atlantic Hurricanes with Air-deployed Drifters" (Peter Niiler and Rick Lumpkin)
• DBCP-XXII, October 15-20, Jeju, Korea: "The Global Drifter Program Report" (Peter Niiler for Rick Lumpkin)
• DBCP-XXIII, October 15-20, 2007, Jeju, Korea: "Drifting instrumented chains. New technical developments and application (L.R. Centurioni and P.P Niiler)
• North Pacific Drifter Implementation Group

2.4) Technical Development of Thermistor Chains for Hurricane Drifters: Working with Clearwater Instruments, Inc. we have designed and assembled the components for a new 150 m long thermistor chain/barometer drifter (Fig.4) that can be deployed from the

AXBT chute of a P-3 research or military aircraft. Two prototype systems for the SVP-B-T(z)-Mini will be assembled in early 2008 and tested off the coast of La Jolla, CA. We anticipate that with the FY'08 funds half of the hurricane drifters will be of this new design.

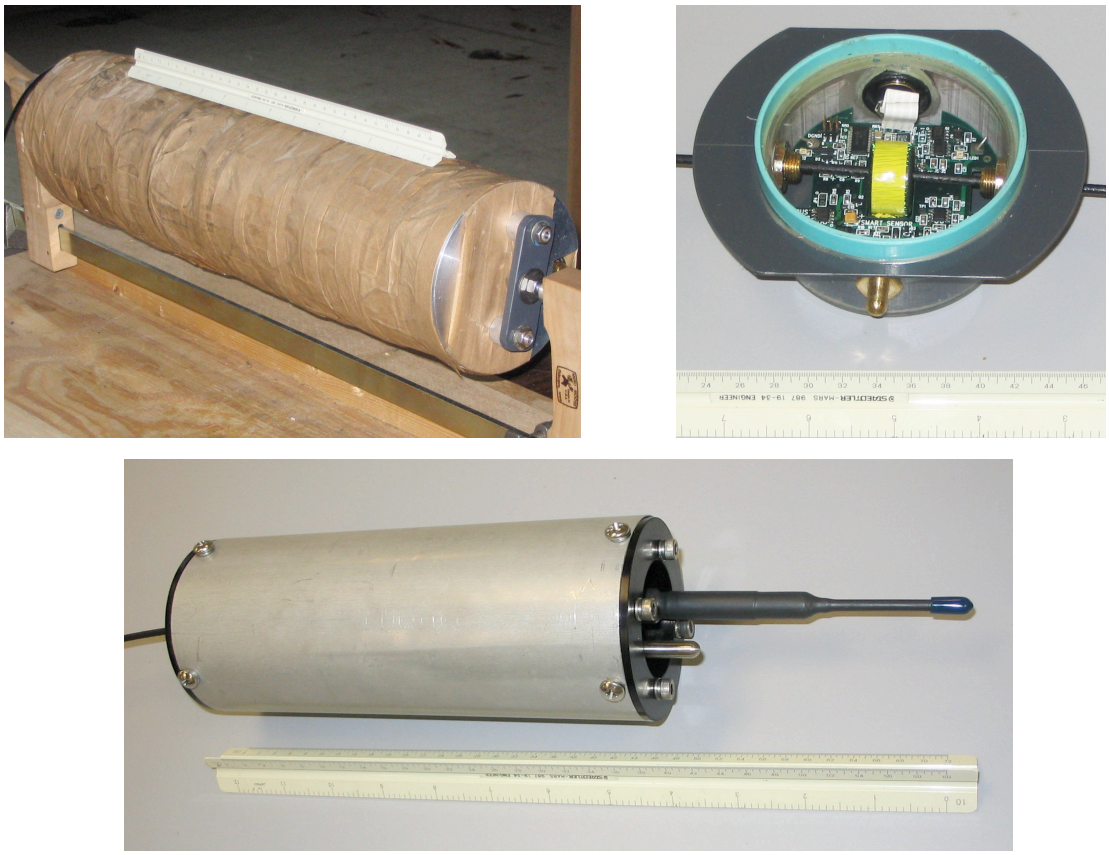


Figure 4. Prototype components of the SVP-T(z)-Mini with 150m, 10 sensor spool (left), T sensor (right) and container for GPS/Iridium antenna and electronics (center bottom) for SVP-TC Mini. Note the size of these components relative to a 1ft. ruler in each photo.

Peter Niiler initiated the request for development of a station keeping sensor system to NOOA/OCO and serves as a technical reviewer to the NOAA/SBIR entitled: "Station Keeping Drifting Data Buoy for Ocean and Meteorological Data Retrieval in Severe Marine Environment". LBI Corp. or Groton CN is the lead contractor for this SBIR

2.5) Collaborations: Collaborations are continuing for deployment of drifters with the Office of Naval Resarch (30 SVP-GPS drifters purchased by ONR were released in the East China Sea in October 2007) and analysis of East Sea drifter data from a joint ONR/GDP/Korea circulation study of the Western Pacific from 1996-2006 (viz. Fig.1). The Korean National Ocean Research Institute (NORI) has implemented an operational surface current map based on the mean velocity derived from these drifter data to which

is added a time variable component based on altimeter and winds. These maps are routinely used by the Korean Coast Guard for aid in rescue of ships in distress (viz: http://makaha.ucsd.edu/MyWeb/NORI/recent.pdf)

Surface Drifter Program

Rick Lumpkin and Silvia Garzoli
NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

Project Summary

The Surface Drifter Program is AOML's contribution to the Global Drifter Program (GDP), a branch of NOAA's Integrated Ocean Observing System, Global Ocean Observing System (IOOS/GOOS) and a scientific project of the Data Buoy Cooperation Panel (DBCP). The primary goals of this project are to maintain a global 5ºx5º array of Argos-tracked Lagrangian surface drifting buoys to meet the need for an accurate and globally dense set of in-situ observations transmitting in real time for weather forecast, and to provide a data processing system for the scientific use of these data that support short-term (seasonal-to-interannual, "SI") climate predictions as well as climate research. AOML's GDP responsibilities are to: (1) recruit ships and manage drifting buoy deployments around the world using research ships, Volunteer Observation Ships (VOS) and aircraft; (2) insure the data is placed on the Global Telecommunications System (GTS) for distribution to meteorological services everywhere; (3) maintain META files describing each drifter deployed, (4) process the data and archive it at AOML and at 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) and near surface (mixed layer) currents. A subset of the drifters also measures air pressure, winds, subsurface temperatures and salinities. These observations are needed to (a) calibrate SST observations from satellites; (b) initialize global SI forecast models to improve prediction skill; and (c) provide nowcasts of the structure of global surface currents. Secondary objectives of this project are to use the resulting data to increase our understanding of the dynamics of SI variability, and to perform model validation studies, in particular in the Atlantic Ocean. Thus, this project addresses both operational and scientific goals of NOAA's program for building a sustained ocean observing system for climate.

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 United States. 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 tropical 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, with a large array of 60 NSF-funded drifters deployed in February through March 2007. CLIMODE is now entering its data analysis phase (2008—2009).

Accomplishments

The global drifter array became the first component of the IOOS that reached completion, with 1250 active drifters in September 2005. This number has since been maintained. During FY07, the drifter array averaged 1259 drifters, with a standard deviation of 32 drifters. The maximum size was 1315 (5 March); the minimum was 1192 (24 September). During the fiscal year, the GDP coordinated worldwide deployments of 1023 drifters, 859 funded by NOAA/OCO; 180 drifters were deployed in the Atlantic between 30ºN and 40ºS. AOML managed observations from 2319 unique drifters during FY07 (this is significantly greater than 1250, as some died while new ones were deployed to maintain ~1250).

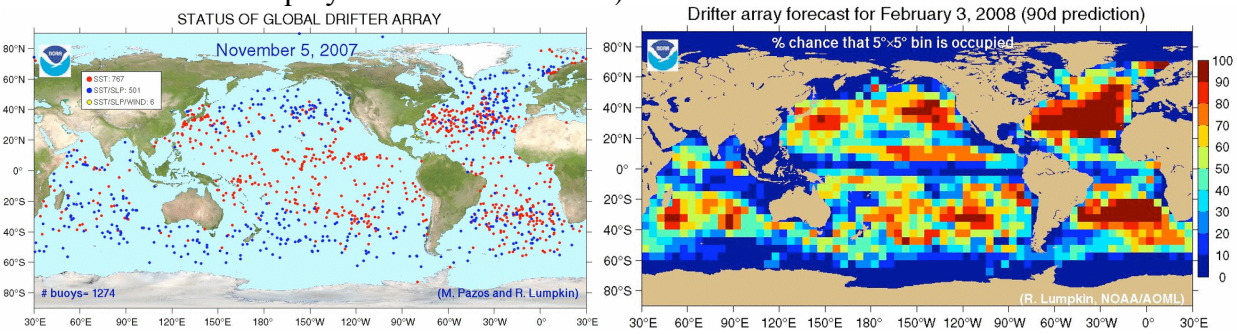


Fig. 1: Global population of drifters as of November 5, 2007 (array size 1274 drifters), and 90 day prediction of coverage (% chance that a 5ºx5º bin will have a drifter if no additional drifters are deployed in the interim).

The main challenge is now to increase the spatial coverage of the array while maintaining its size. We are addressing these challenges by seeking additional deployment platforms and improving our deployment strategies (see FY08 work plan for more details).

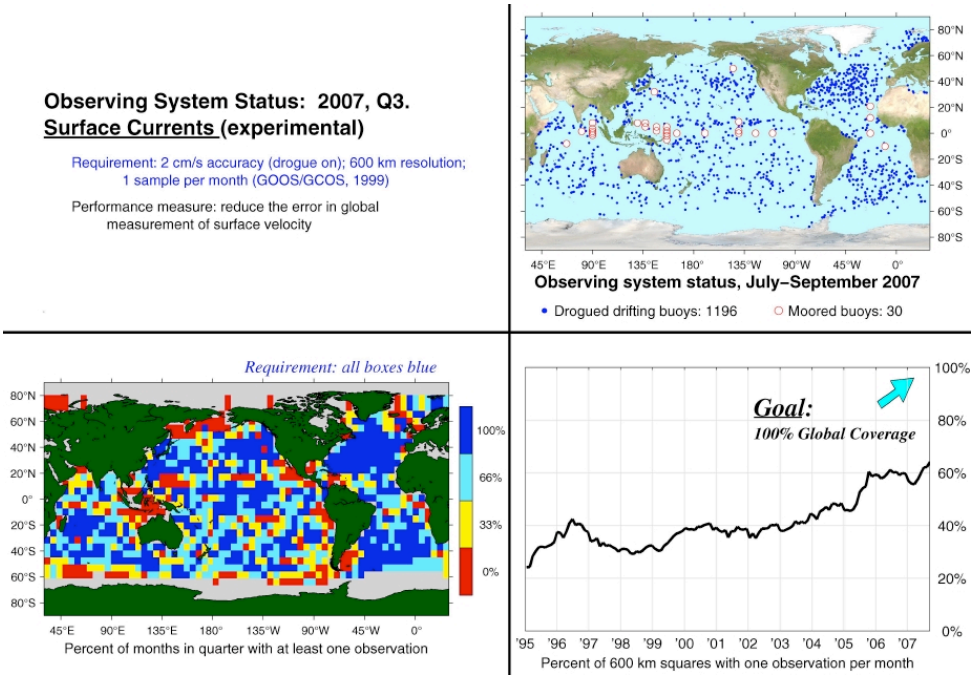


Fig. 2: FY07 Q4 (July-September; Q3 of calendar year) report evaluating the spatial coverage of the IOOS for near surface current measurements. Upper right: location of drifting (blue dots) and moored (bullets) buoys during the quarter. Drifters dominate the overall IOOS' spatial coverage. Lower left: percent of months in quarter with at least one measurement. Lower right: spatial percent of global ocean sampled at GOOS/GCOS requirements.

2007 marks the beginning of the International Polar Year; we have thus placed added emphasis on high-latitude deployment opportunities. Working with Principal Investigator Kjell Orvik (Bergen, Norway), we have had 60 drifters (15 with barometers) deployed off the Norwegian coast in June and October 2007. More deployments are planned for 2008. We will also be increasing the density of deployments off the Antarctic coast in Austral summer 2008, in collaboration with NOAA/NMFS cruises (in addition to ongoing Southern Ocean deployments with other collaborators).

We have also begun working closely with Korean collaborators at several Korean institutions, and with their assistance have seen 17 drifters deployed during FY07. As part of this effort, M. Pazos and S. Dolk of AOML participated in the Ocean and Coastal Observation Panel Meeting convened by Terry Schaefer and Rene Eppi (NOAA/OAR).

In FY07, AOML conducted a general study of the performance of drifters from the four major manufacturers. This study focused on drogue (sea anchor) detection and drifter lifetime. We had previously identified a problem with drogue detection using the submergence sensor, particularly problematic for drifters from one manufacturer (Technocean), and had communicated the problem to them. Although they had implemented an engineering solution (reducing the submergence sensitivity), our FY07 evaluation revealed that the problem was not solved. As a consequence, the Surface Drifter Program is recommending that all manufacturers include a tether strain sensor for drogue detection; we are working with Scripps and the drifter manufacturers to see positive progress on this. We also noted that another of the major

manufacturers (Clearwater) was having a large increase in the "death rate" across the array starting in spring 2007 (Fig. 3). The death rate for the other three manufacturers averaged 49—51 drifters dead per 1000 drifters per month, which requires ~750 deployments per year to maintain an array of 1250. The Clearwater death rate increased to a maximum of over 100, which would require >1500 deployments per year. This problem was rapidly communicated to Clearwater, who conducted an in-house evaluation and determined that the problem was most likely due to battery problems. Our ongoing analysis suggests that the problem may have been limited to a specific batch of batteries, as the death rate for Clearwater drifters has been decreasing in the most recent two months.

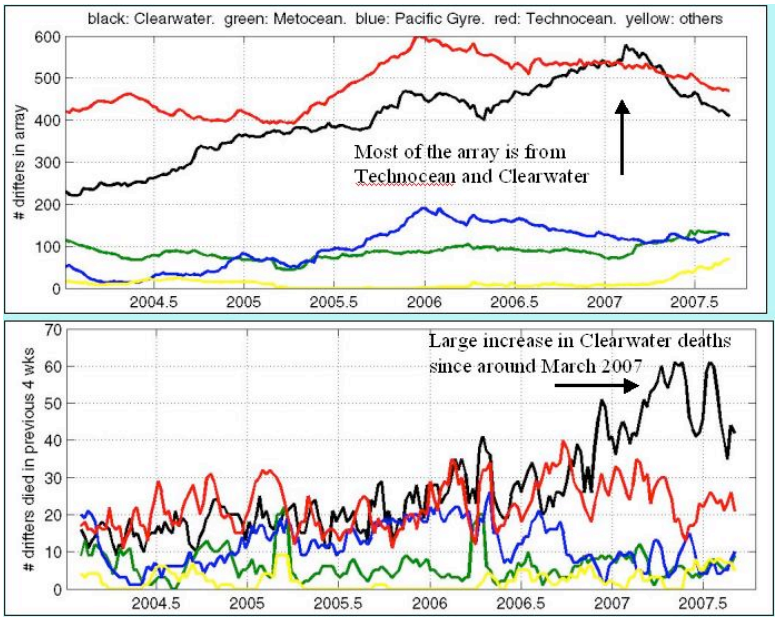


Fig. 3: top: time series of the number of drifters by manufacturer. Two manufacturers, Technocean and Clearwater, manufacture most drifters in the global array. Bottom: numbers of dead drifters per four week period, by manufacturer. The death rate for Clearwater drifters increased in early 2007, and has begun to decline by late 2007.

A subcomponent of the Global Drifter Program, the Atlantic Drifters, was funded with the objectives to fill gaps in the observational network, in order to accurately describe the basin-scale Atlantic current and SST seasonal-to-interannual variations. This program was started to address the data coverage deficiency in the tropical and subtropical south Atlantic (20°N to 40°S). Lumpkin and Garzoli (2005) analyzed the time mean and seasonal variability of the equatorial currents using the resulting drifter data, and shed new light on different branches of the equatorial system and its variability.

The PIs are currently working on the analysis of the data collected in the South Atlantic to characterize the near-surface circulation. Particular focus is on the time-mean pathways of the boundary currents (Confluence of Brazil and Malvinas; the Agulhas/Benguela system) and the variations of the upper ocean exchanges associated with the bifurcation of the South Equatorial Current at the coast of Brazil.

Empirical orthogonal Function (EOF) analysis is applied to the data to define the modes of variability of the basin and at each one of the individual regions. A methodology is developed to

locate the Bifurcation of the South Atlantic Current and the Confluence of the Brazil Malvinas Currents with interesting results.

Fig.4 shows the mean surface currents field as derived from the drifter data, superimposed on SST.

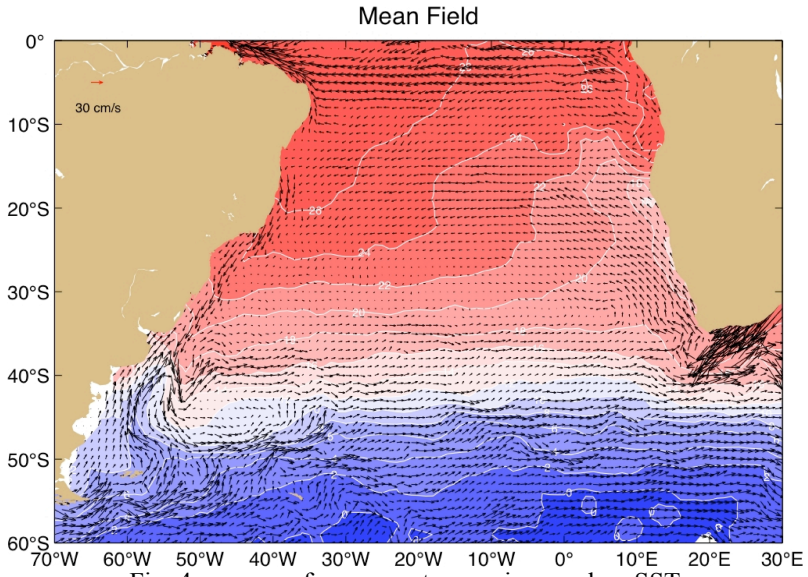
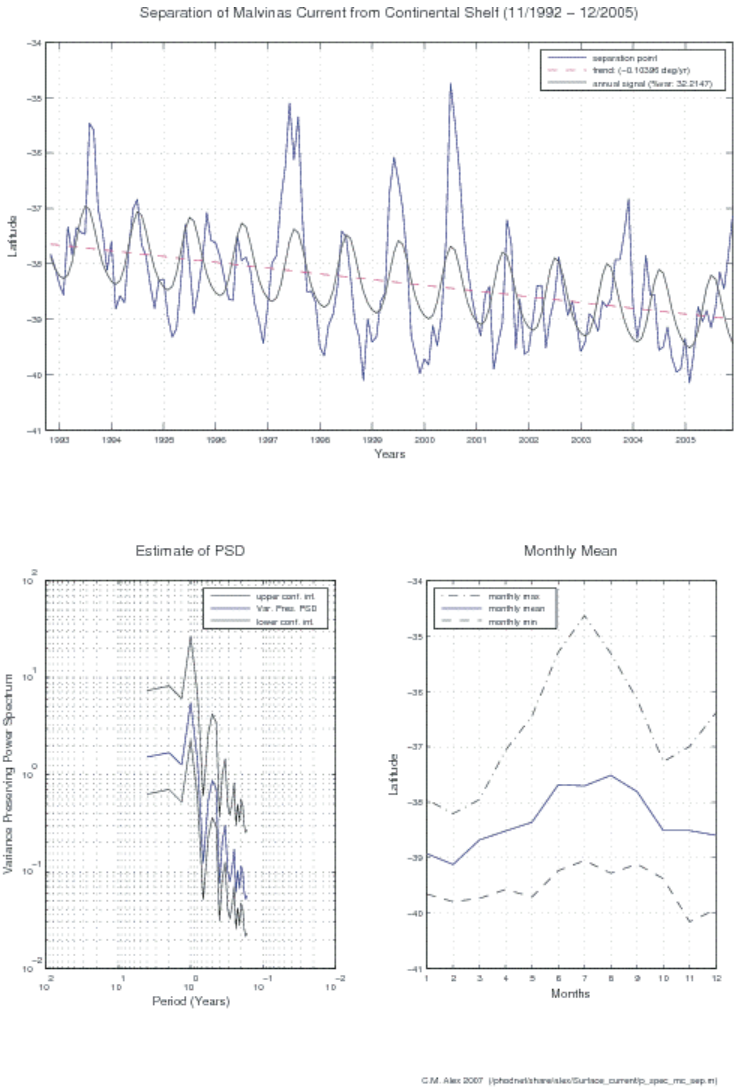


Fig. 4: mean surface currents superimposed on SST

At the western boundary, the bifurcation of the South equatorial Current is clearly seen at around 15°S, and the confluence of the cold and fresh Malvinas Current with the warm and saltier Brazil Current is observed occurring in the mean at 35°S. The eastern boundary is characterized by the Benguela Agulhas system, indicated by the retroflection of the Agulhas Current south of South Africa and the Benguela Current flowing in the north-west direction as a component of the South Atlantic Gyre.

The EOF analysis of the data at the Confluence region indicates a first mode of variability that corresponds to the annual cycle of the Confluence front. The first mode explains 41% of the total variance of the system. During southern hemisphere summer (January-March), the Brazil Current intensifies and reaches its southernmost position. The Malvinas Current concurrently retreats. During Austral winter (June -August) the opposite situation is observed.



The full data set has been analyzed to study the inter-annual variability of the Confluence front as observed by the surface drifters. A methodology is developed to determine the point where the Brazil Current separates from the coast. Results are shown at left. The top panel indicates the latitude of separation for the Brazil Current from the coast. Of interest is the trend that the series indicating that the Confluence front has been moving southward during the last 14 years. This result was also observed from altimeter data for the same period of time and related to an expansion of the subtropical gyre (G. Goni, pers. comm.).

The lower left panel is the spectral analysis of the time series, and the lower right panel the climatology obtained from the time series obtained from the time series after the linear trend is removed.

Overall, the annual cycle is the dominant signal. The percentage of variance explained is lower than climatology (32%), indicating inter-annual variability. A semiannual period is also observed in the spectra. Similar analyses are being done to study the Bifurcation of the South Equatorial Current and the Benguela/Agulhas system.

Meetings:

R. Lumpkin and M. Pazos (AOML) attended the 22nd Data Buoy Cooperation Panel (DBCP) meeting in La Jolla, California on October 16—20, 2006. There, they presented the results of the 2006 drifter comparison study and the 2006 Global Drifter Program Report, and attended numerous subpanel meetings. M. Pazos attended the June 2007 DBCP Training Course on Buoy Program Implementation and Data Management in Ostend, Belgium. R. Lumpkin attended the August 2007 CLIMODE Principal Investigators' meeting in Massachusetts.

Outreach:

Members of AOML's surface drifter group have given presentations for local groups, and were involved in an episode of the nationally-syndicated "edutainment" children's program "Aqua-

Kids". This episode, aired in October 2007, featured the deployment of several drifters off the Miami coast and an extensive interview with R. Lumpkin about the Drifter Program, NOAA's GOOS, and NOAA's climate monitoring efforts. Lumpkin also authored a chapter of the National Geographic and Smithsonian Institution's "Hidden Depths: Atlas of the Ocean by NOAA" dealing with the subject of ocean circulation, and worked with Smithsonian employees on the "drifters" exhibit for the upcoming Ocean hall of the Natural History museum.
In June 2007, M. Pazos (AOML) helped organize the DBCP Training Course on Buoy Program Implementation and Data Management. This course was developed for collaborators in several African countries and held in Ostend, Belgium. She also taught one of the classes in the course, and developed a training CD that includes information on drifter deployment and data access.
In the last several years, AOML/PhOD scientists (Enfield, Garzoli, Goni, Lumpkin) have participated in cruises conducted from the M/V *Explorer*, a ship operated by Semester at Sea, University of Virginia. During the cruises, our scientists taught the students how to deploy drifters and gave lectures related to the Global Drifter Program and the science conducted with the data collected. We are also participating in a partnership with the US Navy in a Capacity building and partnership program between oceanographic institutions in the US and West Africa. As part of this effort, AOML personnel will train participants in the collection and use of drifter data.

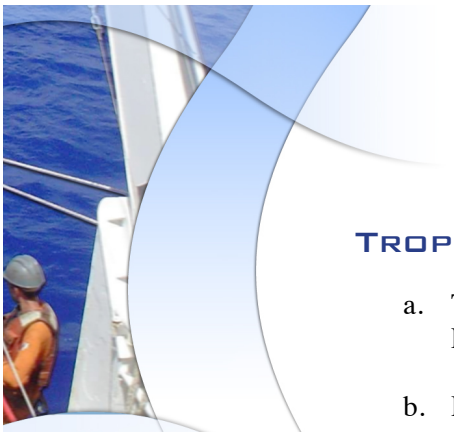
Publications and Reports:

Griffa, A., R. Lumpkin and M. Veneziani, 2007: Cyclonic and anticyclonic motion in the upper ocean. *Geophys. Res. Letters*, accepted.

Lumpkin, R. and M. Pazos, 2007: Measuring surface currents with Surface Velocity Program drifters: the instrument, its data, and some recent results. Chapter 2 of "Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics", ed. A. Griffa, A. D. Kirwan, A. Mariano, T. Özgökmen and T. Rossby, Cambridge University Press.

Lumpkin, R. and G. Goni, 2007: State of the Ocean in 2006: Surface Currents. In "State of the Climate in 2006", ed. A. Arguez, *Bulletin of the American Meteorological Society*, **88** (June).

Lumpkin, R. 2007: Water Movement: Circulation. Chapter in "Hidden Depths: Atlas of the Ocean by NOAA".



Tropical Moored Buoys

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

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

c. Tropical Atmosphere Ocean (TAO) Array

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

Michael J. McPhaden[1] and Rick Lumpkin[2]
[1] NOAA Pacific Marine Environmental Laboratory, Seattle WA
[2] NOAA Atlantic Meteorological and Atmospheric Laboratory, Miami

1.0 Project Summary:

This report describes FY 2007 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/

Four 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 Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA), Flux Reference Stations, and Tropical Pacific Salinity. Discussion of these elements is followed by comments about fishing vandalism, point current meter measurements, a summary of community service, and a list of FY 2007 publications supported by this research. Chris Meinig of PMEL will submit a separate progress report on Engineering Development, a fifth element of the Tropical Moored Buoy Array program.

2.0 Accomplishments

2.1 PIRATA

As of September 30, 2007 the PIRATA Array consists of 17 ATLAS moorings and one subsurface ADCP. This includes the 10 ATLAS mooring PIRATA core array configuration (as agreed upon for the 2001-2006 consolidation phase of the program), three 'Southwest (SW) Extension" moorings, and 4 "Northeast (NE) Extension" moorings. The SW Extension moorings were first deployed in August 2005 and initial

capitalization costs were supported by INPE in Brazil. NOAA has since assumed responsibility for ongoing equipment replacement and refurbishment. Two NE Extension moorings were deployed in June 2006 and two additional sites deployed in May 2007. A "Southeast (SE) Extension" mooring sponsored by the University of Capetown, South Africa, was deployed in June 2006 and recovered in June 2007, but not redeployed. This site may be reoccupied if sustained funding becomes available.

PMEL is charged with providing equipment and technical support for ATLAS moorings and instrumentation, and support for data processing, dissemination, and display. France provides equipment and processing for the subsurface ADCP site. France and Brazil provide ship time and support for equipment shipments and also provide technician support at sea. NOAA provided ship time in FY 2006 and again in FY 2007 to support the Northeast Extension.

Seven (7) ATLAS moorings were recovered and 8 moorings (5 core array and 3 SW Extension) were deployed from the R/V Antea in November/December 2006 (32 sea days, 32 PMEL person-days). Two (2) NE Extension moorings were recovered and 4 deployed from the NOAA Ship Ron Brown in May 2007 (29 sea days, 58 PMEL and 116 AOML person-days). Five of the core array moorings were recovered and deployed from the NO Atalante in May/June 2007 (about 44 sea days, no NOAA participation). The SE Extension mooring was also recovered on this cruise.

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

PIRATA data are available from the PIRATA web site (www.pmel.noaa.gov/pirata/) and the TAO web site (www.pmel.noaa.gov/tao/disdel/disdel.html). There 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 87% overall for FY 2007, 12% higher than for FY 2006. The significant increase was due in large part to the fact that no PIRATA moorings suffered major vandalism in FY 2007. The sites with the lowest data return were 0 º, 35 ºW (67%) and 0 º, 10 ºW (74%). These sites were also two of the sites with lower data return rates in FY 2006. We can only speculate on the cause of the reduction in vandalism this past year. Perhaps fish catch is down, resulting in less fishing in the area.

Real-time PIRATA data return by variable for FY 2007 (and for comparison, FY 2006) is shown below. Three Flux Reference sites were enhanced for current, longwave radiation (LWR) and barometric pressure (BP) in 2006 (two in June and one in

November). The NE and SE Extension moorings (deployed in June 2006 and June 2007) all measure currents as well. Data return for all variables in FY 2007 improved or was nearly equal compared to FY 2006 values.

Real time current velocity data return in the initial year after being added to some moorings was disappointingly low. Data losses were primarily due to problems with battery life and telemetry issues. Efforts to improve these measurements are in progress (see Section 4).

	AIRT	SST	T(Z)	WIND	RH	Rain	SWR	LWR	SAL	BP	CUR	ALL
FY 2007	94	91	89	90	92	73	86	100	84	100	45	87
FY 2006	72	78	73	91	67	74	87		72			75

AOML's contribution to PIRATA is focused on gathering supporting data and providing scientific leadership during the deployment/recover cruises of the PIRATA Northeast Extension (PNE) moorings. During the May 2—29 2007 PNE cruise of the R/V Ronald H. Brown, AOML personnel and collaborators from Howard University, NOAA/NESDIS, NOAA/ESRL and the University of Miami collected a suite of observations, including: 37 CTD casts to 1500 m depth, including casts at all four PNE ATLAS sites; Seabeam bathymetric surveys at the ATLAS sites; and continuous shipboard ADCP measurements along the ship track by the 75 kHz Ocean Surveyor system. The cruise was also used to opportunistically deploy 9 Argo floats, 17 surface drifting buoys, and 122 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. Meteorological observations included skin SST, radiation, direct turbulent flux measurements, and atmospheric sonde and ozone sonde profiles, some during a major dust outbreak from the Sahel region. As noted above, this cruise represented 29 sea days, with 116 AOML person-days and 58 PMEL person-days.

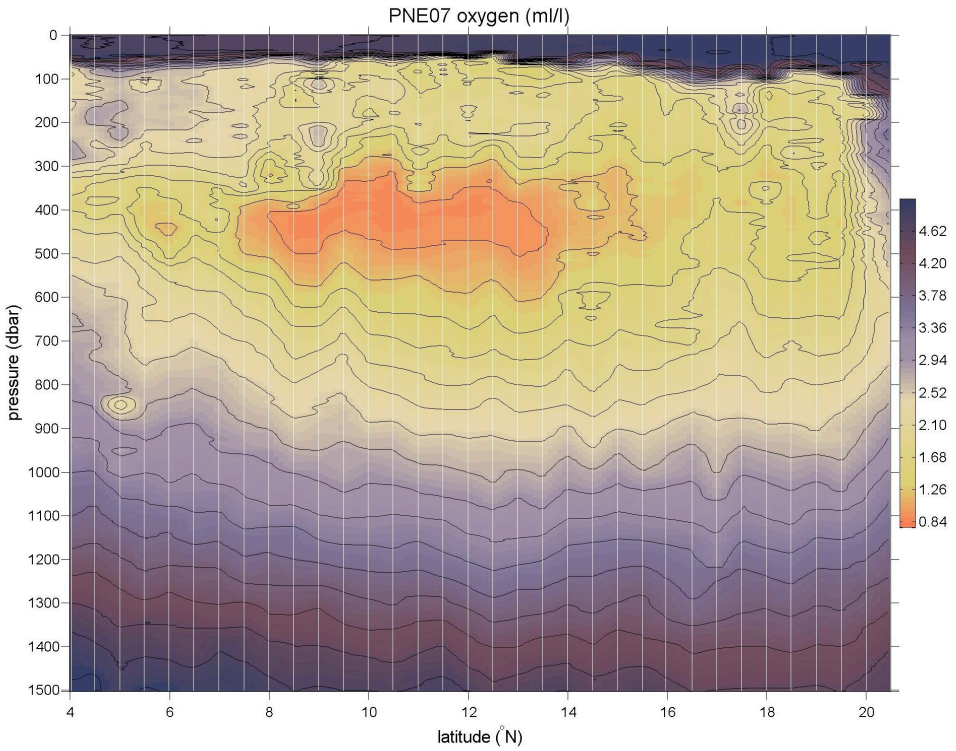


Figure showing calibrated oxygen (ml/l) along 23°W, from 4°N to 20.5°N, measured during the 2007 PNE cruise. The oxygen minimum zone of the tropical North Atlantic is clearly visible at 8—14°N at a depth of 300—500 dbar.

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 2007, a total of 7515 separate user requests delivered 61,492 PIRATA data files, the latter of which represents a 30% increase 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.

CLIVAR Atlantic Panel and the OOPC reviews of PIRATA were concluded in FY 2007. These reviews fully endorsed the PIRATA effort and strongly encouraged its continuation. The reviews suggested areas where improvements in products and services to the oceanographic and climate communities were possible. In response to these

reviews, PMEL enhanced its PIRATA web site with additional technical information. The reviews also suggested that more emphasis should be given to the analysis of intraseasonal variability in the mooring records. AOML and PMEL scientists are now activity engaged in this analysis with new data collected from the PIRATA NE Extension.

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

The CLIVAR/GOOS Indian Ocean Panel (IOP) developed an implementation plan for a multi-component ocean observing system, IndOOS. A key element of the system is a 47 element moored buoy array, the Research moored Array for African-Asian-Australian Monsoon Analysis and prediction (RAMA). The first elements of the array were deployed by Japan in 2000-2001 by India in 2002. PMEL and India's National Institute of Oceanography (NIO) deployed the first ATLAS moorings in 2004.

The number of PMEL sites in RAMA increased from 5 to 9, bringing the total number of sites deployed to 15, or 32% complete. One of the new ATLAS sites was deployed on a PMEL/NIO cruise in August-October 2006 (38 sea days, 76 PMEL person days) from the Indian R/V Sagar Kanya. A total of 5 ATLAS and 1 subsurface ADCP moorings were deployed from this cruise. Two new ATLAS sites were deployed in November 2006 from the Indonesian research vessel Baruna Jaya 1 (14 sea days, 28 PMEL person days). In January-February 2007 PMEL deployed one ATLAS and one subsurface ADCP mooring in collaboration with France's *Laboratoire d'Océanographie - Expérimentation et Approches Numériques* (LOCEAN) from the NO Suroit (44 sea days, 44 PMEL person days) as a contribution to the VASCO CIRENE Experiment. The moorings were deployed at one of the southwest RAMA sites. The IOP plan does not call for an ADCP mooring at this site, thus the subsurface mooring was recovered after the 44-day process study concluded. Four ATLAS moorings were recovered and new moorings deployed in September-October 2007 from the Baruna Jaya 3 (27 sea days, 54 PMEL person days).

PMEL has been actively engaged in developing partnerships with institutions in Indonesia and India to secure ship time necessary for implementing and maintaining the RAMA. For the Baruna Jaya cruises, ship time was obtained via cooperative agreements between NOAA and Indonesia's Agency for the Assessment and Application of Technology (BPPT) and the Ministry for Marine Affairs and Fisheries (DKP). Sid Thurston (CPO) and Renee Eppi (OAR International Activities) were instrumental in developing these agreements. Similarly, PMEL has spearheaded efforts within NOAA to develop an MOU with the Ministry of Earth Science (MoES) in India for cooperative programs across a wide range of topics. The first Implementing Arrangement, which is scheduled for signing in December 2007, will be for development of RAMA. As part of thie IA, it is expected that India will pledge 60 days of ship time per year for 5 years.

All ATLAS moorings deployed in the Indian Ocean have the PIRATA suite of instrumentation, plus one additional water temperature measurement, 2 additional salinity measurements and one near surface velocity measurement. One of the ATLAS moorings

is enhanced for flux reference measurements (see 2.3 below).

RAMA real-time data return was 49% overall for FY 2007, substantially lower than in TAO or PIRATA. This was mainly due to higher rates of vandalism in the Indian Ocean basin (see 2.6 below). Two of the moorings recovered in September 2007 had not been transmitted for 8 or 9 months. Some data will be recovered from these moorings in delayed mode, which will increase the percent data return for RAMA. Data return for the PMEL ADCP deployed at 0, 81°E was 100% for the nearly two year period 27 October 2004 to 22 September 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 and is a contribution to the Global Ocean Observing System and international research programs. PMEL is a major contributor to OceanSITES in the context of the Tropical Ocean Atmosphere (TAO) mooring array in the tropical Pacific, PIRATA and RAMA. Five equatorial Pacific moorings within the TAO/TRITON Array (4 ATLAS and 1 TRITON), three PIRATA moorings, and two (1 ATLAS and 1 TRITON) RAMA moorings presently have air-sea heat, moisture and momentum flux measurement capability. The RAMA plan calls for 8 flux sites when completed. Enhancements to the primary ATLAS measurements in each array provide the functionality for all flux reference moorings to measure shortwave and longwave radiation, precipitation, sea level pressure, water temperature with higher vertical resolution, surface and subsurface salinity at 8 depths, and velocity at one or more depths.

2.4 Tropical Sea Surface Salinity

FY 2007 funding provided support to continue progress towards making sea surface salinity (SSS) measurements at all surface mooring sites. At the end of FY 2007 all PIRATA and RAMA moorings and 54 of 55 TAO moorings were equipped to measure surface salinity. The final TAO site will be enhanced to measure SSS in FY2008.

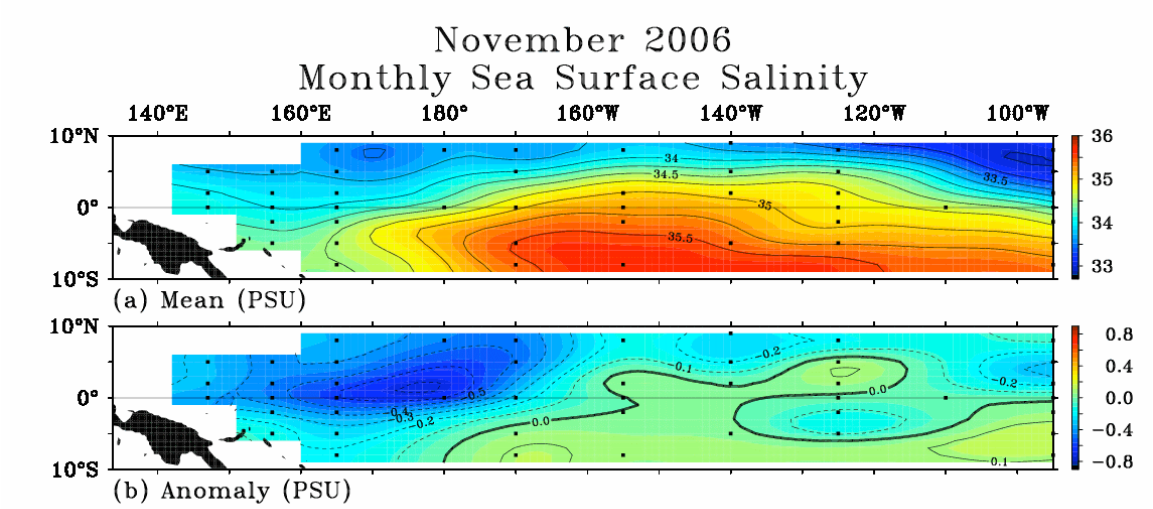


Figure showing salinity for November 2006 based on TAO/TRITON SSS measurements. Anomalies show freshening related to the 2006-07 El Niño event. West of the date line anomalies are associated with an eastward shifts rainfall linked to changes in the Walker circulation; freshening north of the equator in the eastern and central Pacific is related to a southward shift in the ITZC towards the unusually warm waters of the equatorial cold tongue. Anomalies are based on an objective analysis of deviations from the monthly climatological November mean based on World Ocean Atlas salinities. Dots indicate sites where TAO/TRITON monthly means (based on at least 15 days of data) are available.

3. Vandalism

Vandalism continues to present a problem in all three tropical ocean basins. PMEL has documented ATLAS equipment losses over 7.5 years in TAO and PIRATA, and over nearly 3 years in RAMA. Percentage losses of all or significant portions of mooring systems were 12% in TAO, 13% in PIRATA and 36% in RAMA. In addition to these, ~15% of individual sensors were lost in TAO and PIRATA, and ~ 40% in RAMA. PMEL has developed modifications to ATLAS moorings designed to reduce the loss of equipment and data to vandalism: New hardware which inhibits the removal of sensors and the buoy towers was introduced on moorings deployed in September 2007. Buoys on some surface moorings deployed in 2008 will modified to inhibit vandals from climbing aboard or attaching a line to the buoy. Prototype versions of these moorings will not have any meteorological sensors. If the modifications prove successful in reducing mooring loss, surface sensors protected from removal and damage may be reintroduced to the moorings.

4. Current Meter Performance

In the summer of 2007 PMEL conducted a detailed review of Sontek Argonaut MD current meter performance over the past 6 years, during which time it has been the primary source of point velocity measurements in TAO, PIRATA, and RAMA. It was found that the current meters returned significantly less data than typically returned from other instruments on ATLAS moorings. For example, annual average data return

computed for the ensemble of all measurement types in the TAO Array is typically in the 85% to 92% range. Argonaut MD data return rates over the six-year period year were 48% in real time and 60% in delay mode. Review of individual deployment and instrument maintenance records revealed that there were multiple reasons for the lower data return. These included telemetry problems (which affected real time data return rates only), battery failure, failure of instrument circuitry, compass calibration stability and transducer integrity.

Based on the relatively low data return rates for the Argonaut-MD, PMEL is looking at alternative instruments to replace the Sontek Argonaut MD. One possibility is a new short-range Doppler current meter under development at YSI RDI, Inc. PMEL has worked with the manufacturer on design criteria and testing of prototypes of this instrument and will continue to explore other possible replacements as opportunities arise.

5. Community Service

McPhaden, the TAO Project Director, is chairman of the Tropical Moored Buoy Implementation Panel and serves on the PIRATA Scientific Steering Committee (SSC), the OceanSITES Science Team, the CLIVAR/GOOS Indian Ocean Panel, the CLIVAR Pacific Panel, the CLIVAR Global Synthesis and Observations (GSOP) Panel, and the JCOMM Observations Coordination Group. He is 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 and a PIRATA SSC meeting (in Miami). He has also provided input to meetings of the WCRP Joint Scientific Committee and JCOMMOPS. He lectured on ENSO and climate change to the National Science Teachers Association in November 2006 and participated in an international review of the UK/US RAPID Climate Change Program. McPhaden was a contributing author for the Fourth Assessment Report of the IPCC (which won a share of the 2007 Nobel Peace Prize). He has agreed to run for president of AGU.
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 2006 (La Jolla, CA). He also worked with the Climate Program Office and the International Activities staff in developing plans for collaboration with Indonesia towards the implementation of RAMA.

Lumpkin, project collaborator at AOML, is scientific advisor for the Global Drifter Program and serves on the PIRATA SSC alongside McPhaden. He is also a member of the CLIVAR Tropical Atlantic Climate Experiment (TACE) working group on observations. He organized and convened the 12th PIRATA meeting in Miami, FL on November 1—3, 2006, and attended the PIRATA SSC meeting in Brest, France on 26—28 March 2007. In December 2007, he will co-convene (with Brian King) the CLIVAR/GSOP workshop on velocity observations.

6. Publications (Refereed Literature)

Bourlès, B., A. J. Busalacchi, E. Campos, F. Hernandez, R. Lumpkin, M. J. McPhaden, A. D. Moura, P. Nobre, S. Planton, J. Servain, J. Trotte and L. Yu, 2007: The PIRATA

Program: History, Accomplishments, and Future Directions. Bull. Am. Meteorol. Soc., submitted.

Cheng, W., M.J. McPhaden, D. Zhang, and E.J. Metzger, 2007: Recent changes in the Pacific subtropical cells inferred from an eddy resolving ocean circulation model. J. Phys. Oceanogr., 37, 1340-1356.

Delcroix. T., S. Cravatte, and M.J. McPhaden, 2007: Decadal variations and trends in tropical Pacific sea surface salinity since 1970. J. Geophys. Res., 112(C3), C03012, doi:10.1029/2006JC003801.

Foltz, G.R. and M.J. McPhaden, 2007: Seasonal mixed layer salinity balance of the tropical North Atlantic Ocean. J. Geophys. Res., in press.

Foltz, G. R., and M. J. McPhaden, 2007: Impact of barrier layer thickness on SST in the central tropical North Atlantic. J. Climate, submitted.

Foltz, G. R., and M. J. McPhaden, 2007: Impact of Saharan dust on tropical North Atlantic SST. J. Climate, accepted.

Griffa, A., R. Lumpkin and M. Veneziani, 2007: Cyclonic and anticyclonic motion in the upper ocean. Geophys. Res. Letters, accepted.

Lumpkin, R. and G. Goni, 2007: State of the Ocean in 2006: Surface Currents. In "State of the Climate in 2006", ed. A. Arguez, Bulletin of the American Meteorological Society, 88 (June).

McPhaden, M. J., 2007: Evolution of the 2006-07 El Niño: The Role of Intraseasonal to Interannual Time Scale Dynamics. *Advances in Geosciences,* accepted.

McPhaden, M.J., S.E. Zebiak, and M.H. Glantz, 2006: ENSO as an integrating concept in Earth science. Science, 314, 1740-1745.

McPhaden, M.J., M.F. Cronin, and D.C. McClurg, 2007: Meridional Structure of the Surface Mixed Layer Temperature Balance on Seasonal Time Scales in the Eastern Tropical Pacific. J. Climate, accepted.

Morris, V., P. Clemente-Colón, N. R. Nalli, E. Joseph, R. A. Armstrong, Y. Detrés, M. D. Goldberg, P. J. Minnett and R. Lumpkin, 2006: Measuring Trans-Atlantic Aerosol Transport from Africa. EOS 87 (50), 12 Dec.

Yoneyama, K. et al, 2007: MISMO field experiment in the tropical Indian Ocean. Bull. Am. Meteor. Soc., submitted.

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

Christian Meinig
NOAA Pacific Marine Environmental Laboratory, Seattle, WA

1. PROJECT SUMMARY

This continuation proposal requests funds to advance the state of NOAA's open ocean observation systems with the development of an easy to deploy and low cost mooring systems which make use of new and commercially available sensors and instrumentation and which addresses issues of improved data return rates in areas prone to vandal induced data losses. 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. A candidate mooring system presently under development at PMEL is the Platform and Instrumentation for Continuous ocean Observations (PICO) mooring. A web site containing comprehensive information on the system under development can be found at http://www.pmel.noaa.gov/pico/

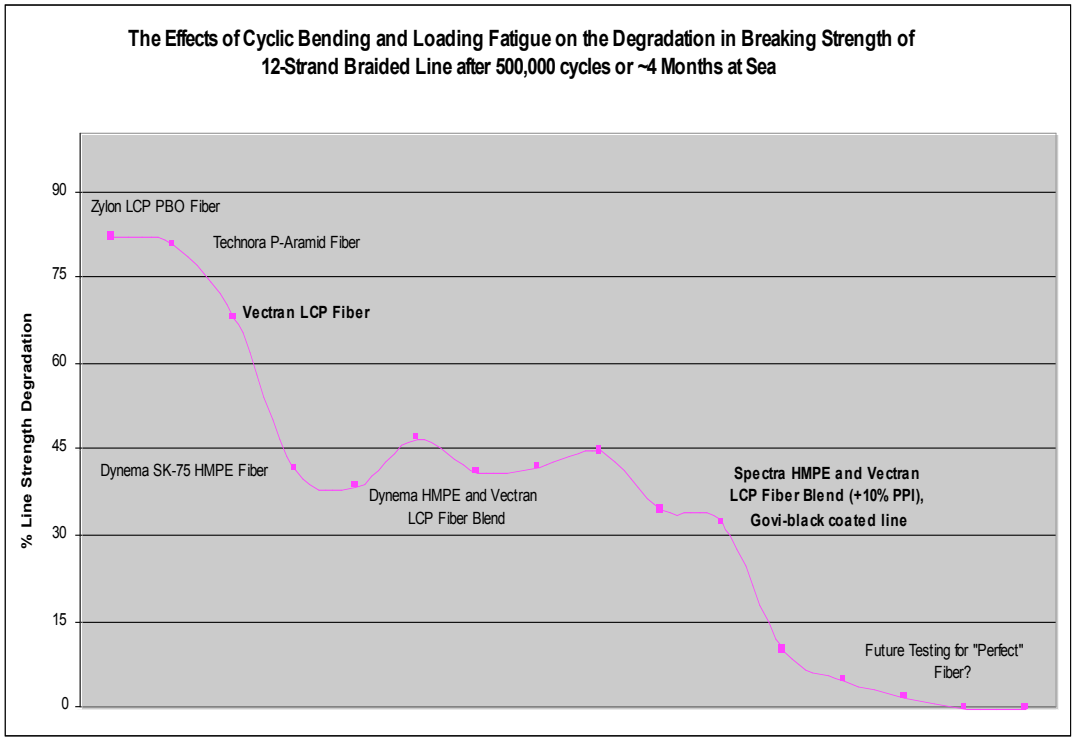
2. Accomplishments:

From FY '07 Work Statement:

a. Run test mooring line sections on the PMEL Dynamic Line Testing (DLT) machine to evaluate the design for repeated bending of synthetic mooring lines and strain relief terminations.

Results:

The PICO concept advocates a small, relatively inexpensive, vandal resistant buoy that can be easily deployed from ships / boats of opportunity. These requirements present significant engineering challenges, particularly in the design and development of a robust, highly survivable (5 year +) mooring system. The most complicated, and dynamic component of the PICO mooring system is the upper 700m jacketed line segment with inductive capability. With this in mind, we focused in FY'07 on the dynamic testing and characterization of six different mooring lines for the effects of repeated bending (400,000 cycles) on breaking strength of the mooring line. The results show that a blended Dyneema and Vectran line showed superior properties for mooring use. To our knowledge this type of basic mooring material testing has not been done in the community. A report titled: *Continued Development of a Slack Line, ReverseCatenary Mooring for a Small, Deep Ocean Instrument Platform; Lawrence-Slavas, 2007* was generated and will be presented at the upcoming ONR/MTS Buoyworkshop in early 2008.



b. Static and dynamic modeling of PICO lines to optimize performance through line design and configurations will be conducted. The WHOI Cable model will be used exclusively for this effort.

Results:

The effects, on the PICO mooring's dynamic responses, from the addition of a profiler, appear to be largely dependant upon the vertical location (depth) of the profiler. Fixing the profiler at a depth of 325m consistently yields the most severe results, and this location should be used for future mooring modeling. The profiler's effects on static tension and mooring catenary can be considered to be negligible. The influences of profiler depth on the vertical movement of the mooring remain inconclusive. Surprisingly, the addition of a weighted line section only has a moderate effect on the PICO mooring's catenary and line slope between 325m and 650m (at most 8%, assume the model has a "built-in" +-5% error). The addition of the weighted section has no beneficiary effect on the tension spread, but it does have a pronounced effect on the static tension at the buoy. Under calm current conditions and choppy seas the additional weight reduces the PICO buoy's tendency towards shock loading by greatly increasing the mean tension, while only slightly increasing the tension spread (see figure #32). Based on these results, it is recommended that the weighted line section be retained within the PICO mooring

c. Mooring hardware will be ordered to carryout two deep water deployments.

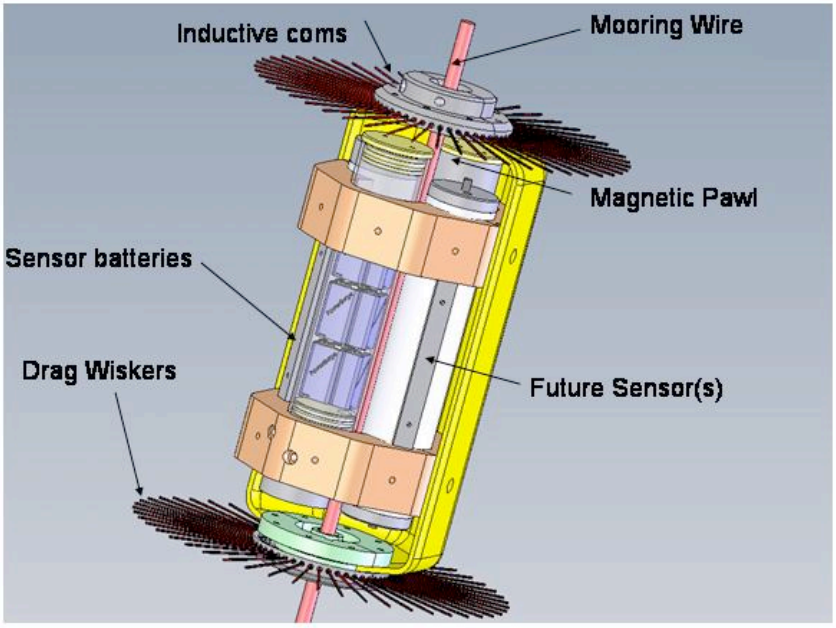
Results:

Despite the late arrival of funds, complete mooring systems were design and procured for deep water deployments and the system was tested with favorable results in Puget Sound for 5 days. An engineering ocean deployment is being planned for early in 2008 off San Diego or Hawaii in approx 3500m of water.

d. Continue development of a wave driven crawler mechanism for the PICO Profiler.

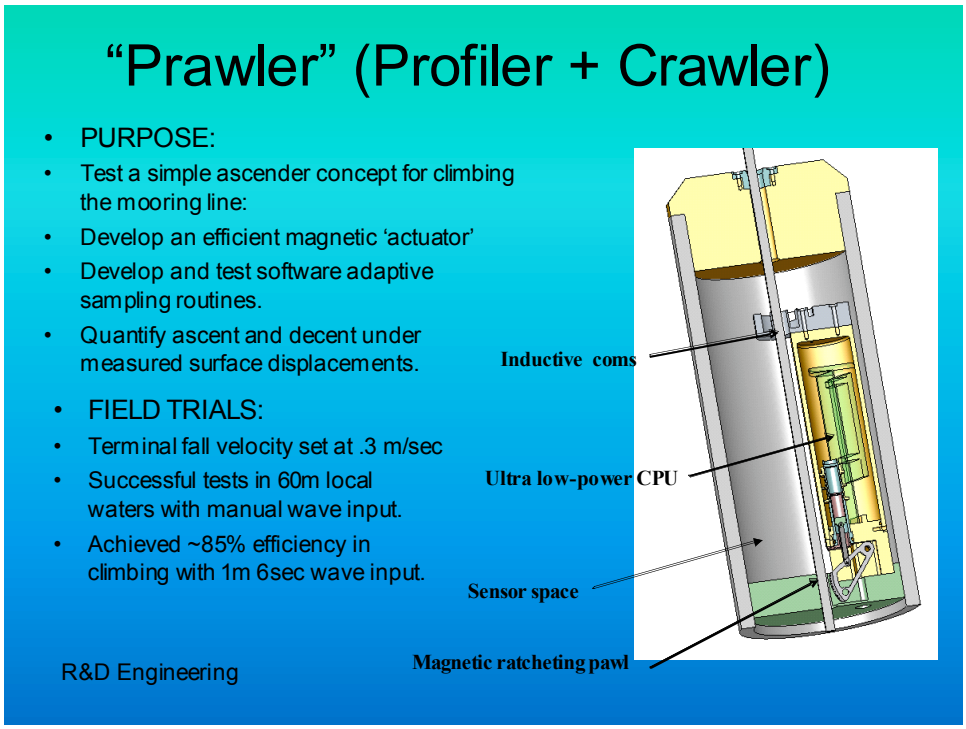
Results:

A novel wave driven crawler mechanism, now named "Prawler" (Profiler & Crawler) was built and tested in 2007. The Prawler uses the swell and wind wave energy from the surface buoy to engage and disengage a magnetically actuated pawl to climb the mooring line. Upon reaching a predetermined height a pawl releases and the Prawler falls at ~.3 m/s down the mooring line and samples the water column during decent. Present tests have been focused on collecting temp, pressure and engineering values, but future additions could include many type of sensors. During a 5 day test in Puget Sound the Prawler "prawled" and sampled over 3km in September 2007. These are very encouraging results, especially when considering the small waves that the buoy was subjected to in Puget Sound. With funding, a deep ocean test is being planned for early 2008 off San Diego or Hawaii.



PMEL 'Prawler' as deployed in Puget Sound

Prawler and PICO mooring tests and concepts were presented at the DBCP in Oct '06 in Jeju, Korea.



e. Analyze data collected with prototype Seabird Jenna CTD and incorporate 2nd generation sensors, sampling and communications schemes.

Results:

PMEL developed FLEX, electronics, firmware and bi-directional software has been developed and is now deployed on the KEO and PAPA mooring systems as in-situ comparisons with the standard ATLAS systems. Partnerships were formed with Seabird Electronics and Teledyne RDI on next generation instrument development and some instruments are commercially available or nearly available.

The Doppler Volume Sampler (DVS) measures velocity profiles, temperature and is inductively coupled via a Seabird modem. PMEL and RDI worked closely on developing the specifications, testing and evaluating the instrument and is an exciting example how government and industry can partner to advance instrumentation. Complete details at: http://www.rdinstruments.com/dvs.html

The Seabird SBE-51 is being evaluated by Seabird and PMEL as a novel instrument to make high precision, long endurance conductivity measurements and transmit those data

via inductive modems. This sensor is still under evaluation and is currently deployed in the North Pacific for in-situ comparisons.

The FLEX electronic (data logger, telemetry and serial interface) systems are performing very well and within specifications. The systems are currently under in-situ evaluation at PAPA and KEO. Realtime data can be viewed for PAPA at: http://www.pmel.noaa.gov/stnP/data.html. The FLEX system was deployed in Sept '07 and the website in still under development.

RDI-PMEL partnership example:
Doppler Velocity Sampler

Tropical Atmosphere Ocean (TAO) Array

Landry Bernard[1] and Michael J. McPhaden[2]
[1] NOAA National Data Buoy Center, Stennis Space Center, MS
[2] NOAA Pacific Marine Environmental Laboratory, Seattle, WA

1. PROJECT SUMMARY

FY 2007 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 site containing comprehensive information on the TAO program can be found at (http://www.tao.noaa.gov/). This report summarizes the progress and accomplishments of the TAO project in FY2007. In FY 2007, 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 2007 PROGRESS

2.1 TAO/Triton Array

2.1.1 Background

FY 2007 was the seventh 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/).

2.1.2 TAO Project Highlights

At present, TAO/TRITON data show atmospheric and oceanic conditions and trends that indicate a weak La Niña exists in the tropical Pacific. Many forecast models that rely heavily on TAO/TRITON data for initialization, suggest that the La Niña will likely continue into early 2008 and may strengthen.

2.1.3 Field work

NDBC is responsible for maintaining 55 ATLAS sites at and east of 165°E. At four of these sites (165°E, 170°W, 140°W, 110°W along the equator) current meters are attached to the ATLAS mooring lines, and a nearby subsurface Acoustic Doppler Current Profiler

(ADCP) mooring is deployed. During the past year, NDBC deployed 56 ATLAS moorings and 2 subsurface ADCP current meter moorings in the tropical Pacific. One experimental TAO Refreshed buoy was deployed in the Pacific for a side by side test with TAO Legacy buoys. Four Refreshed TAO buoys were deployed in the Gulf of Mexico as part of development tests.

2.1.4 Ship Time and Sea Time

In FY 2007, 232 days at sea were allocated to the program by NOAA's Marine and Aviation Operations (NMAO) (191 days on *Ka'imimoana* and 41 days on *Ronald H. Brown*) to support the TAO portion of the TAO/TRITON array. This total includes transit days for repositioning the ships and traveling to and from the shipyard. NDBC participated in 629 person-days at sea (number of people times days at sea) and deployed 58 moorings. Due to budget shortfalls at NMAO, *Ka'imimoana's* schedule was cut by approximately 30 sea days in FY2007, reducing the number of buoys serviced for the year. For comparison, during FY 2006, 262 days at sea (220 days on *Ka'imimoana* and 41 on *Ronald H. Brown*) were required to maintain the array, and 71 moorings were deployed.

As part of the TAO Transition, PMEL participated in 261 person-days at sea assisting NDBC with TAO operations and in support of TAO fieldwork.

2.1.5 Data Return

Percentage real-time data return for primary TAO variables integrated over the 55 sites for FY 2007 follows:

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

All parameters were approximately the same, except the lower wind data during 2007. A primary reason for the lower percentages continues to be the effects of vandalism in the two easternmost lines. Real-time return wind percentages for FY 2007 are 58% and 66%, for lines 95W and 110W, respectively. During FY 2007, twenty-two sites recorded real-time return percentages less than 80% for wind data and thirteen of those reported less than 50% return. The slight increase in the ALL category is due to the increase in the T(z) percentages. The T(z) data account for approximately 80% of the total TAO data.

Eighteen point-source current meters continue to be deployed on the TAO moorings along the equator, near the ADCP moorings. The real-time data return during FY 2007 was 65.8%, an increase of 7.9% from FY 2006. This variable will continue to be reported. PMEL completed a six-year analysis of the point-source current meter performance and has forwarded the results to NDBC and to the manufacturer of the instrument.

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 241 CTD casts were made on TAO cruises in FY 2007, which was a decrease over FY 2006 (58). This large reduction in CTD data resulted from reduction in sea days, equipment problems and several unforeseen problems that required a reduction in CTDs conducted to support ship's needs. The shipboard ADCP data are forwarded to, processed, archived, and distributed by Eric Firing and colleagues at the University of Hawaii.

2.1.7 Guest Investigator Research Projects Using TAO Moorings and TAO Cruises

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

a. Ongoing ancillary projects on TAO cruises for FY 2007 (Project, Principal Investigator, Institution (Ship):

- Underway CO2, Richard Feely, NOAA/PMEL (KA and BROWN)
- Turbulent flux measurements and wind profiler, Chris Fairall and Jeff Hare, NOAA/ESRL (BROWN)
- Carbon cycle, Michael Bender, Princeton University (BROWN)
- Discreet Gas Sampler, Michael Bender, Princeton University (KA)
- Dissolved Inorganic Carbon (DIC) Analysis, Andrew Dickson, Scripps Institution of Oceanography (KA)
- Argo float deployments, Greg Johnson, PMEL (KA)
- Global Drifter Program, Rick Lumpkin, NOAA/AOML (KA and BROWN)
- Iron limitation, Mike Behrenfeld, NASA/Goddard (BROWN)
- CO2 moorings, Chris Sabine, NOAA/PMEL/Francisco Chavez, MABARI (KA)
- Bio-optical measurement and nutrient analysis, Francisco Chavez, MBARI (KA)
- 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)
- Equatorial Box Project, Michael Behrenfeld, Oregon State University (KA)
- Microstructure Chipod development, James Moum, Oregon State University (KA)
- Nutrient Samples, Cathy Cosca, PMEL (KA)
- Lagrangian Float, Ren-Chieh Lien, Eric D'Asaro, University of Washington,(KA and BROWN)
- Tsunami/DART, NDBC, Shannon McArthur
- Turbidity/fluorescence CTD measurements, Pete Strutton, Oregon State University (KA)

b. One-time or limited-term ancillary projects on TAO cruises for FY 2007 (Project, Principal Investigator, Institution (Ship):

- Moored Fluorometer deployments, Pete Strutton, Oregon State University (KA)
- Nutrient-poor seawater collection, Calvin Mordy, PMEL (KA)
- Nitrate and O_2 isotope analysis, Patrick Rafter, Scripps Institution of Oceanography (KA)
- Oxygen Concentration and Isotopic Composition in Upper Ocean, Michael Bender, Oregon State University.

2.2 TAO Project Web Pages

During FY07, the official TAO web site maintained by NDBC at http://tao.noaa.gov/ provided easy access to TAO/TRITON data sets, as well as updated technical information on buoy systems, sensor accuracies, sampling characteristics, and graphical displays. The NDBC TAO web site received 3,436,127 hits and delivered 3,095,018 TAO files to the end users. These web statistics represent a significant increase from previous years partly do to NDBC's usage of Webalizer for web stats, while PMEL uses a custom process. The underlying statistical calculations between PMEL and NDBC numbers are different due to the lack of an industry standard in how files are defined for web statistics purposes. However, while the two sets of numbers cannot be compared across organizations, each set of numbers is relevant when comparing to previous numbers produced by the same organization to determine web activity in terms of growth/decline. NDBC also stood up a mirror web site at NWS Headquarters in Silver Spring, MD. This mirror site is globally load balanced and will automatically redirect any traffic destined for the NDBC web farm to the Headquarters web farm when the NDBC network is inaccessible.

2.3 Operational Use of TAO/TRITON Data

TAO/TRITON data are distributed via the Global Telecommunications System (GTS) to national and international operational forecast centers, such as NOAA's National Centers for Environmental Prediction and the Department of Defense's Fleet Numerical Meteorology and Oceanography Center. Within NOAA, these data are used for operational weather and Pacific tropical cyclone forecasting. The National Core Processing Center for Multi-Channel Sea Surface Temperature (MCSST) uses TAO/TRITON and PIRATA sea surface temperatures distributed via the GTS to perform

validation and improvement to the MCSST processing algorithms. TAO/TRITON and PIRATA are the only moored data used in the MCSST analysis. The Global Temperature-Salinity Profile Program (GT/SPP) collects the TAO/TRITON subsurface temperature and salinity distributed over the GTS and makes them available in real-time via NOAA's National Oceanographic Data Center web site.

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

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, 9 complete moorings systems were confirmed lost in the Pacific due to the effects of vandalism and 6 other mooring were missing towers. Two mooring remain adrift in the array and may be lost, but not yet confirmed.

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

2.5 Public Service

NDBC participated in Data Buoy Cooperation Panel (DBCP) meetings. NDBC represents the North Pacific Data Buoy Advisory Panel, which is interested in data buoys located in the North Pacific Ocean, and is comprised of members from Canada, China, Japan, Korea, Mexico, and the United States. NDBC also participated in the 6th meeting of the North Pacific Data Buoy Advisory Panel, chaired the Drifter Evaluation Panel, and co-chaired the Science and Technology Workshop.

NDBC attended the NOAA Climate Observation Division 5th Annual System Review Meeting in Silver Spring, Washington DC. The NDBC TAO Project Manager, Dr. Teng, presented a poster paper titled "NOAA's Tropical Atmosphere Ocean (TAO) Buoy Array" at the meeting. Dr. Teng also attended the "Waves and Operational Oceanography 2007 Workshop" and "GLOBWAVE Project Workshop" at the France Research Institute for the Exploitation of the Sea (IFREMER) in Brest, France and discussed PIRATA with their representatives.

NDBC Chief Scientist serves as a US representative to the PIRATA Resources Board, and is actively involved in the PIRATA effort including a working group to identify national contributions to PIRATA. The NDBC Chief Scientist also participated in PIRATA 12 meetings.

NDBC hosted Ms. Hester Viola's during November 2006. Ms. Viola is the Data Buoy Cooperation Panel (DBCP) and Ship Observations Team (SOT) Technical Coordinator. NDBC hosted Ms. Yui Hashimoto of JAMSTEC and NOAA's Office of Climate Observation in March 2007.

NDBC has a standing group of Regional Association Coordinators for the Coastal Ocean Observing System, who provide NDBC updates to the eleven Regional Associations and assimilate suggestions from them for future operations. Landry Bernard, TAO serves as a member of the IOOS Steering Team and was elected as a Marine Technology Society Fellow in 2007. NDBC will serve as the Co-Chair of the Technical Program for the MTS/IEEE(OES) OCEANS 2009 Conference.

With the USCOE Hydrologics Laboratory, NDBC organized and prepared a National Waves Plan and participated in the review and final edits to the document. The NDBC Chief Scientist attended Pirata meetings in Miami, FL in November 2006.

Given the proximity of NDBC's new hurricane buoys to the PIRATA array, NDBC, in consultation with the PIRATA Science Steering Committee, continues 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 2007 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 2007 TAO Transition efforts focused on five areas: (1) NDBC continued the daily/monthly/quarterly QA/QC of TAO real-time and delayed data, (2) NDBC continued as the "Official" TAO web site for QA/QC data, (3) NDBC assumed responsibility for all TAO cruises, (4) development and testing of the TAO refreshed buoy system which is to replace obsolescent components and sensors, and (5) NDBC continued enhancements to a 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 2007:

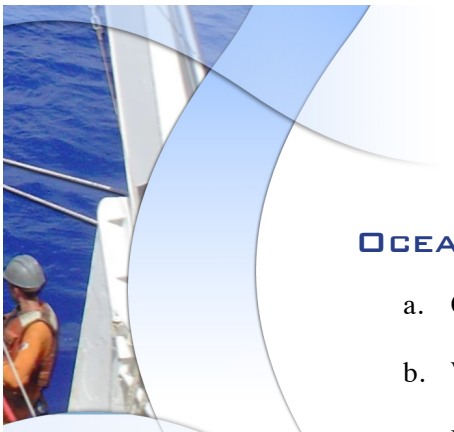
- NDBC took over control of the Service ARGOS account and the management of the release and non-release of TAO data via GTS.
- Established the TAO mirror web site at NWS Headquarters in Silver Spring, MD.
- Migrated the legacy data into the refresh database after an internal parallel testing period.
- Continued to make DAC Management Console enhancements.
- Developed a Draft Data Management Plan
- Updated the TAO IT Detailed Architecture Plan.
- Updated and released the KA ship web page and CTD Cast Data Delivery page.
- Updated the DMAC Operating Procedures Manual for Delayed Mode Data
- Completed the Atlantic PIRATA buoy web page integration into the NDBC TAO and NDBC standard web sites.
- Distributed the Atlantic PIRATA buoy data via GTS using the process that will support the refreshed TAO buoys.
- Established the OPeNDAP services for TAO data distribution.

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

- Sensor calibration procedures were developed.
- A shorter, easier to handle payload tube was developed and is being evaluated.
- A Lithium battery pack was developed and is being evaluated.
- A smaller form factor anchor design was developed and is being evaluated.
- An ocean sensor laboratory comparison test was performed between TAO legacy and refresh equipment.
- A flux site configuration of the TAO refresh was developed and is being evaluated.
- A standard TAO configuration was deployed at 2S140W and 9N140W.
- A standard TAO configuration was deployed at 41042 in the PIRATA array.

During FY 2007, NDBC accomplished the following goals for data/IT part of theTAO refresh:

- Continued to enhance the NDBC refreshed TAO database.
- Continued to enhance the TAO real-time processing systems for NDBC AMPS payloads.
- Continued to enhance the NDBC DAC Management Console.
- Continued to enhance the TAO data display and data delivery web pages.
- Supported the use of the DAC management console and Engineering web pages in support of test buoys deployed in the Gulf of Mexico and the Pacific.



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. Southern Ocean Modern Observations/Weddell Sea Moorings

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

Robert A. Weller and Albert J. Plueddemann
Woods Hole Oceanographic Institution, Woods Hole, MA

Project Summary

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

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

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. New engineering and capability upgrades are being implemented and evaluated now at Stratus and at NTAS. In October 2007 an NDBC surface wave sensing and telemetry (Iridium) system was deployed on the Stratus buoy. In early 2007, the NTAS mooring was deployed with new hardware to permit telemetry of upper ocean data from instruments on the mooring line.

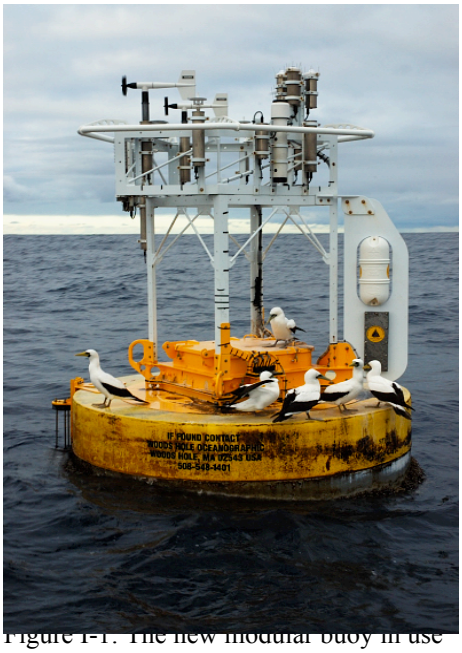


Figure I-1: The new modular buoy in use at all Ocean Reference Stations. Photo taken during the 2006 Stratus deployment and recovery cruise.

Task II: Stratus Site:

The stratus surface mooring was originally deployed in October 2000. It has been annually redeployed and recovered since that time, including the most recent done during the October 9-November 8, 2007 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 (http://uop.whoi.edu/projects/Stratus/stratus.htm), arriving within hours of when it was observed. These data are exchanged in near real time with ECMWF and NCEP; they in turn provide operational data at the model grid point nearest the buoy. It is also shared with the Chilean Navy (SHOA). The same data are shared with CLIVAR investigators, especially modelers interested in the Stratus region and VAMOS/VOCALS investigators in the U.S. and in South America. This meteorological data are used to assess the realism of operational atmospheric models in the stratus region. Once per minute as well as hourly surface meteorological time series are provided to the VOCALS and other investigator communities (including Sandra Yuter, Chris Bretherton, Meghan Cronin) after recovery. The surface meteorological data have been made available to the satellite community (including radiation – Langley, winds – Remote Sensing Systems and JPL, SST – Dick Reynolds, all variables – the SEAFLUX project).

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

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

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.

That models need to be improved is evident in Figure II-1, a comparison of the daily-averaged incoming shortwave radiation climatology (average of six years of data) with the incoming shortwave radiation climatology from ERA-40 (ECMWF 40-year reanalysis) and NCEP-2 (National Center for Environmental Prediction reanalysis). During October to December, the models produce too few clouds, and as a consequence supply too much insolation to the sea surface, with the error close to 50 W m^{-2}.

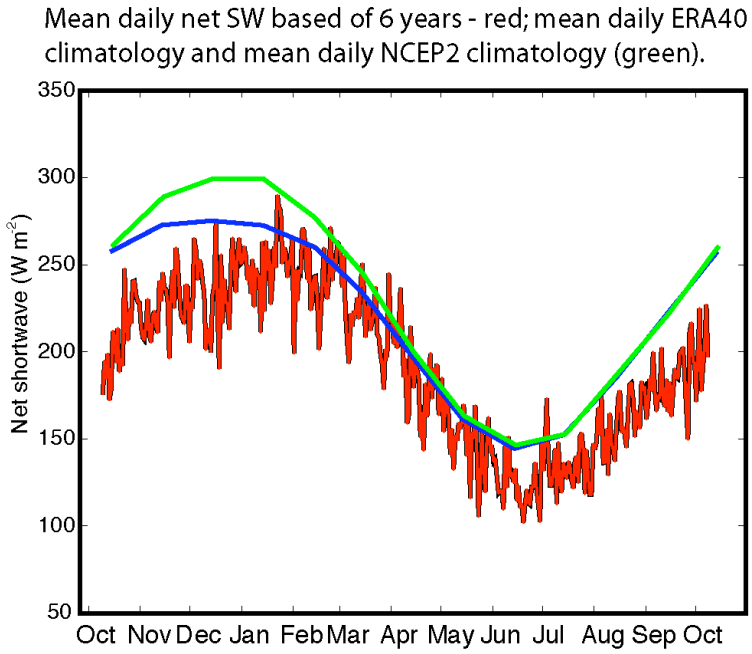


Figure II-1. Comparison of observed incoming shortwave radiation at the Stratus Ocean Reference Station (mean daily, averaged over 6 years, in red) with the monthly climatological incoming shortwave radiation from ERA40 (blue) and NCEP2 (green).

The Stratus cruises serve the wider scientific community by providing a platform on which to study the regional ocean. Additional researchers who participated in collaborative research or benefited from shared ship time in FY2008 have come from many institutions: NOAA Earth System Research Laboratory, Servicio Hydrografico y Oceanografico de la Armada (SHOA, Chile), the NOAA National Data Buoy Center), INOCAR (Institute of Naval Oceanography, Ecuadorian Navy), the Argo float program, the NOAA surface drifter program, Gerard Eldin (France), the Peruvian Navy Hydrographic Service, and IMARPE (Institute of Marine Research, Peru). Ten Argo floats, 13 surface drifters, and 4 French profiling floats were deployed during the cruise. A new NDBC DART buoy was deployed. Weller applied for sampling clearance from Ecuador and Peru, and during the transit this year from Rodman, Panama, sampling was done in collaboration with these countries to investigate the La Niña event then underway. The 2007 Stratus cruise also hosted a teacher from NOAA's Teachers-at-Sea program (Meghan O'Leary). The work this year included recovering and redeploying the WHOI meteorological sensors on the Chilean Navy tsunami warning buoy at 20°S, 75°W; this tsunami warning installation was installed in 2006 with WHOI meteorological sensors on the surface buoy and ocean sensors on the mooring line. The deployment marked the beginning of a growing partnership between the ORS project and SHOA. We serviced self-recording ASIMET modules on the tsunami buoy and temperature and temperature/salinity recorders on the buoy's mooring line (Fig. II-2).

Figure II-2: Chilean Navy (SHOA) DART buoy equipped with WHOI meteorological sensors. Shown here the nternally recording sensor modules being recovered and replaced with fresh modules in October 2007.

Task III: NTAS Site:

The Northwest Tropical Atlantic Station (NTAS) project for air-sea flux measurement was conceived in order to investigate surface forcing and oceanographic response in a region of the tropical Atlantic with strong SST anomalies and the likelihood of significant local air-sea interaction on seasonal to decadal time scales. The strategy is to maintain a meteorological measurement station at approximately 15° 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* in April 2007 in order to retrieve the existing mooring (NTAS-6, deployed 25 February 2006) and replace it with a new mooring (NTAS-7). 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-7 mooring was deployed on 19 April 2007 and the NTAS-6 mooring was recovered on 24 April. 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 very good, with all meteorological sensors showing complete records except for wind, for which one system had 97% return. Since the second system had a complete wind record, no data will be missing in the final (combined) data set.

The 2007 NTAS cruise represented the second year of collaboration with the National Data Buoy Center (NDBC) and the first year of collaboration with the

Meridional Overturning Variability Experiment (MOVE). NDBC operations included servicing sensors and electonics on the 41041 "Middle Atlantic" buoy (Fig. III-1), recovery of a subsurface telemetry mooring deployed in 2006 at the 41042 site, and deployment of a replacement mooring at the same site. The MOVE effort involved deployment of four Pressure/Inverted Echo Sounders (PIES; Fig. III-1). Three PIES were deployed at sites between Guadeloupe and the NTAS mooring, and one was deployed southeast of Barbados. Three Argo floats were deployed during the cruise at the request of NOAA AOML. A novel drifter designed by J. Boyle of W. Connecticut State U. to measure heat transfer across the air-sea interface was deployed in the vicinity of the NTAS buoy as part of an engineering field test.

Figure III-1. NDBC personnel in the midst of servicing operations on the 6-meter NOMAD buoy at Station 41041 (left). Deployment of Pressure/Inverted Echo Sounder (PIES) sensor by C. Begler of Scripps as part of MOVE operations (right).

A unique aspect of the NTAS-7 cruise was an Education and Outreach program done in cooperation with the Joint Oceanographic Institutions (JOI). JOI Program Assistants Jessica Sharoff and Karinna Sjo-Gaber created a "live", interactive web site documenting the seagoing experience. The site had content for media, museums, teachers, and elementary to high school students. The outreach effort was successful, with an estimated 2,300 first-time visitors to the site during the cruise, along with 4 press releases, 4 newspaper articles, 15 web links from other sites, and an article in WHOI's online magazine *Oceanus*. The site was archived at JOI after the cruise, and can be viewed at http://joiserver.joiscience.org/mission1551.

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

and are shared with the Baseline Surface Radiation Network (BSRN) and the GEWEX (Global Energy and Water Cycle Experiment) Radiation Panel.

A major engineering initiative this year was the implementation of an inductive telemetry system on the NTAS mooring to collect and telemeter data in near-real time from subsurface instruments. An electro-mechanical (EM) interface was developed (Fig. III-2), including a specially designed universal joint, a six-meter electro-mechanical "compliant section", and a wire coupling assembly with a bell mouth and socket to accept a specially terminated shot of 7/16" jacketed mooring wire. A communications subsystem was developed to support inductive telemetry. The system was built around an ASIMET controller board, and included a Seabird Inductive Modem and a custom built Iridium communication module. The controller polls addresses on the inductive loop and places sensor data, obtained at 5 to 15 minute intervals, in a buffer. After 4 hours the Iridium module obtains the buffered data, creates and logs 4 one-hour averages, formats the averages as a Short Burst Data (SBD) message, and sends the SBD message via Iridium.

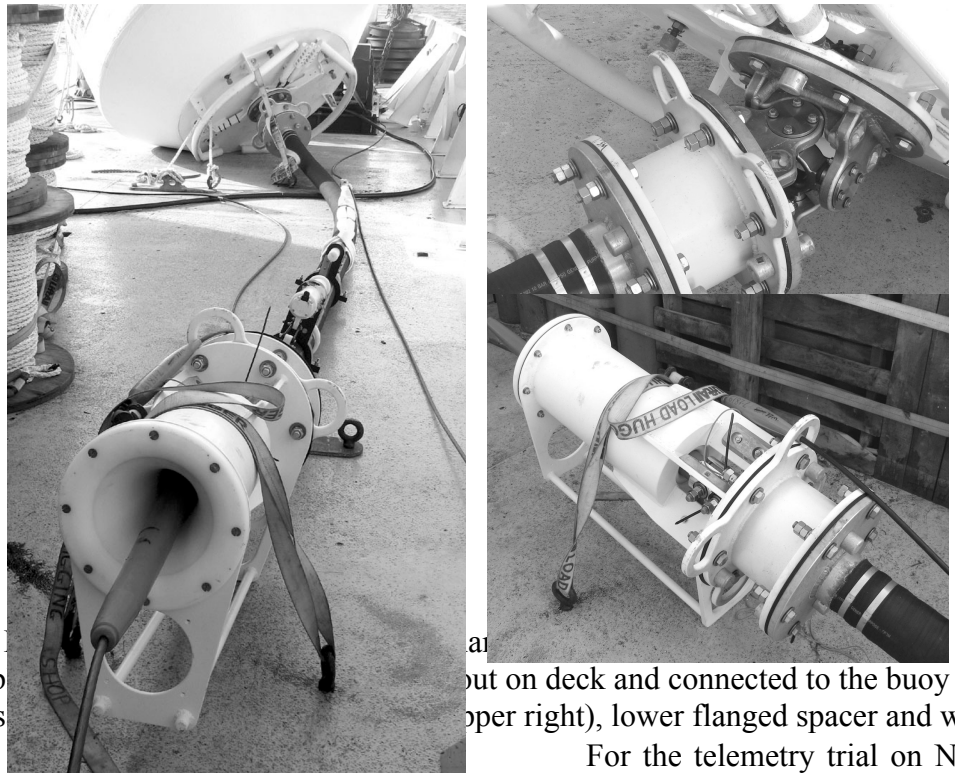


Figure I ar
assemb ut on deck and connected to the buoy (left),
univers per right), lower flanged spacer and wire-

For the telemetry trial on NTAS-7, the mooring line was outfitted with four instruments from the UOP inventory which contained inductive modems: Three Seabird SBE-37s at 25, 45 and 65 m and a Sontek Argonaut current meter 14 m. The telemetered message is a subset of the data returned from inductive polling. For example, only temperature and conductivity (later converted to salinity) are transmitted from the SBE-37s, and the Argonaut data record is reduced to just 8 variables. The inductive coupler on the current meter failed soon after deployment, but temperature and salinity data are being obtained routinely and are available from the UOP web site. (Fig. III-3).

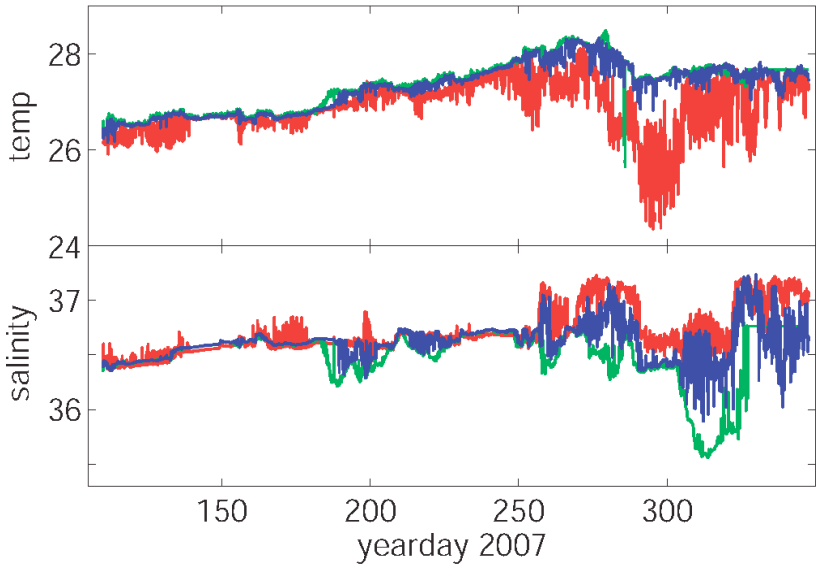


Figure III-3. NTAS-7 subsurface temperature (upper) and salinity (lower) at 25 m (red), 45 m (green), and 65 m (blue) depth from inductive telemetry system (obtained and plotted in December 2007 from the UOP web site).

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 2007 on the U. Hawaii ship *Kilo Moana*. The field work was done in cooperation with Roger Lukas and other HOT investigators from U. Hawaii. In preparation for this cruise, three ASIMET systems were

assembled and tested. The WHOTS-4 mooring was deployed on 25 June 2006 and the WHOTS-3 mooring was recovered on 28 June. The period between deployment and recovery was dedicated to a comparison of the two buoy systems, with the shipboard system as an independent benchmark. The standard *Kilo Moana* meteorological sensors were complemented by installation of a UOP AutoIMET system similar to that used on Volunteer Observing Ships. Data return from the two WHOTS-3 ASIMET systems was very good, with only one significant failure – one of the precipitation sensors failed four days prior to deployment. The remaining sensors operated for the full 368 day deployment.

The WHOTS-2 and WHOTS-3 moorings were used as test-beds for Iridium data telemetry systems developed under the ORS Engineering, Oversight and Data task. Both systems performed well, and the electronics from WHOTS-2 were used as the basis for the NTAS-7 subsurface telemetry system. The electronics deployed on WHOTS-3 will be dedicated to an NTAS-8 subsurface telemetry implementation. Thus, the WHOTS-4 buoy reverted to standard Argos telemetry without an Iridium system.

Commercial bird barrier strips were installed on the WHOTS-3 buoy to reduce data contamination and sensor shadowing due to birds and their accompanying guano deposition. Evaluation of the buoy prior to and after recovery indicated that the prevention efforts were largely successful, little evidence of birds having perched on the on the tower and sensors. The same barrier strips were installed on the WHOTS-4 buoy.

In cooperation with C. Sabine and S. Maenner of PMEL, and with the assistance of D. Sadler (U. Hawaii), a pCO2 system was incorporated in the WHOTS-4 buoy (Fig IV-1).

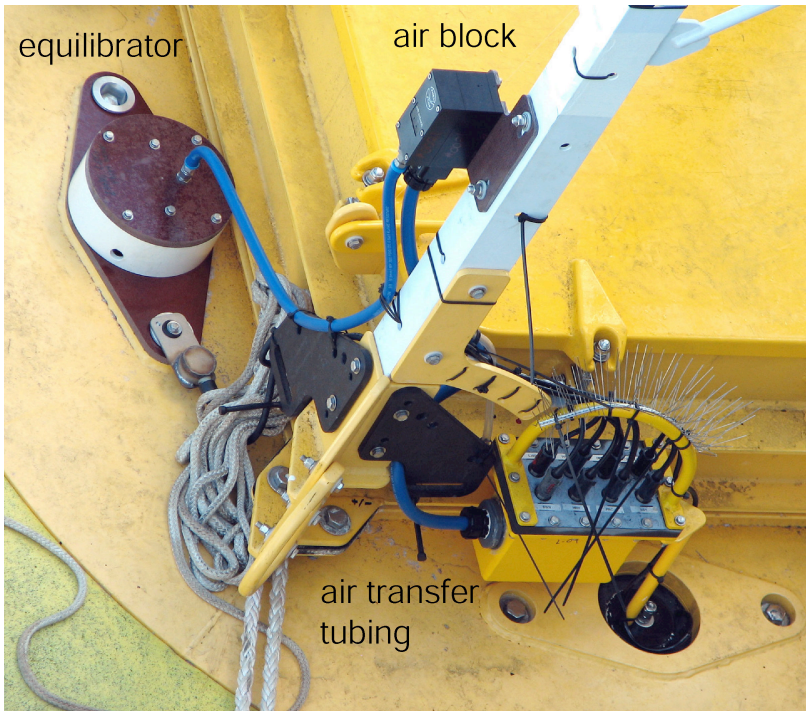


Figure IV-1. Principal external components of pCO2 system on the WHOTS-4 buoy. The equilibrator tube extends through a hole in the foam hull into the water below. Air transfer tubing within a protective conduit (blue) connects the equilibrator to the air block and the air block to instrumentation inside the buoy well.

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

Publications and Reports:

Bigorre, S. R. Weller, J. Lord, S. Whelan, N. Galbraith, D. Wolfe, L. Bariteau, V. Ghate, U. Zajaczkovski, A. Vera, S. Maenner, and B. Hoyt, 2007. Stratus Ocean Reference Station (20°S, 85°W), Mooring Recovery amd Deployment Cruise, R/V *Romald H. Brown*, Cruise 06-07, October 9 – October 27, 2006. *Woods Hole Oceanogr. Inst. Tech. Rept. WHOI-2007-01*, 154 pages.

Colbo, K. and R. A. Weller, 2007: The accuracy of the IMET sensor package. *J. Atmos. Oceanic Technol.*, in press.

Colbo, K and R. A. Weller, 2007: The variability and heat budget of the upper ocean under the Chile-Peru stratus. *J. Mar. Res*., in press.

Colbo, K., R. Weller, J. Lord, J. Smith, P. Bouchard, C. Fairall, D. Wolfe, E. Serpetzoglou, A. G. V. Tisandie, J. F. S. Bustos, F. Bradley, and J. Tomlinson 2005: Stratus Ocean Reference Station (20° S, 85° W), Mooring Recovery and Deployment Cruise: R/V *Ronald H. Brown* Cruise 12-04, December 5 – December 23, 2004. Woods Hole Oceanogr. Inst. Tech. Rept., WHOI-2005-06.

Cronin, M. F., N. A. Bond, C. W. Fairall, and R. A. Weller, 2006: Surface Cloud Forcing in the East Pacific Stratus Deck/Cold Tongue/ITCZ Complex. *J. Climate*, **19**, 392-409, doi: 10.1175/JCLI3620.1.

Cronin, M. F., N. Bond, C. Fairall, J. Hare, M. J. McPhaden, R. A. Weller. Enhanced oceanic and atmospheric monitoring underway in Eastern Pacific. EOS, Transactions, AGU, 83(19), pages 205, 210-211, 7 May 2002.

Goldsmith, R.A. and A.J. Plueddemann, 2002. Moored buoy site evaluations, *Marine Geography*, J. Breman, Ed., ESRI Press, pp 73-77.

Hutto, L., R. Weller, J. Lord, J. Smith, P. Bouchard, C. Fairall, S. Pezoa, L. Bariteau, J. Lundquist, V. Ghate, R. cstro, and C. Cisternas, 2006: Stratus Ocean Reference Station (20° S, 85° W), Mooring Recovery and Deployment Cruise: R/V *Ronald H. Brown* Cruise 05-05, September 26 – October 21, 2005. *Woods Hole Oceanogr. Inst. Tech. Rept., WHOI-2006-06*.

Hutto, L., R. A. Weller, J. Lord, J. Smith, J. Ryder, N. Galbraith, C. Fairall, S. Stalin, J. C. Andueza and J. Tomlinson, 2004. Stratus Ocean Reference Station (20° S, 85° W), Mooring Recovery and Deployment Cruise: *R/V Revelle* Cruise Dana 03, November 10 – November 26, 2003. *Woods Hole Oceanogr. Inst. Tech. Rept., WHOI-2004-04*.

Hutto, Lara, Robert A. Weller, Jeff Lord, James Ryder, Alice Stuart-Menteth, Nancy Galbraith, Paul Bouchard, Jenny Maturana, Oscar Pizarro, and Jaime Letelier, 2003. Long-Term Evolution of the Coupled Boundary Layers (Stratus) Mooring Recovery and Deployment Cruise Report R/V *Melville*. *Woods Hole Oceanogr. Inst. Tech. Rept.,* WHOI-2003-02, UOP-2003-01.

Lucas, Lisan E., Bryan S. Way, Robert A. Weller, Paul R. Bouchard, William M. Ostrom, Albert S. Fischer, Carlos F. Moffat, Wolfgang Schneider, Melanie R. Fewings, 2001. Long-Term Evolution and Coupling of the Boundary Layers in the Stratus Deck Regions of the Eastern Pacific (STRATUS). *Woods Hole Oceanogr. Inst. Tech. Rept.,* WHOI-2001-04, UOP-2001-01.

Plueddemann, A.J., R.A. Weller, R. Lukas, J. Lord, P.R. Bouchard and M.A. Walsh, 2006. WHOI Hawaii Ocean Timeseries Station (WHOTS): WHOTS-2 Mooring Turnaround Cruise Report. *Woods Hole Oceanogr. Inst. Tech. Rept., WHOI-2006-08,* 67 pp.

Plueddemann, A.J., W.M. Ostrom, N.R. Galbraith, P.R. Bouchard B.P. Hogue, B.R. Wasnewski and M.A. Walsh, 2006. The Northwest Tropical Atlantic Station (NTAS): NTAS-4 Mooring Turnaround Cruise Report. *Woods Hole Oceanogr. Inst. Tech. Rept., WHOI-2006-09,* 65 pp.

Plueddemann, A.J., W.M. Ostrom, N.R. Galbraith, J.C. Smith, J.R. Ryder, J.J. Holley and M.A. Walsh, 2003. The Northwest Tropical Atlantic Station (NTAS): NTAS-3 Mooring Turnaround Cruise Report, *Woods Hole Oceanogr. Inst. Tech. Rept., WHOI-2003-04,* 69 pp.

Plueddemann, A., 2003, In-situ meteorology from the Northwest Tropical Atlantic Station, *Proc. U.S. CLIVAR Atlantic Conf.*, Wash, DC, pp 9-13.

Plueddemann, A.J., W.M. Ostrom, N.R. Galbraith, P.R. Bouchard, G.H. Tupper, J.M. Dunn and M.A. Walsh, 2002. The Northwest Tropical Atlantic Station (NTAS): NTAS-2 Mooring Turnaround Cruise Report, *Woods Hole Oceanogr. Inst. Tech. Rept., WHOI-2002-07,* 68pp.

Plueddemann, A.J., N.R. Galbraith, W.M. Ostrom, G.H. Tupper, R.E Handy, and J.M. Dunn, 2001. The Northwest Tropical Atlantic Station (NTAS): NTAS-1 Mooring Turnaround Cruise Report. *Woods Hole Oceanogr. Inst. Tech. Rept., WHOI-2001-07,* 55 pp.

Upper Ocean Processes Group, 2007. Oceanscience Underway CTD. *UOP Technical Note,* December 2007, http://uop.whoi.edu/techdocs/TN-Dec07.pdf

Upper Ocean Processes Group, 2007. Inductive telemetry for UOP Ocean Reference Station moorings, *UOP Technical Note,* August 2007, http://uop.whoi.edu/techdocs/TN-telemetry-NTAS-Aug07.pdf

Vallée, C., K Huang, and R. Weller, 2002. Long-Term Evolution and Coupling of the Boundary Layers in the Stratus Deck Regions of the Eastern Pacific (STRATUS) Data Report. *Woods Hole Oceanogr. Inst. Tech. Rept., WHOI-2002-06*, UOP-2002-03.

Vallée, C., R. A. Weller, P. R. Bouchard, W. M. Ostrom, J. Lord, J. Gobat, M. Pritchard, T. Westberry, J. Hare, T. Uttal, S. Yuter, D. Rivas, D. Baumgardner, B. McCarty, J.

Shannahoff, M.A. Walsh, and F. Bahr, 2002. Long-Term Evolution of the Coupled Boundary Layers (STRATUS) Mooring Recovery and Deployment Cruise Report, NOAA Research Vessel *R H Brown*, Cruise RB-01-08, 9 October – 25 October 2001. *Woods Hole Oceanogr. Inst. Tech. Rept.,WHOI-2002-02*, UOP-2002-01.

Whelan, S.P., R.A. Weller, R. Lukas, F. Bradley, J. Lord, J. Smith, F. Bahr and P. Lethaby and J. Snyder, 2007. WHOI Hawaii Ocean Timeseries Station (WHOTS): WHOTS-3 Mooring Turnaround Cruise Report, *Woods Hole Oceanogr. Inst. Tech. Rep.* WHOI-2007-03, 103 pp.

Western Boundary Time Series in the Atlantic Ocean.

Molly Baringer, Christopher Meinen and Silvia Garzoli
NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

PROJECT SUMMARY

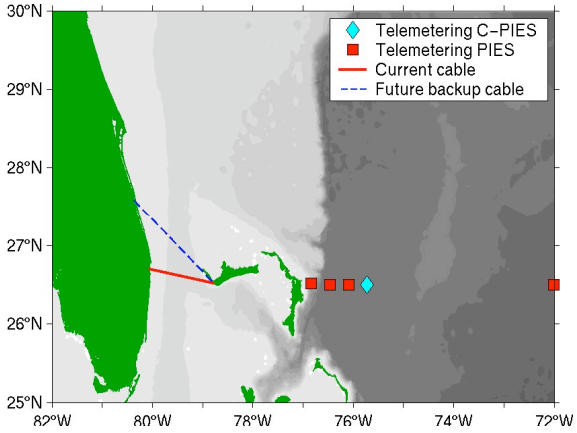


Figure 1: *Observational components of the Western Boundary Time Series project in the North Atlantic.*

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

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

This project consists of two components to monitor the western boundary currents in the subtropical Atlantic: *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.

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 25 years of daily mean voltage-derived transports have been obtained for the Florida Current using out-of-service and in-use cables spanning the Straits of Florida. The cable voltages can be converted to physically meaningful transport estimates i.e., intensity of the flow, using electromagnetic induction theory. These transport measurements contain interannual and decadal changes on the order of 10% of the long-term mean transport, and during some periods the decadal changes track the North Atlantic Oscillation Index. The strong correlation of Florida Current transport variability with the North Atlantic Oscillation, 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, provided sufficient ship-time is available.

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 26.5ºN. Events such as the intense convection period in the Labrador Sea and the renewal of classical Labrador Sea Water in the 1980's are clearly reflected in the cooling and freshening of the Deep Western Boundary Current waters off Abaco with the arrival of a strong chlorofluorocarbon pulse approximately 10 years later. This data set is unique in that it is not a single time series site but in instead a time series of transport

sections, including high quality water property measurements, of which very few are available in the ocean that approach even one decade in length. This task includes annual cruises across the DWBC to measure the water mass properties and transports. With the cooperation of University of Miami researchers (Drs. Johns and Beal) and funding from the National Science Foundation for the Meridional Overturning Circulation and Heat transport Array (MOCHA), and sharing of personnel and ship-time resources, these cruises have been conducted twice each year since 2004. This level of sampling will continue through 2014.

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

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

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

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

provide a measurement of the primary routes of ocean heat, carbon, and fresh water transport and hence include the bulk of the Meridional Overturning Circulation.

Project web sites:

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

FY 2007 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 although during the period from January 2007 through October 2007 there was a slight low-bias in the cable transports relative to the dropsonde cruise data. This offset has been traced to a failure in one of the anodes (Earth ground), and it is expected that the data will be completely recoverable with additional processing during early FY08. 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.

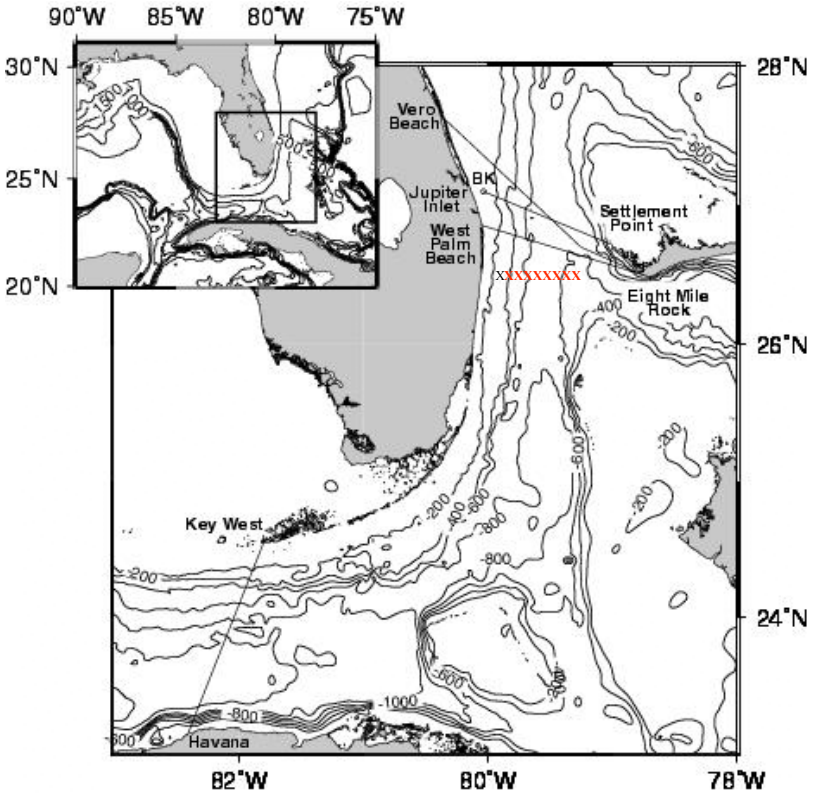


Figure 2: *Location of submarine telephone cables (solid black) and nine stations (red) occupied during calibration cruises.*

FY 2007	FY 2006	FY 2005	FY 2004	FY 2003
100% Return[1]	98% Return	88% Return[2]	87% Return[2]	89% Return

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).

Planned Cruise	FY 2007	FY 2006	FY 2005	FY 2004	FY 2003
1	13-Dec-2006	11-Nov-2005	19-Nov-2004 dropsonde lost	9-Dec-2003	clearance problems
2	15-Dec-2006	17-Nov-2005	29-Nov-2004	16-Dec-2003	clearance problems
3	29-Mar-2007	2-Feb-2006	17-Feb-2005	9-Jan-2004	equipment problems
4	19-Jun-2007	14-Mar-2006	24-Feb-2005 section incomplete due to weather	13-Jan-2004 – GPS failure on two stations	18-Mar-03
5	10-Jul-2007	27-Mar-2006	18-May-2005	7-May-2004	June 7, 2003 – dropsonde failure
6	5-Sep-2007, dropsonde electronics problems	22-Jun-2006	21-Jun-2005 dropsonde lost	24-May-2004	no dropsonde
7	27-Sep-2007	30-Jun-2006	31-Aug-2005	Jun 7, 2004	no dropsonde
8	Postponed to early FY08 due to weather	20-Jul-2006		Jun 11, 2004	no dropsonde
9		15-Sep-2006		Aug 24, 2004	
10				1-Sep-2004 - GPS antenna failure	
	87.5% successful	100% successful	50% successful[3]	100% successful[4]	13% successful[5]

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

[1] Presuming January – September time period is successfully corrected for the small observed bias, which is likely.
[2] Note a pair of hurricanes destroyed the recording equipment and damaged the infrastructure in Sept. 2004.
[3] Final cruise postponed to next fiscal year due to weather/scheduling issues. Two dropsonde instruments were lost due to equipment malfunctions. One cruise was only partially completed due to weather.
[4] Two additional cruises were planned for FY04 due to dropsonde failures in FY03.
[5] Sections missing due to: dropsonde failure (4) and clearance problems (2).

Small charter boat calibration trips

A total of seven 1-day surveys were conducted using a dropsonde profiler (the final cruise has been postponed to the next 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. Some electronic failures of the dropsonde resulted in some lost data for one cruise. This equipment failure, plus the retirement of key engineering staff has necessitated the complete redesign of the dropsonde system to be completed in FY2008.

Full Water Column calibration cruises:

Two-day cruises on RV Walton Smith are generally scheduled four times per year. Sufficient ship-time funds for only three of the cruises were provided in FY07 (the final cruise of FY07 was postponed into early FY08 due to ship availability). All cruises include nine stations with full water column CTD, lowered ADCP, and continuous shipboard ADCP. The station locations are shown in Figure 2. Table 3 below includes the cruise dates and number of water samples taken for oxygen concentration (O2) and salinity (S).

FY2007		FY2006		FY 2005		FY 2004		FY 2003	
Date	Samples	Date	Samples	Date	Samples	Date	Samples	Date	Samples
Dec 2006	13-14, 60 O2, 48 S	Dec 2005	14-16, 60 O2, 48 S	Dec 2004	3-4, 58 O2, 44 S	Jan 2003	8-9, 55 O2, 46 S	Nov 2002	19-20, 43 O2, 44 S
Jun 2007	28-29, 60 O2, 48 S	Jan 2006	29-31, 60 O2, 48 S	Jun 2005	3-4, 58 O2, 45 S	May 2004	6-7, 47 O2,	Mar 2003	21-22, 59 O2, 49 S
Oct 2007	4-5, 60 O2, 48 S	Jun 2006	25-27, 60 O2, 48 S	Jul 2005	11-12, 58 O2, 45 S	Jul 2004	4-5, 56 O2,	July 2003	2-3, 56 O2, 46 S
		Sep 2006	18-19, 68 O2, 48 S	Nov 2005	20-23, 60 O2, 48 S	Aug 2004	27-28, 55 O2, 42 S	Oct 2003	2-3, 57 O2, 43 S
75% of planned cruises completed		100% of planned cruises completed		100% of planned cruises completed		100% of planned cruises completed		100% of planned cruises completed	

Table 3: Cruise dates for 2-day calibration cruises on the R/V Walton Smith. Note FY2005: The last cruise planned for in FY 2005 was postponed for early FY 2006. Note FY 2007: Only three cruises were completed due to lack of ship-time charter funds.

Task 2: Deep Western Boundary Current time series

Two full-water-column cruises of CTD, lowered ADCP, and shipboard ADCP were conducted during FY07 within the Florida Straits and east of Abaco Island, Bahamas on the NOAA Ship Ronald H. Brown. 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 22-Apr 10, while the second took place during Sept 11-22. (The latter cruise was scheduled to begin on Sep 8, however the Brown was unable to sail on time due to an insufficient number of engineers for safe manning of the vessel; this delay in sailing resulted in the loss of about 10% of the planned CTD stations.) 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 (CPIES). Four additional temporary IES/PIES sites were deployed during the September 2006 cruise between the permanent sites to test array resolution.

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

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.

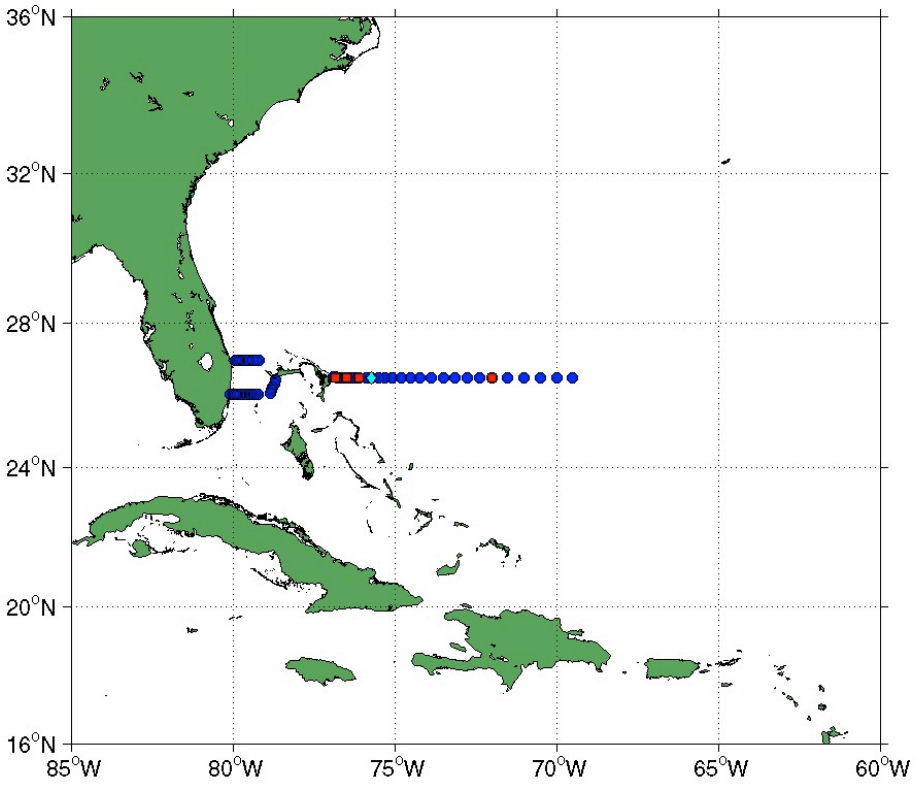


Figure 3: *Approximate locations of full water column hydrographic stations sampled on the two cruises in FY 2005. Blue circles denote CTD sites. Red squares denote PIES moorings and the cyan diamond denotes a CPIES mooring. Note the five CTD stations east of 72°W were not occupied during the September 2007 cruise due to time constraints that resulted from a departure delay as a result of insufficient staffing for the Brown engineering department.*

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 (Meinen et al., 2004; 2006). 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 (Meinen et al., 2006) utilizing the PIES/C-PIES mooring data has shown that there is no 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.

3. Two publications in the journal ***Science*** appeared using the data from this program in concert with the observations made by the international MOCHA/RAPID array (Cunningham et al., 2007; Kanzow et al., 2007). These papers demonstrated that the first year of data from the joint US/UK array is capturing the net MOC transport across 26.5°N with a high degree of accuracy. The papers also demonstrate that the MOC is more highly variable at time scales of weeks to months than had previously been assumed.

Peer Reviewed Publications:

1. Cunningham, S. A., T. Kanzow, D. Rayner, M. O. Baringer, W. E. Johns, J. Marotzke, H. R. Longworth, E. M. Grant, J. J-M. Hirschi, L. M. Beal, C. S. Meinen, and H. L. Bryden, "Temporal Variability of the Atlantic Meridional Overturning Circulation at 26.5°N", *Science*, 317, 935, DOI: 10.1126/science.1141304, 2007.
2. Kanzow, T., S. A. Cunningham, D. Rayner, J. J-M. Hirschi, W. E. Johns, M. O. Baringer, H. L. Bryden, L. M. Beal, C. S. Meinen, and J. Marotzke, "Observed flow compensation associated with the Meridional Overturning at 26.5°N in the Atlantic", *Science*, 317, 938, DOI: 10.1126/science.1141293, 2007.
3. Baringer, M. O., and C. S. Meinen, "The Meridional Overturning Circulation and Oceanic Heat Transport", in "Supplement to State of the Climate in 2006", A. Arguez, ed., *Bulletin of the American Meteorological Society*, 88(6), s1-s135, doi:10.1175/BAMS-88-6-StateoftheClimate, 2007.
4. 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.

Abstracts/Meeting Proceedings:

1. Bryden H., S. Cunningham, T. Kanzow, D. Rayner, M. Baringer, W. Johns, J. Marotzke, H. Longworth, E. Grant, J. Hirschi, L. Beal, C. Meinen, Circulation at 25°N, 2007. (IUGG XXIV General Assembly, July 2-13, Perugia, Italy.)
2. Cunningham, S. A., T. O. Kanzow, D. Rayner, M. O. Baringer, W. E. Johns, J. Y. Marotzke, J. J.-M. Hirschi, L. M. Beal, C. S. Meinen, H. L. Bryden, H. R. Longworth, E. M. Grant, Monitoring the Atlantic Meridional Overturning Circulation at 26.5°N, 2007. (RAPID Annual Meeting 2007, June 18-20, Plymouth, United Kingdom.)
3. Kanzow, T., S. Cunningham, J. Hirschi, D. Rayner, J. Marotzke, C. Meinen, W. Johns, M. Baringer, H. Bryden, L. Beal, Origin and dynamics of intra-seasonal variability of the meridional overturning circulation observed at 26.5°N, 2007. (RAPID Annual Meeting 2007, June 18-20, Plymouth, United Kingdom.)
4. Rayner, D., S. A. Cunningham, T. O. Kanzow, H. L. Bryden, J. J.-M. Hirschi, J. Y. Marotzke, W. E. Johns, L. M. Beal, M. O. Baringer, C. S. Meinen, Status of

the transatlantic mooring array at 26.5°N - Spring 2007, 2007. (RAPID Annual Meeting 2007, June 18-20, Plymouth, United Kingdom.)

5. Meinen, C. S., M. O. Baringer, and S. L. Garzoli, Variability in the Atlantic Meridional Overturning Circulation: Latest results from the NOAA Western Boundary Time Series project, 2007. (Office of Climate Observations Annual Review, June 5-7, Silver Spring, Maryland.)
6. Meinen, C. S., D. S. Luther and M. O. Baringer, Evolution of the Gulf Stream structure, transport, and vertical coherence from the Straits of Florida to the Southeast Newfoundland Ridge, 2007. (Office of Climate Observations Annual Review, June 5-7, Silver Spring, Maryland.)
7. Johns, W., S. Cunningham, T. Kanzow, H. Bryden, J. Marotzke, M. Baringer, L. Beal, C. Meinen, J. Hirschi, D. Rayner, Variability of the Atlantic meridional overturning circulation during 2004-2005 as observed from the 26°N RAPID-MOC Array, 2007. (AGU Joint Assembly, May 22-25, Acapulco, Mexico.)
8. Meinen, C. S., D. S. Luther, and M. O. Baringer, Evolution of the Gulf Stream structure, transport, and vertical coherence from the Straits of Florida to the Southeast Newfoundland Ridge, 2007. (EGU General Assembly, April 15-20, Vienna, Austria.)
9. Baringer, M. O., Heat transport variations in the subtropical North Atlantic. (Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.)
10. 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.)
11. 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.)
12. Cunningham, S., 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. (Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.)
13. Bryden, H. L., T. O. Kanzow, H. R. Longworth, S. A. Cunningham, M. O. Baringer, L. M. Beal, J. J.- M Hirschi, W. E. Johns, C. S. Meinen, J. Marotzke, D. Rayner, Variability in the Atlantic meridional overturning circulation at 25°N. (Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.)
14. 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. (Rapid Climate Change International Conference, October 24-27, 2006, Birmingham, United Kingdom.)

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

Meghan F. Cronin, Christian Meinig, and Christopher L. Sabine
NOAA Pacific Marine Environmental Laboratory, Seattle, WA

PROJECT SUMMARY

Overview

As a NOAA contribution to the global network of Ocean Sustained Interdisciplinary Timeseries Environmental Observatory (OceanSITES) timeseries reference stations, in June 2004, an air-sea flux buoy site was launched at 144.5°E, 32.3°N in the Kuroshio Extension recirculation gyre. The mooring, referred to as the Kuroshio Extension Observatory (KEO), carries a suite of sensors to monitor carbon dioxide uptake; air-sea heat, moisture and momentum fluxes; temperature and salinity to 500 m, and near-surface currents. The Kuroshio Extension (KE) is the North Pacific's western boundary current after separating from the coast near 35°N. The KE jet carries approximately 140 milllion cubic meters per second (140 Sv) of warm water eastward into the North Pacific. About a third of this is forced by the basin-scale winds and associated with the wind driven Sverdrup transport and the other 90 Sv is due to a tight recirculation gyre whose size varies on seasonal-decadal time scales.

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

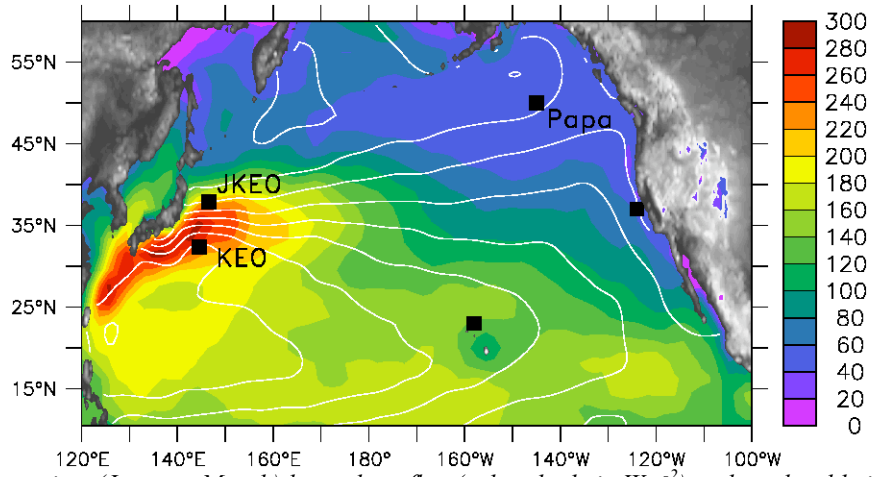


Fig 1. Climatolocial wintertime (January-March) latent heat flux (color shade in Wm^{-2}) and sea level height (white contours) for the North Pacific. Squares indicate OceanSITES time series reference sites.

The ocean has particularly strong influence on the atmosphere in the KE region because the

heat content is extraordinarily large on the southern side of the KE jet. Indeed, wintertime cooling erodes the seasonal 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. In addition to having some of the largest air-sea heat fluxes found in the entire basin, the region also characterized by intense carbon dioxide uptake. Without uptake of significant amounts of the CO_2 released from human activity, climate change would be much more pronounced. The KE region thus plays a critical role in the global carbon cycle and climate system.

The KEO project is working closely with international research communities. The KEO site was within the study domain of the 2-year (June 2004 - June 2006) National Science Foundation-funded Kuroshio Extension System Study (KESS). KEO data are being combined with KESS data for a series of analyses on mode water formation, seasonal thermocline erosion, recirculation gyre strength, and air-sea interaction associated with summer typhoons and winter storms in the region. KEO data also serve the operational community and are being used as reference time series to assess numerical weather prediction analyses and reanalyses (e.g. Kubota et al. 2007).
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 success of the KEO time series reference site, PMEL has been approached by several other potential partners. In particular, the KEO project is working closely with scientists from the Japan Agency for Mrin-Earth Science and Technology (JAMSTEC) and in February 2007, JAMSTEC Institute of Observational Research for Global Change (IORGC) in partnership with NOAA PMEL successfully deployed a NOAA-designed KEO mooring (JAMSTEC-KEO or "JKEO") north of the Kuroshio Extension jet. In addition, as part of a NSF-funded Carbon and Water Cycle project led by biogeochemical scientists from the University of Washington, in June 2007 PMEL deployed a KEO-type air-sea flux mooring at the Ocean Weather Station Papa in the Northeast Pacific. The Papa and JKEO offshoots of KEO represent an expansion of the OceanSITES array. Meteorological data from all three sites are available in near-real time through the Global Telecommunication System (GTS). Near-realtime surface and subsurface data as well as delay mode data are available in ascii and the standard OceanSITES netcdf formats through website browsers and anonymous ftp sites. 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/. For JKEO, see: http://www.jamstec.go.jp/iorgc/ocorp/ktsfg/data/jkeo/ and for Station Papa see: http://www.pmel.noaa.gov/stnP/.

FY2007 ACCOMPLISHMENTS

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

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

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

The KEO mooring was redeployed using charter funds for two sea-days on the R/V Kaiyo in September 2007. As shown in Fig. 2, the KEO-2007 mooring has a larger 2.5 m discus hull than the original retrofit TAO buoy. The new hull will make the buoy more robust to the drag caused by the strong full-water column currents. In addition, the larger hull will enable the buoy to carry a larger payload, for example, a wave sensor package. The upgrade also included a barometric pressure sensor and duplicate meteorological sensors on an independent data logger and telemetry system (Fig. 2). Given the high number of typhoons in this region, this redundancy is prudent. Other changes to the KEO-2007 design included reduction in the overall number of subsurface modules.

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 (20 on KEO-2007) depths down to 525m (12 of which are telemetered), subsurface salinity at 15 (11 on KEO-2007) depths down to 525m (5 [6 on KEO-2006] of which are telemetered), and pressure at 7 (5 on KEO-2007) 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

During the 2006 typhoon season, KEO-2006 survived three class 5 typhoons. The only damage was the loss of the relative humidity sensor during the passage of third typhoon SOULIK on October 17 2006. Although we were very pleased by the minimal damage, because the KEO-2006 deploy did not have duplicate meteorological sensors, the loss of the critical relative humidity sensor meant that the air-sea heat fluxes could not be computed. Thus arrangements were made for a repair. We are very grateful to JAMSTEC, the Fisheries Agency of Japan, and the R/V Shoyo-maru for their assistance in repairing this sensor in January 2007, and the OAR Office of International Activities for their help in arranging the repair. The KEO data provide an unparalleled in situ data set for typhoon (hurricane) studies.

On April 17, 2007, the buoy broke away from its mooring line and began drifting eastward in the fast-moving Kuroshio Extension. Because the buoy position is monitored on a daily basis, the project was immediately alerted of the failure and therefore able to make arrangements for a rescue. Within several weeks, the R/V Melville was able to recover the KEO buoy and its surface instrumentation. Since the high-resolution meteorological data are stored in the surface electronics "tube", the recovery included not only valuable equipment, but also valuable data. Investigation of the recovered hardware and data revealed very strong evidence that the buoy had been picked up out of the water and damaged, likely by a fishing vessel. The KEO project is extremely grateful to the chief scientist (Dr. Craig Lee), the science party, and the captain and crew of the R/V Melville for the rescue.

Data returns are reported in Table 1 for the full 365 days of FY07 as well as for the 202 days total that a mooring was on site; this includes 198 days in the water before the cable parted (4/17/2007) and four days of the KEO-2007 real-time data in FY07. KEO2007 was deployed on 9/26/2007. Prior to the 9/26/2007 redeployment date, data return is based upon all sensors mounted on the mooring. FY07 data returns are noticeably worse than FY06 numbers due to the break and the loss of all instruments below the bridle. Since there are many subsurface temperature and salinity modules that do not report in real-time, these numbers are a significantly skewed by the loss of the subsurface instruments. In addition, several sensors (current meters in particular) had telemetry problems. We are investigating other current meter manufacturers. As with previous years, the meteorological sensors had a very good data return when the mooring was in the water.

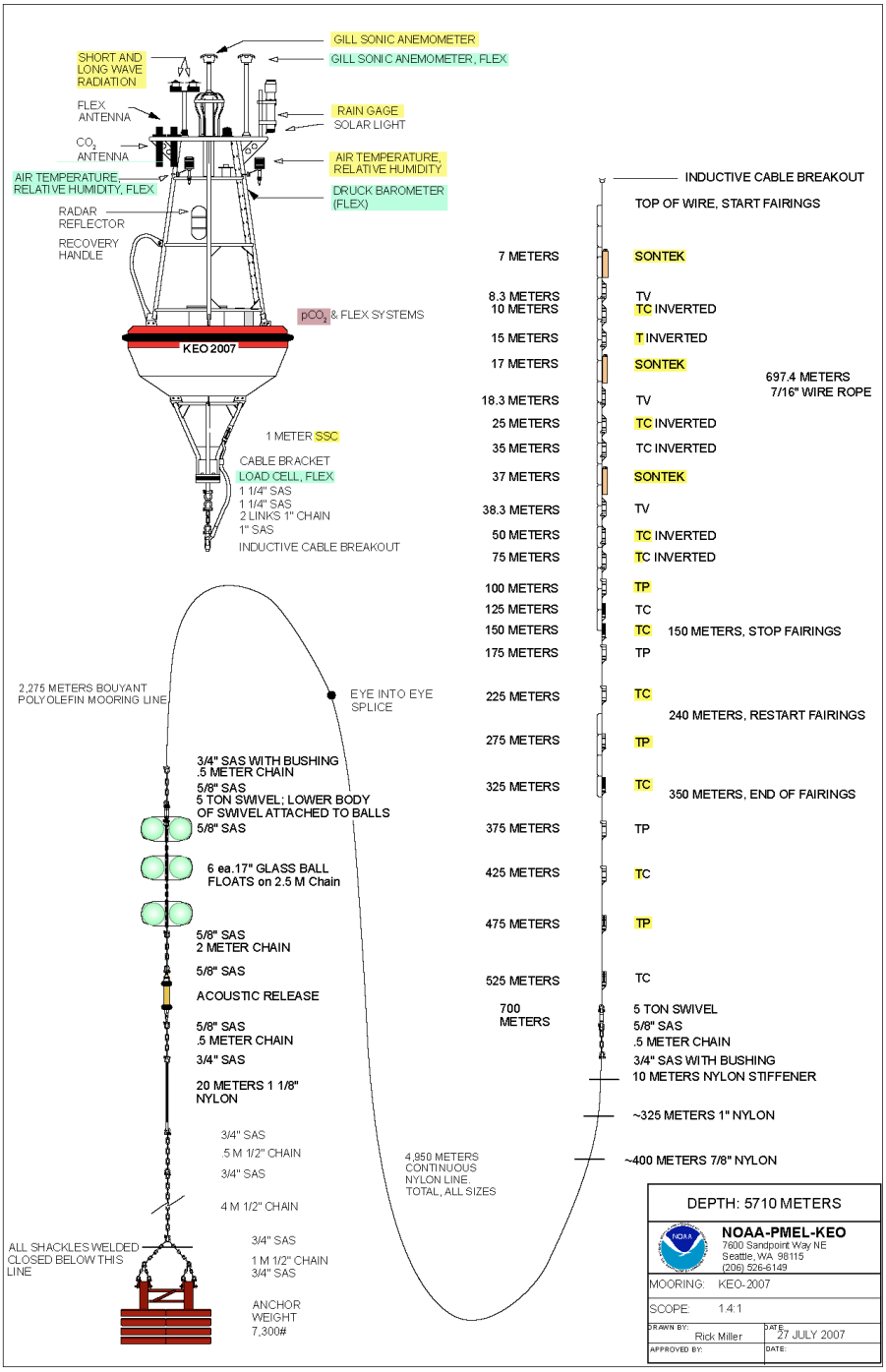


Fig. 2. KEO diagram. Telemetered measurements from three independent systems are highlighted in yellow(ATLAS); green (FLEX) and pink (pCO_2).

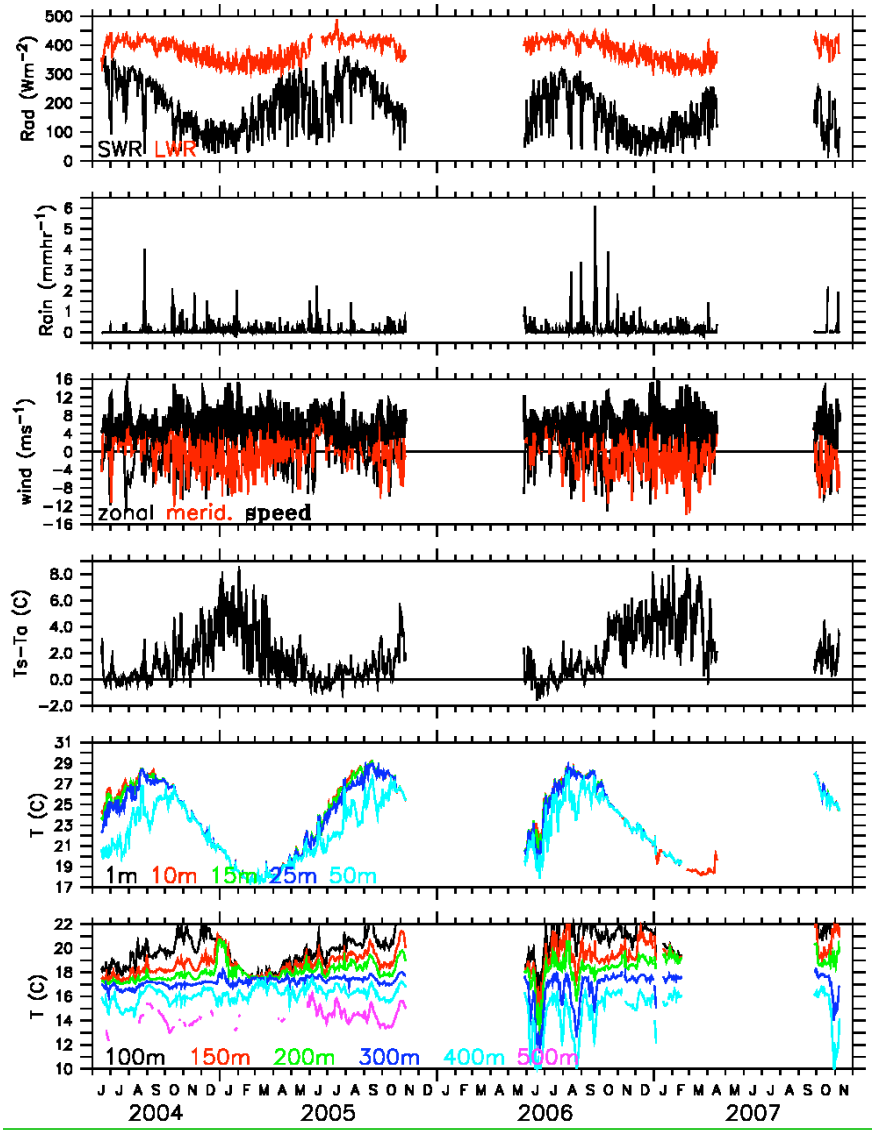


Fig. 3. Select KEO daily-averaged data through November 1 2007.

	FY07 Data Returns	
	full year	**while on site**
Meteorological variables	51%	93%
Upper ocean temperature	16%	29%
Upper ocean salinity	16%	28%
Near surface currents	10%	17%

Table 1. KEO data return for FY07 based upon daily-averaged delay-mode data and telemetered daily-averaged data after Sep 30, 2007.

The PMEL KEO group has also deployed two other KEO-type flux moorings with pCO_2 systems during FY07: At the JKEO site (38N, 146.5E) north of the KE jet mooring, through a partnership with JAMSTEC; and at station Papa (50N, 145W) in the Northeast Pacific, through a partnership with the University of Washington. The JKEO mooring, deployed in February 2007, is funded by JAMSTEC and operated by PMEL. Its sensor suite is similar to KEO-2006, but with fewer subsurface sensors. In February 2008, the NOAA-designed JKEO mooring is scheduled to be recovered and a JAMSTEC-designed K-TRITON mooring will be deployed that will be operated by JAMSTEC.

The station Papa mooring, deployed in June 2007, is funded through a subcontract on a NSF-funded Carbon and Water Cycle project led by biogeochemical scientists from the University of Washington. Like KEO and JKEO, the station Papa mooring monitors air-sea heat, moisture, momentum and carbon dioxide fluxes, and subsurface temperature, salinity, and currents. In addition it carries a second wind sensor, a barometric pressure sensor, a pH sensor, and two systems which measure O_2 and gas tension, from which the biological CO_2 pump can be inferred. With this suite of sensors, the station Papa mooring can be considered the first Ocean Acidification deep ocean mooring. Longterm funding for the Station Papa air-sea flux mooring still needs to be secured to continue the Papa mooring past the planned final recovery in August 2009.

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

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

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

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

Prior to FY07, the KEO data had 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 a second buoy in the region (JKEO), this decision was reviewed and it was decided that meteorological data from all three sites should be made available through the GTS. This way operational meteorological centers can use all available data in operational weather forecasts. The KEO project strongly believes however that the reference site data should be withheld from reanalysis products so that the products will remain independent of the time series reference site data used to assess them. Each time series reference station has a unique World Meteorological Organization (WMO) identifying number containing the digits "84" for this purpose.

Following the best practices for process studies advocated by the U.S. CLIVAR Process Study and Model Improvement Panel, a consolidated KESS data set is being served through the centralized access point. Thus a duplicate KEO data set for the first two years is also available through the KESS homepage: http://uskess.org/.

All three sites (KEO, JKEO, and Station Papa) can be considered as contributions to the Global Earth Observation System of Systems (GEOSS) and a manuscript describing the strategy of

these moorings has been submitted to the IEEE Systems journal special issue for GEOSS (Cronin et al. 2007).

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

KEO data are a critical component of various scientific studies in progress. In particular, FY07 represents the second year of a 3-year NOAA CLIVAR project titled "Role of Air-Sea Interaction in the Kuroshio Extension Recirculation Gyre", with PIs Cronin and Dr. N. Bond (UW JISAO). In November 2006, both Cronin and Bond participated in the KESS workshop help at the University of Rhode Island. In addition, during FY07, the U.S. CLIVAR working group on Air-Sea Interactions in Western Boundary Currrent regions was initiated (http://usclivar.org/Organization/wbc-wg.html). Both Cronin and Bond are members of this working group and have participated in the monthly teleconferences and at the August 2007 Working Group meeting in Portland OR.

Two KEO analyses are currently in press. Bond and Cronin (2007) analyzed the regional weather and climate patterns associated with anomalously high and low fluxes at KEO. The analysis shows that during the cool season, prevailing winds at KEO are northwesterly and anomalous heat loss by the ocean is associated with increased northerly winds (cold air outbreaks). During summer, on the other hand, prevailing winds switch to be southerly and anomalous cooling tends to occur during enhanced southeasterly winds out of the deep tropics. When the analysis was extended to identify weather patterns associated with anomalous fluxes on seasonal time scales, a surprising result was found. The warm seasons with anomalous heat fluxes tend to have composite patterns similar to the episodic composites, but the cool seasons with anomalous heat fluxes have composite circulation patterns that are weak and little resemble their episodic event counterparts. It's not just a matter of having more or less cold-air outbreaks. Instead, these results suggest that on interannual timescales, the ocean may be playing an important role in determining wintertime heat flux anomalies.

The KEO data have also been used as a time series reference to assess Numerical Weather Prediction (NWP) forecast analyses and reanalyses, and other numerical and satellite products. In particular, Kubota et al. (2007) used the KEO data to assess the radiative and turbulent heat flux fields of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) and NCEP/Department of Energy (DOE) reanalyses (referred to as NRA1 and NRA2) and found that:

- Overall, the NRA latent heat losses were too large relative to KEO. For NRA1, the latent heat bias was 41 W/m^2; for NRA2, the bias was 62 W/m^2 (there was a 21 W/m^2 bias between the two products).
- Although the magnitude of the fluxes had significant biases, the NRA were able to capture many of the synoptic disturbances. The cross-correlation between the KEO latent heat flux and the co-incident NRA latent heat fluxes were greater than 0.9 for both NRA1 and NRA2.
- The bias in the NRA latent heat flux could be reduced significantly by using a more sophisticated bulk algorithm for its heat flux calculations.
- Of all the state variables (SST, humidity, air temperature, wind speed), humidity contributed the largest source of error to the NRA flux. During summer when prevailing winds are from the south (of maritime origin), the NRA humidity is too low, while during the winter when prevailing winds are from the north (of continental origin), the humidity

is too high. Although the prevailing wind systems are well reproduced, the air humidity does not seem to be properly modified by boundary layer effects.

- The NRA SST had significant errors in comparison to KEO measurements. The RMS error in latent heat flux was significantly reduced when the NRA SST was replaced with the Microwave Optimum Interpolation (MWOI) SST, indicating that both reanalyses could be improved by assimilating better SST data.

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

FY07 Bibliography

Bond, N. and M. F. Cronin, 2007: Regional weather patterns during anomalous air-sea fluxes at the Kuroshio Extension Observatory (KEO). *J. Climate*, In Press.

Cronin, M. F., C. Meinig, C. L. Sabine, H. Ichikawa, and H. Tomita, 2007: Surface mooring network in the Kuroshio Extension. *Submitted to IEEE Systems*.

Donohue, K. A., and colleagues, 2007: An integrated system study of the Kuroshio Extension. *Submitted to EOS.*

Kubota, M., N. Iwabe, M. F. Cronin, and H. Tomita, 2007: Surface heat fluxes from the NCEP/NCAR and NCEP/DOE reanlayses at the KEO buoy site. *J. Geophys. Rev*., In Press.

7. List of Acronyms

CLIVAR	Climate Variability and Predictability
DOE	Department of Energy
FLEX	Flexible Low-powered Electronics for ocean eXeriments
GTS	Global Telecommunications System
IORGC	Institute of Observational Research for Global Change
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
JKEO	JAMSTEC-Kuroshio Extension Observatory
KE	Kuroshio Extension
KEO	Kuroshio Extension Observatory
KESS	Kuroshio Extension System Study
K-TRITON	Kuroshio-TRIangle Trans-Ocean buoy Network
MWOI	MicroWave Optimum Interpolation
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NRA1	NCEP/NCAR Reanalysis
NRA2	NCEP/DOE Reanalysis
NSF	National Science Foundation
NWP	Numerical Weather Prediction
OceanSITES	Ocean Sustained Interdisciplinary Time series Environmental Observatory
PMEL	Pacific Marine Environmental Laboratory
RMS	Root-Mean-Square
SST	Sea Surface Temperature
STMW	Subtropical Mode Water
TAO	Tropical Atmosphere and Ocean
UW	University of Washington
WMO	World Meteorological Organization

Southern Ocean Modern Observations/Weddell Sea Moorings

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 (CDW) enters the Weddell Gyre to the east of the Greenwich Meridian. As it traverses the gyre, it feeds bottom water-forming processes on the continental shelves, and interacts with floating ice shelves to produce a variety of Weddell Deep and Bottom water types.

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

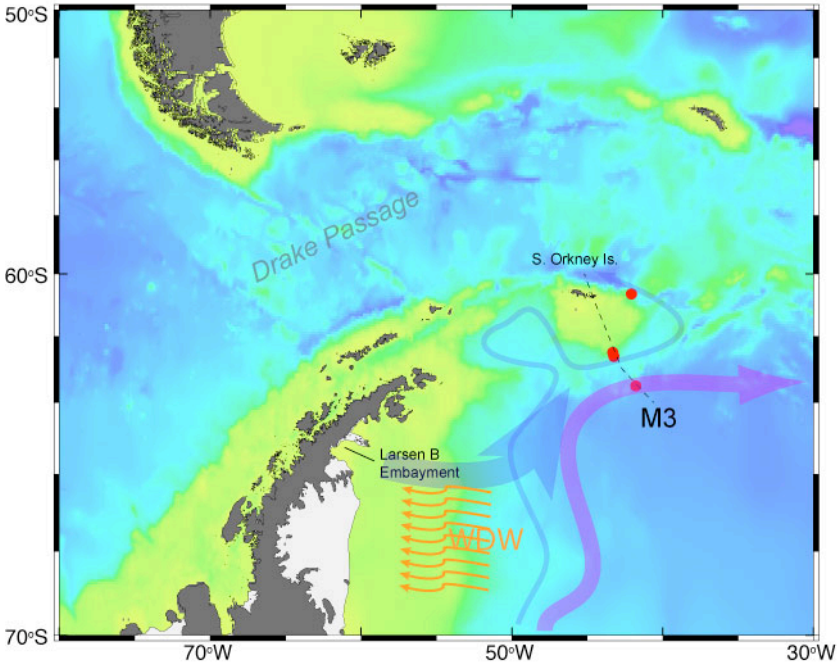


Figure 1. Location of the Weddell Sea moorings (red dots) and repeat CTD/Tracer line (dashed line). Shown schematically are the pathways of deep and bottom waters formed by interaction of WDW with continental and ice shelf waters.

First installed in April 1999, the moorings 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, oceanographic stations to collect profiles of conductivity, temperature and tracers (CTD/tracer) are occupied at the mooring sites and at stations distributed along a line between the mooring locations (Figure 1). The cost of ship time devoted to the mooring work and associated CTD/tracer stations, typically 3 to 5 days, has been supported by funding from OCO.

Accomplishments

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. One member of our group joined a BAS cruise on board RRS Ernest Shackleton in February-March 2007, during which the BAS and LDEO ARCHES moorings were serviced. The newest of the ARCHES moorings, M_4, within the trough feeding Weddell water into the Scotia Sea is now part of an enhanced array of moorings in the trough, using LDEO and BAS equipment to better resolve this branch of bottom water spreading. The configuration of the joint LDEO-BAS array of moorings is shown in Figure 2. Under the cooperative arrangement, the ship time was provided at no cost to OCO in 2007.

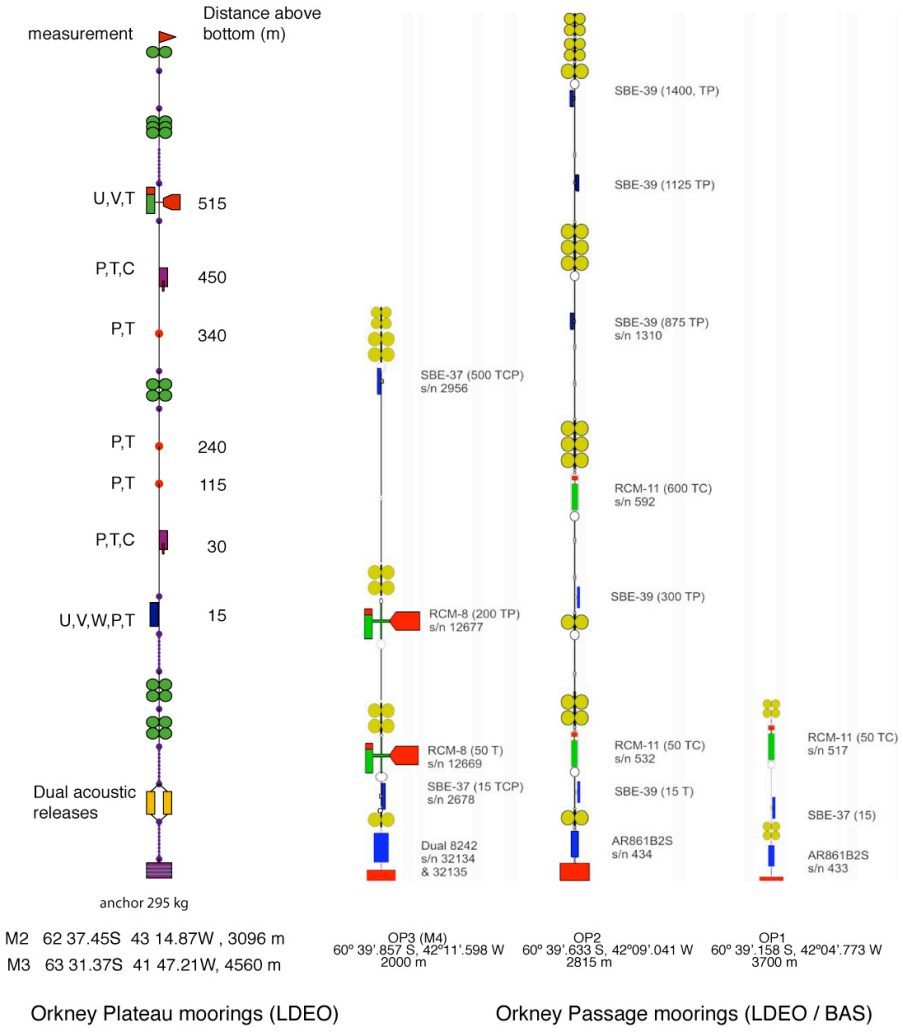


Figure 2. Weddell moorings - configurations and locations.

Recovery of mooring M_3 has extended the deep time series to nearly 8 years (Figure 3).

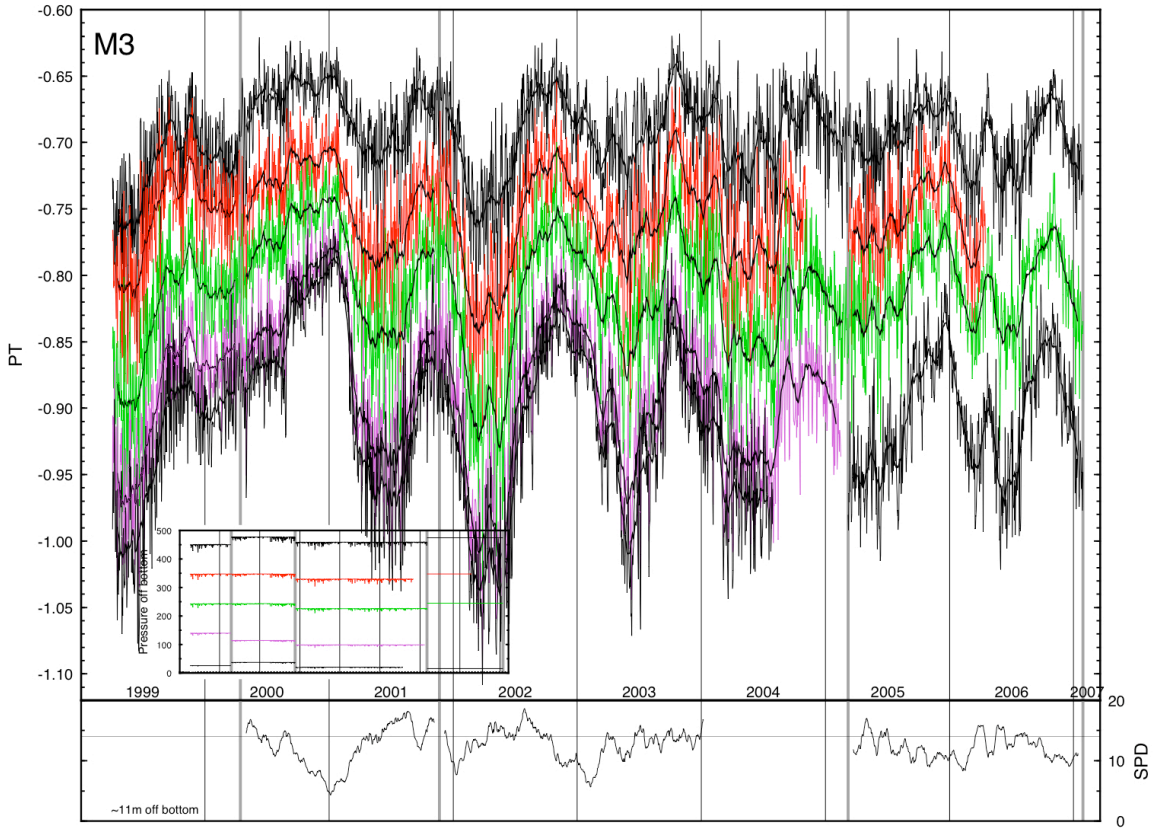


Figure 3. Potential temperature and speed at mooring site M_3

Publications

Meredith M. P., A. Naveira Garabato, A. L. Gordon, and G. C. Johnson (submitted), Evolution of the deep and bottom waters of the Scotia Sea, Southern Ocean, during 1995-2005, *Journal of Climate*.

Monitoring the Indonesian Throughflow in Makassar Strait

Arnold L. Gordon and R. Dwi Susanto
Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY

FY 2007 Progress

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

The ITF amounts to ~12 Sv, 80% of which is channeled through Makassar Strait. The 45 km wide Labani constriction of Makassar Strait near 3°S is an ideal place to measure the bulk of the ITF. There the throughflow was measured during the NSF funded INSTANT program from January 2004 to November 2006, and by the NSF funded Arlindo program from December 1996 to July 1998.

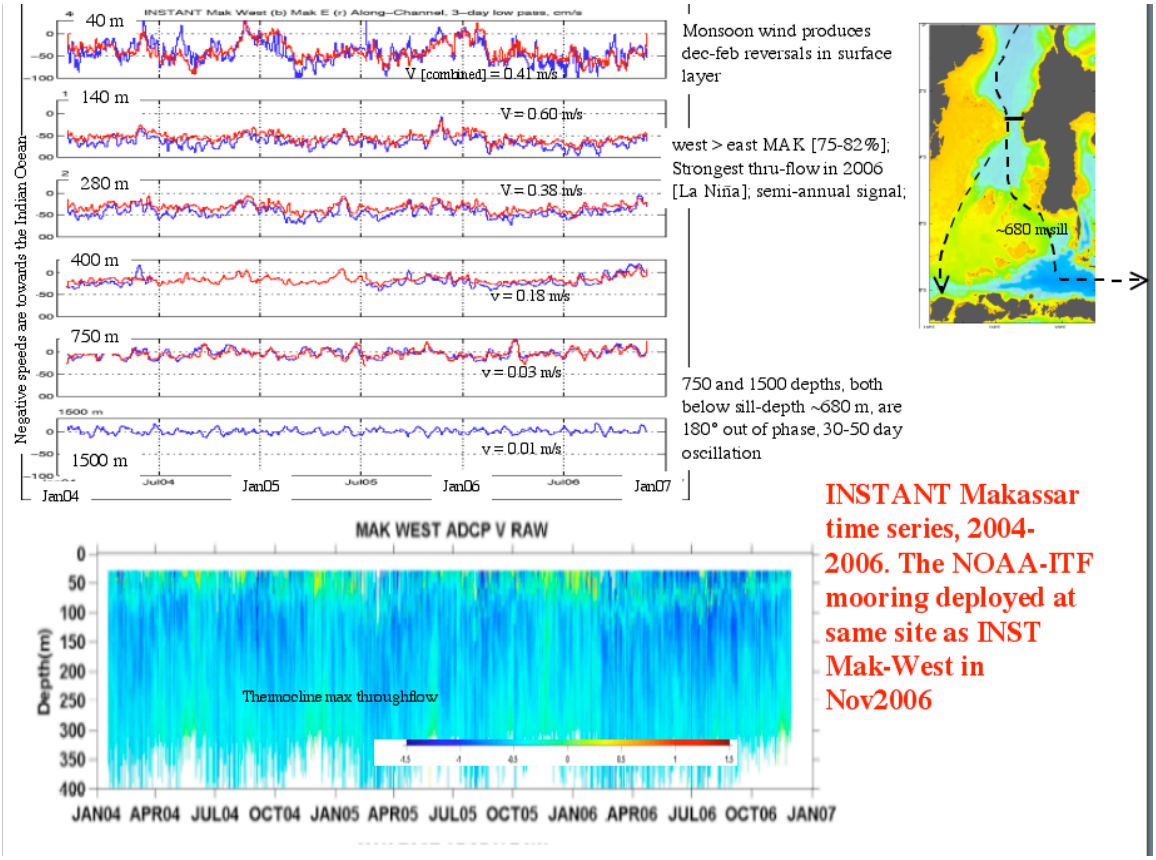


Figure 1 The time series from the ~3 year January 2004- November 2006 INSTANT record in Labani Passage of Makassar Strait. The NOAA-ITF mooring [see figure 2] was deployed in November 2006 at the same site as INSTANT MAK-West [blue line in time series].

Immediately after the INSTANT moorings were recovered in November 2006, with NOAA OCO support, a single mooring at the site of the INSTANT MAK-WEST 2°51.11'S; 118°27.33'E was deployed [Figure 2]. This was done so as not to have a data gap between the INSTANT time series and a long term NOAA OCO sponsored ITF measurement program, hopefully to begin in late 2008. 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. It is important that a long-term time series be based at the MAK-WEST site where we have the proper archived records for it to serve as a reliable indicator of the Makassar and perhaps the entire ITF. The NOAA Makassar mooring will be recovered and redeployed in November 2008, officially beginning the long-term measurement program.

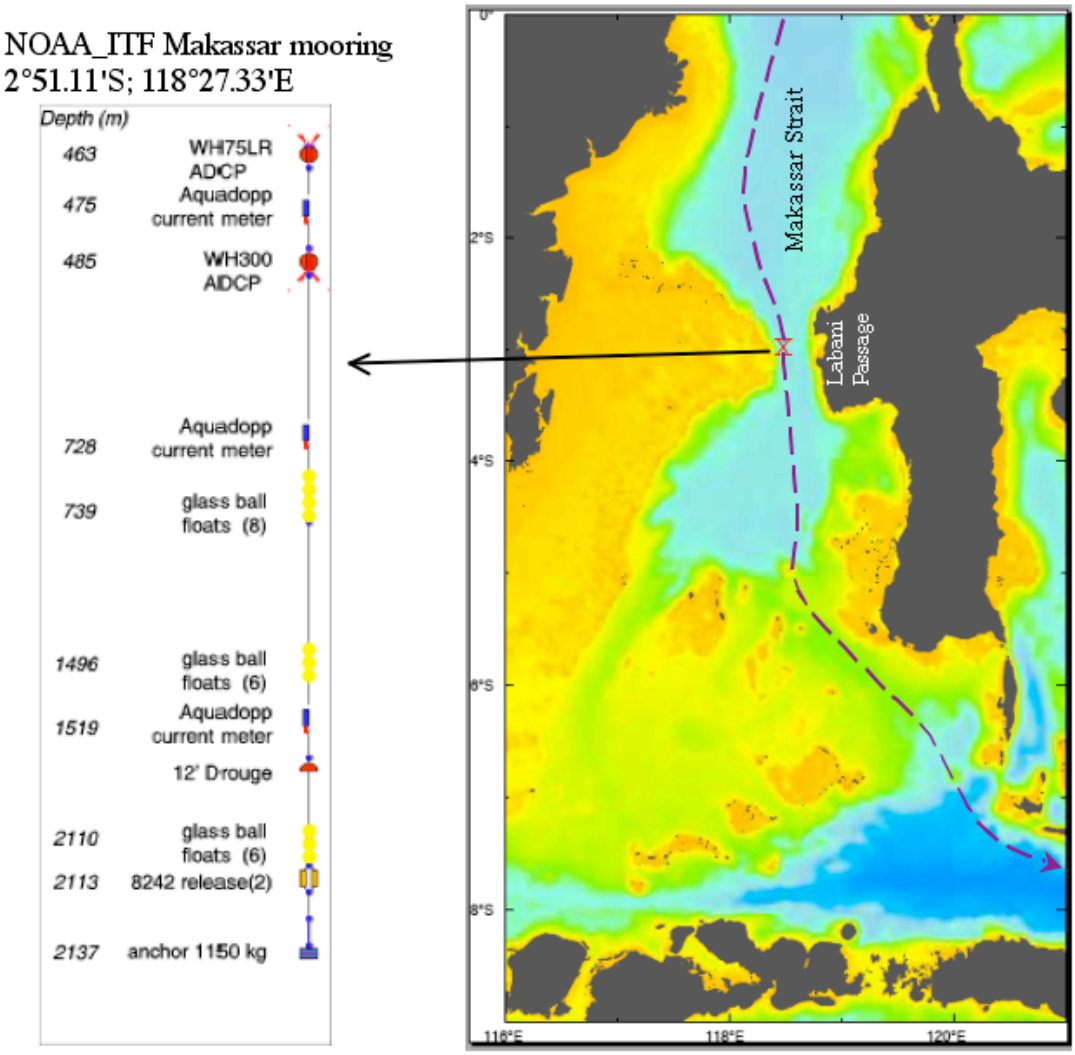


Figure 2: Configuration of the NOAA-ITF Makassar mooring deployed in November 2006 at the Red X in the bathymetry map of Makassar Strait.

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 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 2007 Progress

In the reporting period, the MOVE mooring array was serviced on a German research cruise in December 2006, see map in Figure 1. The prior moorings, all still with German equipment, were recovered, and data were retrieved. The data from the moored instruments are complete and of good quality. Raw data processing has been performed, and scientific data analysis is now possible with the data.

Figure 2 shows a preliminary analysis of the geostrophic transports relative to 5000db, including the entire timeseries at hand to date. Figure 3 contains the upper-ocean (0-1000m) temperature anomalies at mooring M3 from the last deployment period (due to the boundary current there are large mooring subduction/knock-down events).

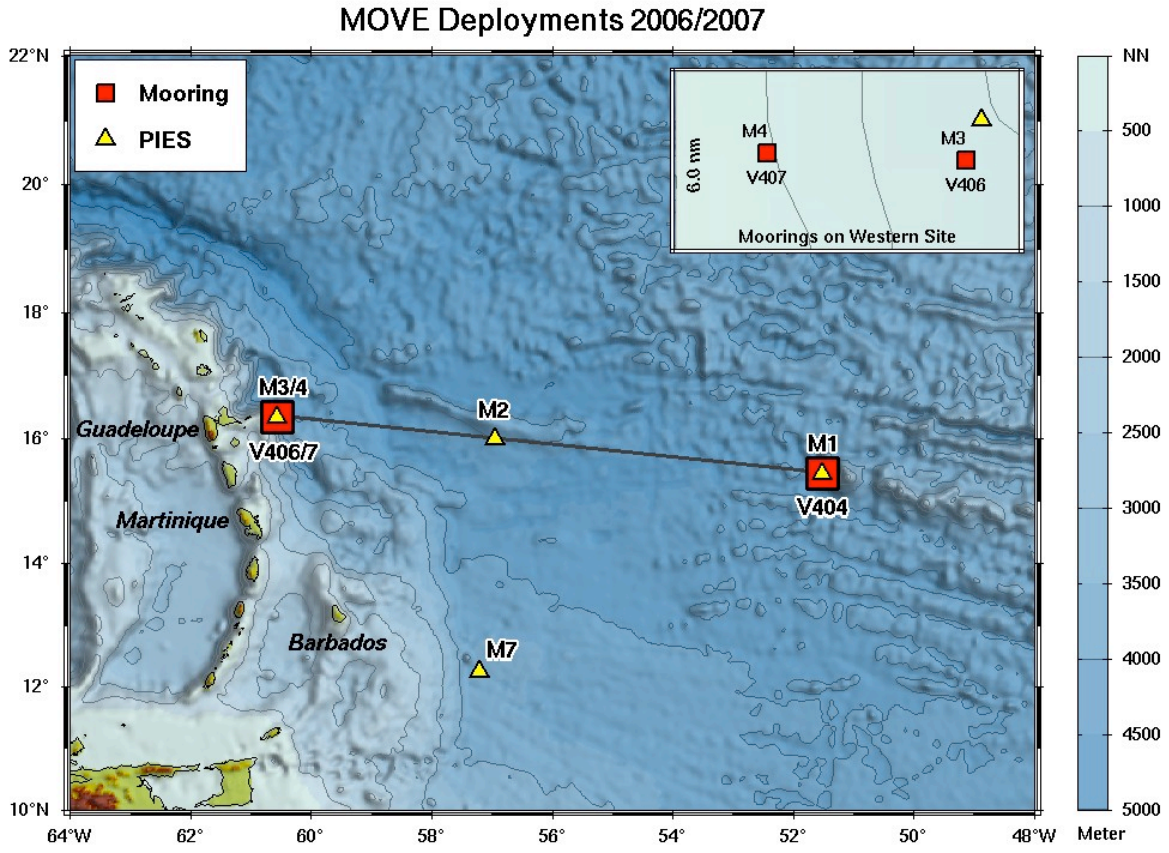


Figure 1: *Map of MOVE moorings M1, M3, M4, and pressure sensors/inverted echosounders (PIES) at locations M1, M2, M3, M7.*

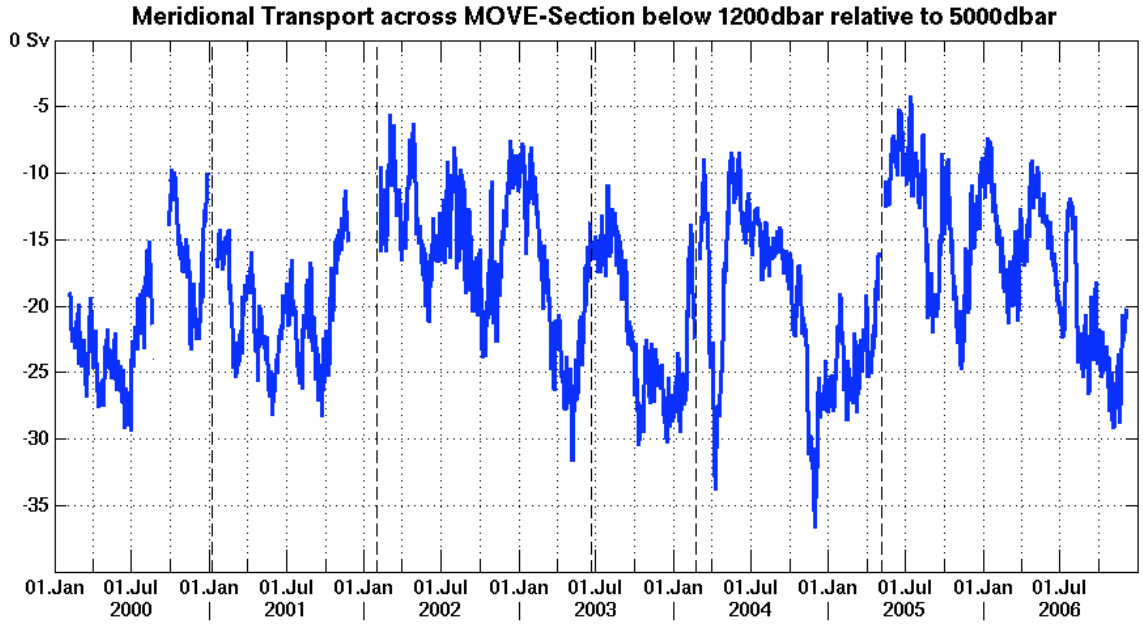


Figure 2: *Timeseries of geostrophic transport between M1 and M3 in the deep water layer (1200-5000db) relative to 5000db. The deployment periods are separated by dashed lines, the last segment represents preliminary data recovered during the reporting period.*

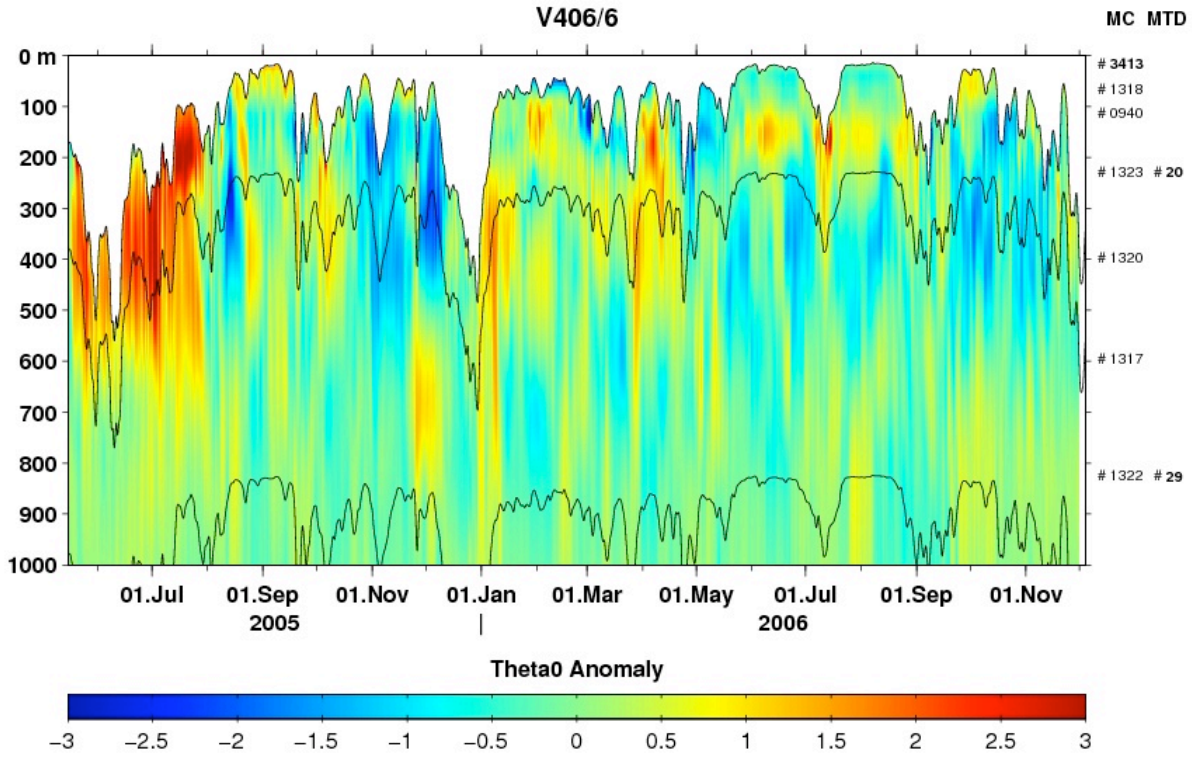


Figure 3: *Potential temperature anomalies in the upper 1000m at mooring M3.*

The moorings were re-deployed during the same cruise in a nearly equivalent configuration, but now with a majority of NOAA funded equipment (but not all). The tables below give information about the moorings deployed and the material contained in them. Much of the items marked as "SIO" were purchased with NOAA funding. The mooring design of mooring M3 shown in Figure 4 gives the typical layout, even though M1 covers only the deep-water layer (and does not reach near the surface like M3).

Mooring Deployments during cruise MSM 04/1, December 2006

Site	*Mooring ID*	*Position*	*Water Depth*	*Depl. Date*
M4	V407/7	16N20.25 60W36.75	3010m	06-Dec-2006
M3	V406/7	16N20.01 60W29.86	4944m	07-Dec-2006
M1	V404/7	15N26.95 51W30.51	4970m	12-Dec-2006

Mooring Instrumentation and Equipment

Site	*Aanderaa RCM*	*Seabird 37 MicroCat*		*Acoustic Release*	*Float, 17" Glass Sphere*	
		inductive	*serial*		*Benthos*	*Nautilus*
M4	4 IFM	-	-	2 SIO	26	10
M3	3 IFM	21 SIO	-	2 SIO	41	24
M1	-	9 SIO	6 IFM	2 IFM	18	26

Each Mooring is equipped with 2 Elkins Titanium swivels, in total 6 swivel are deployed (SIO owned).
Each Mooring has a Top-Float (Aluminum Frame with 2 Benthos Floats), equipped with
- an Argos-Beacon, owned by SIO
- a VHF-Radio-Transmitter, owned by SIO
- a Xenon-Flasher, borrowed from Marfac (SIO)

During the December '06 cruise, it was determined that the inverted echosounders with pressure sensor (PIES) had all stopped recording due to a battery and design flaw by the manufacturer. Most of them could be recovered, since they have a separate battery for the release mechanism. Therefore we participated in the NOAA NTAS cruise in April 2007, and new PIES were then deployed that now have the problem corrected. The table below gives the relevant information for these new PIES which are in the water at present.

PIES Deployments during cruise RB-07-02, April 2007

Site	*PIES s/n*	*Position*	*Water Depth*	*Depl. Date*
M3	197 SIO	16N21.36 60W29.33	4955m	15-Apr-2007
M2	127 IFM	15N59.28 56W56.29	4943m	23-Apr-2007
M1	180 SIO	15N27.04 51W31.62	4965m	24-Apr-2007
M7	128 IFM	12N15.47 57W12.07	4454m	17-Apr-2007

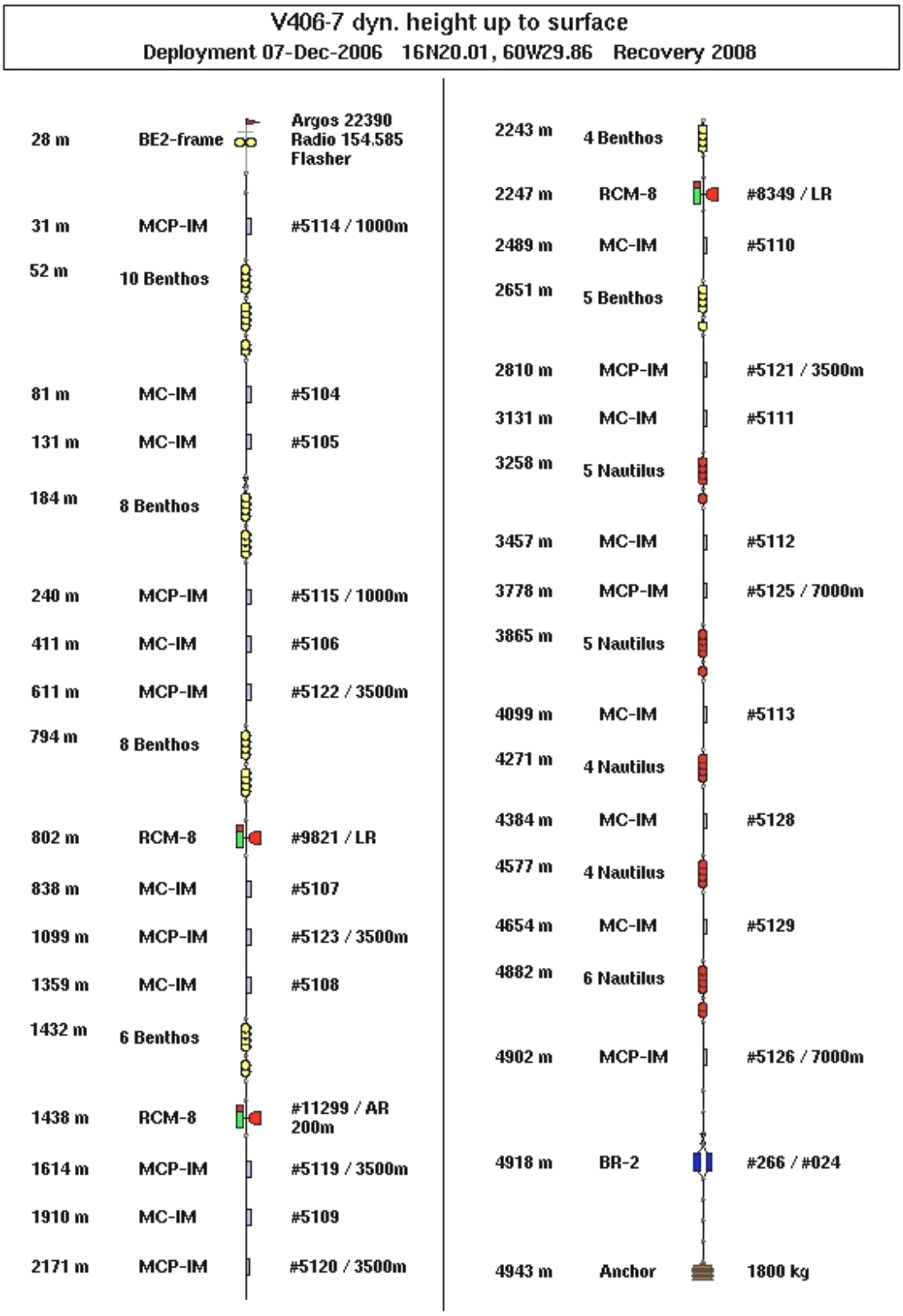


Figure 4: *Design of mooring M3 with each instrument and its depth noted.*

Integrated Boundary Current Observations in the Global Climate System

U.Send, R.Davis, D.Rudnick, P.Niiler, B.Cornuelle, D.Roemmich
Collaborators: S.Gille, N.Schneider, W.Kessler, S.Bograd
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.

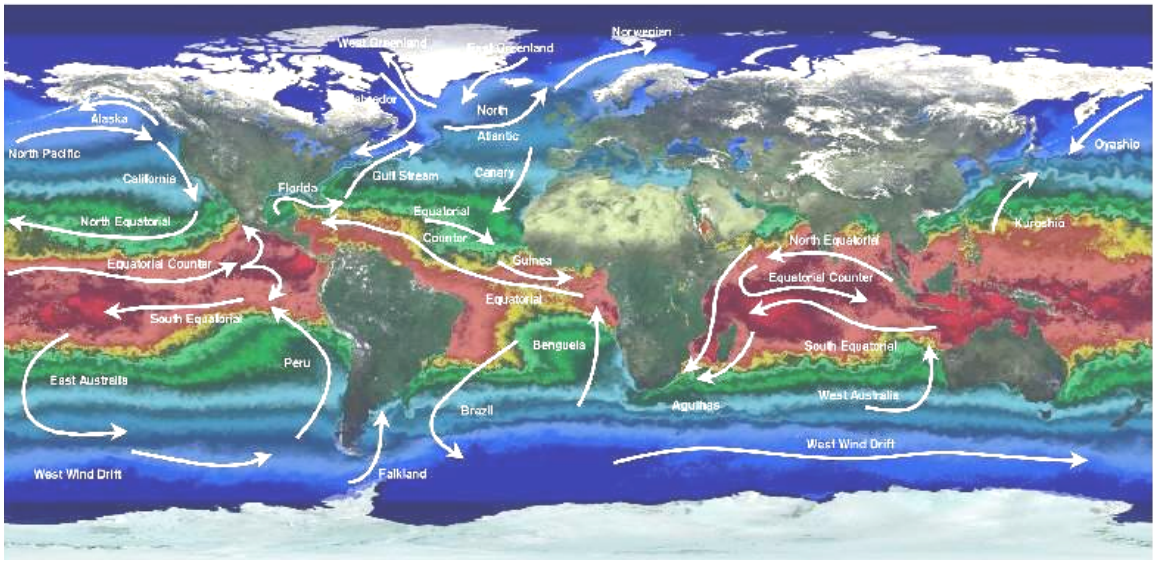
We propose to develop, demonstrate, and implement a system that can fully monitor the intensity (mass and heat transports) of most boundary currents in a sustained and routine mode, delivering indicators about the state of those regimes in near-realtime. To this end we will merge several technologies 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 geostropic 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, implemention of the system in the climatically highly relevant western boundary current of the low-latitude western Pacific is planned (which feeds the Equatorial Undercurrent through the Solomon Sea).

FY 2007 Progress



Task A: Glider Operations in Boundary Current Observing Systems
(Russ E. Davis and Daniel L. Rudnick)

Gliders play two roles within our program to develop techniques for monitoring western boundary currents. In the eventual array, gliders will quantify shallow transport through the section of interest while interrogating deep instrumentation and relaying that data by satellite transmission. While the array technology is being developed and tested, gliders are exploring the western boundary flow toward the equator in the South Pacific where the Boundary Current Array may first be tested. During FY07 we have made good progress on two glider tasks: (1) reconnaissance of the main flows toward the equatorial zone in the western South Pacific and (2) development of an acoustic communication capability for Spray gliders so they can relay to shore data from subsurface instrumentation that has no surface expression.

South Pacific Reconnaissance

The equatorial Pacific is a key climatic region because it is where upper ocean temperature is well enough coupled to the atmosphere that variation of ocean heat content trigger substantial atmospheric interannual variability. While significant predictive skill has been achieved, predictability of equatorial atmospheric variability could potentially be increased if the internal oceanic factors influencing equatorial SST variability were better understood. A majority of the water that feeds the equatorial undercurrent, and thus provides the source waters for equatorial upwelling, comes from the South Equatorial Current (SEC). The SEC feeds the western equatorial zone through complex and poorly understood pathways in the western tropical Pacific including the New Guinea Coastal Current and associated pathways through the Solomon Sea as depicted in Fig. 1. This western boundary complex is a potential target for the first use of the Boundary Current Array technology being developed by CORC.

The reconnaissance task for the Pilot Array addresses the poorly observed connections of the SEC to the equatorial zone using Spray gliders to measure upper-ocean transport in the region and potentially to measure variability of the mass and heat transport between the SEC

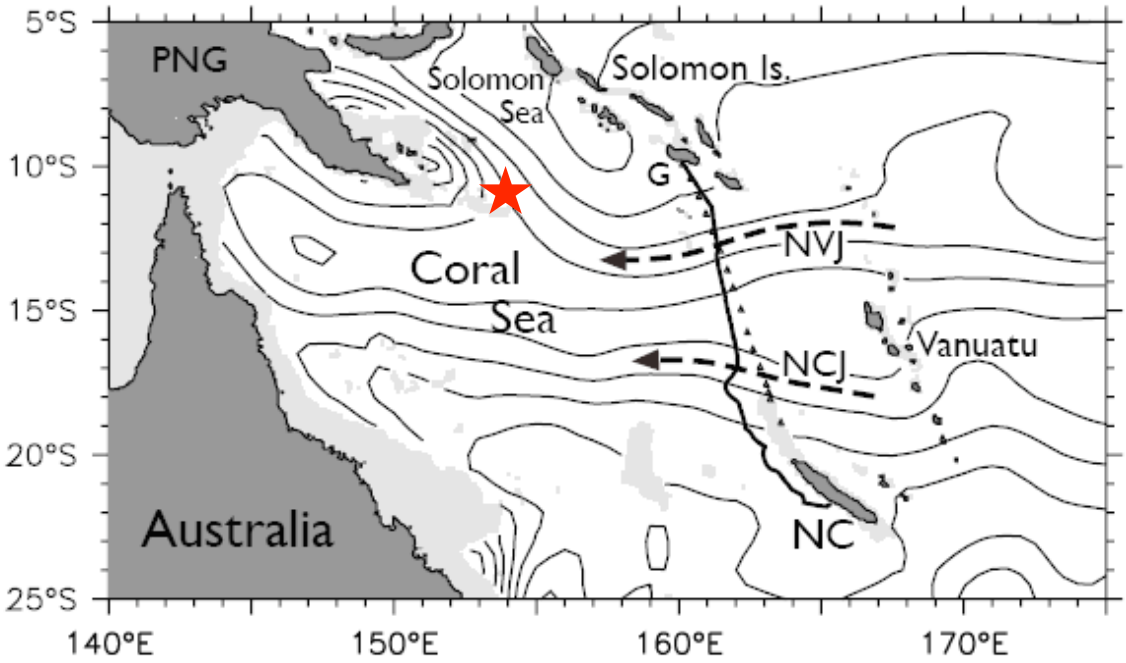


Figure 1: *The Coral and Solomon Seas showing mean flow on the σ_θ =25.5 surface (line contours) and the major land masses (NC=New Caledonia, G=Guadalcanal, the Solomon Islands, and PNG=Papua New Guinea. NCJ and NVJ indicate jets in the South Equatorial Current. The Solomon Sea is the main pathway of this flow to the equator. The line from New Caledonia to Guadalcanal is the path of the first glider crossing. The red star marks the position at the eastern end of the New Guinea continental shelf where a glider was deployed to cross the Solomon Sea to Guadalcanal.*

and the equatorial zone. These gliders cycle vertically between the surface and a depth between 500 and 1000 m. They directly measure horizontal velocity averaged over their operating depth by comparing dead reckoning and actual positions. By measuring temperature and salinity sections, they also measure geostrophic shear which can be referenced with the depth-averaged velocities.

In the reporting period, we have (1) completed and had accepted a paper describing our first glider measurements of the SEC between New Caledonia and Guadalcanal; (2) recovered a second transit from Guadalcanal to New Caledonia; (3) recovered in the Solomon Islands a glider that had crossed the Solomon Sea from New Guinea exploring the potential for gliders to monitor flow toward the equator through the Solomon Sea, and (4) deployed another glider intended to transit from Guadalcanal to New Guinea and return to Guadalcanal

This effort is aimed finding a practical way to monitor mass and heat transport from the SEC to the western equatorial zone where it feeds, and potentially modulates, the thermocline waters that upwell in the equatorial zone, influencing equatorial SST and air-sea coupling in the ENSO cycle. This is a collaboration between SIO (which is responsible for gliders), William Kessler of PMEL (who provides modeling and theoretical expertise), and Lionel Gourdeau of IRD in Noumea (who directs South Pacific operations carried out largely by IRD personnel).

Our first glider section, completed in October 2005, was between Guadalcanal and New Caledonia (the solid line in Figure 1). The results, including confirmation of model-predicted jets near both Guadalcanal and New Caledonia, are reported by Gourdeau, L., W.S. Kessler, R.E. Davis, J. Sherman, C. Maes and E. Kestenare in "Zonal jets entering the Coral Sea" now in press at the *Journal of Physical Oceanography*. The glider measured SEC transport above 600 m (32 Sv) compared well with a hydrographic section taken when the glider section began. We regarded this

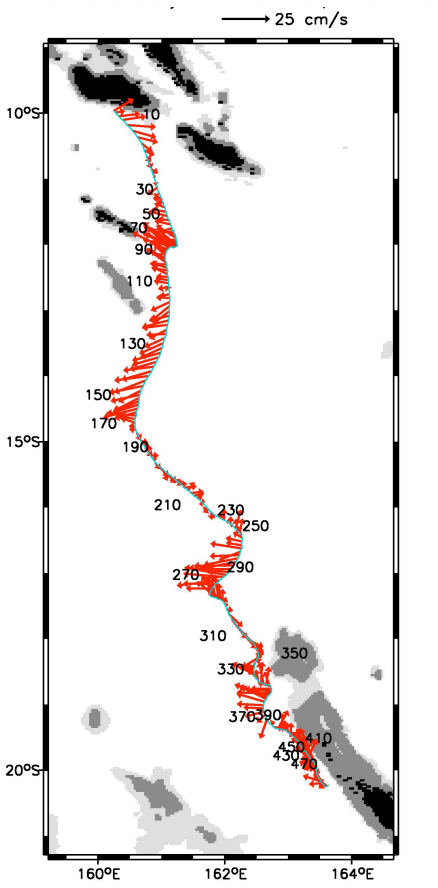


Figure 2: *Trajectory (green line at the base of arrows) and depth-averaged velocity from the surface to 600 m depth (red arrows, scale at the top of the figure). The cruise began in Guadalcanal (north end) on 12 Nov 2006 and was recovered with fish-attack damage in New Caledonia on 1 Mar 2007. Velocities are unreliable after Dive 168 because of fish attack damage to the glider.*

as a successful demonstration of the capability of gliders to measure, and eventually to monitor, such shallow transport.

A second glider was deployed near Guadalcanal in November 2006 and piloted to New Caledonia. Halfway through the transit, while operating well below the surface, Spray 01 was hit/bitten hard enough by something that its attitude and depth were upset and it could not subsequently maintain its cruising speed; this also made subsequent velocity measurements inaccurate (after dive 168 in figure 2). Further into the mission, the CTD salinity underwent a sudden step change of O(0.1) at the same time that attitude and depth records indicate another attack. On recovery, part of the tail was missing and there were coarse abrasion marks on the glider's wings and hull, clearly indicating fish attacks. Like measurement errors caused by bio-fouling, attacks by marine predators are intrinsic to autonomous sampling and, although rare, constitute a real operational factor. The reliable data (north end in Fig. 2) shows weaker westward flow in the SEC that in October-December 2005 cruise but similar jet structure

A third Spray cruise shifted focus from the SEC south of Guadalcanal to the pathways toward the equator through the Solomon Sea. On 18 August 2007, Spray 06 was deployed near Rossel Island (the eastern tip of the New Guinea continental shelf) to cross the Solomon Sea to Guadalcanal. Because so little is known about circulation in this area, the initial crossing, depicted in Figure 3, was used to explore transport pathways through the Solomon Sea.

After observing flow into Mile Bay north of the Louisiade Archipelego and crossing the main western boundary current near Laughlin Island, Spray 06 crossed the Solomon Sea to the vicinity of Bougainville Island and then began working south eastward toward Guadalcanal making repeated crossings of a suspected eastern boundary current. At this point the glider's pitch sensor apparently failed (we have not yet received the glider for post mortem) and it was piloted to an emergency recovery (carried out by W. Kessler and scientists from IRD). Another glider was deployed from Guadalcanal for transit to Rossel Island and a return to Guadalcanal. Similar operations will continue through most of 2008 seeking to learn enough about the paths for SEC flow toward the equator to site the full-scale Boundary Current Array.

Although the problem that interrupted the Solomon Sea crossing cannot be diagnosed until the glider is back in the laboratory, we are concerned that it was caused by a glider equipment failure. We are planning a complete reliability review of Spray's past performance and intend to identify the subsystems most in need of improvement. The possibility of redundant subsystems (like the compass – level), replacement of unreliable components, and improved testing will be weighed against the associated increased operating cost and the cost of failed missions. In

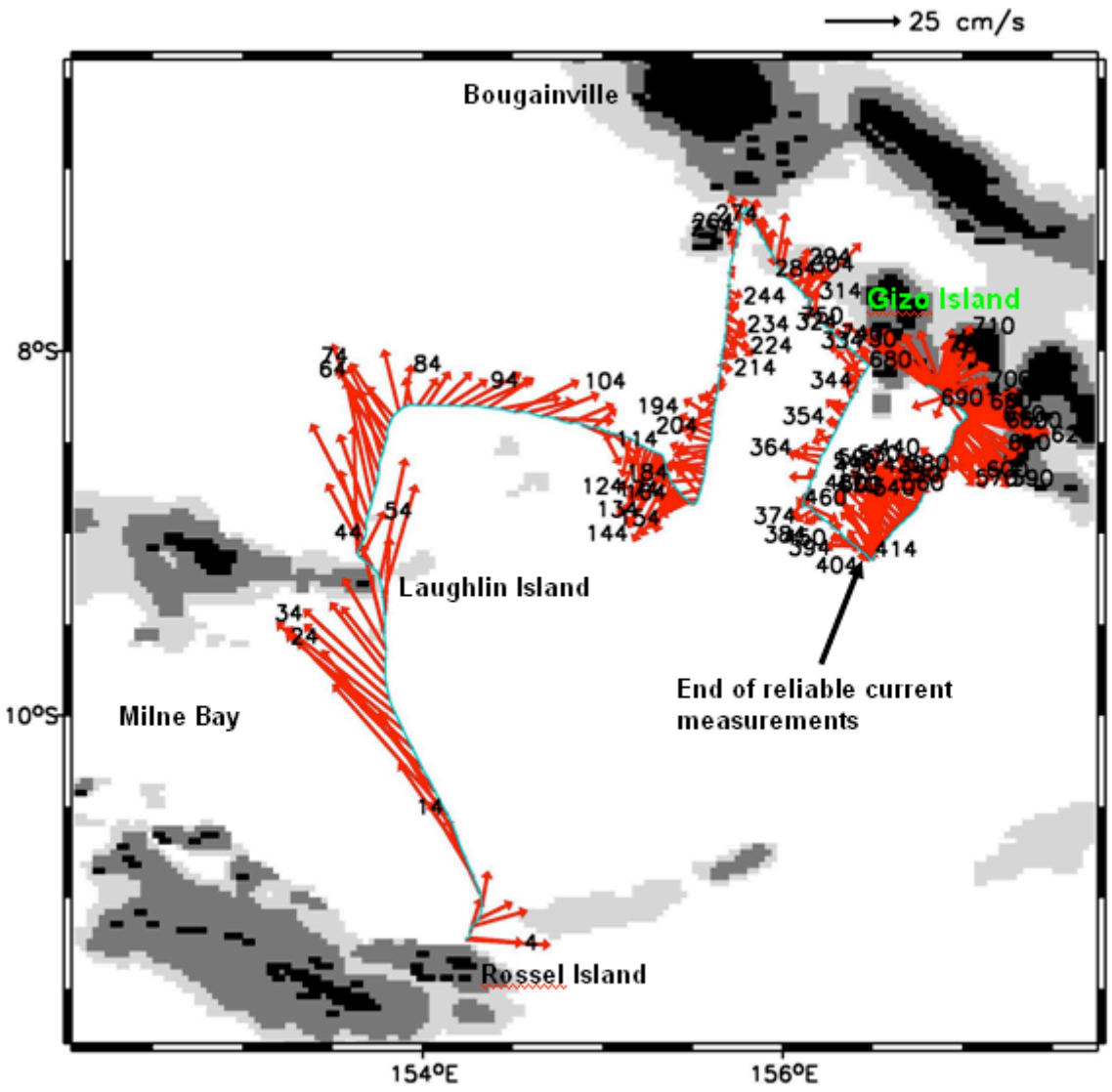


Figure 3: *Trajectory of Aug-Nov 2007 glider crossing of the Solomon Sea (green line) and measured depth-averaged currents (red arrows). Rossel Island is at the tip of Louisiade Archipelego, which extends east from New Guinea. The archipelago blocks flow of the SEC into Milne Bay. The strong observed flow into Milne Bay shows that flow out of Milne Bay toward the New Guinea coast is not so thoroughly blocked. Near dive 410 (black arrow) the glider's pitch sensor failed and velocities become unreliable. The mission was aborted and the glider recovered near Gizo Island.*

remote sites, like the Solomon Sea, the cost of failures is increased and an increased level of reliability may be cost effective.

Acoustic Communication Glider

An essential element of our Boundary Current Array is using an acoustically transponding glider to interrogate subsurface instrumentation with no surface expression to support data relay and to then carry the data to the surface for relay by Iridium satellite. During the reporting period, we designed, constructed, and tested an acoustically transponding Spray glider. A Spray was modified to slightly increase its volume to support a Benthos ATM-885 modem which operates at 11-13 kHz. Electronics are mounted inside the Spray hull and the transducer is mounted in the tail (where an ADCP is sometimes fitted) with the transducer facing downwards. Aside from a slight increase in

mass and length, the acoustically transponding glider is a normal Spray capable of measuring high resolution temperature and salinity sections and depth averaged currents.

The acoustically transponding Spray was tested on 14 November when it was operated in 900 m of water within a kilometer of the PIES mounted on the bottom. Although tests between the PIES and a shipboard modem indicated that communications should be reliable at 1200 baud, we operated the PIES-Spray acoustic link at a much more conservative 140 baud speed. With Spray floating at the surface and free of the ship, Spray interrogated the PIES and successfully received the entire PIES data record of 2420 bytes. The PIES data was then relayed through Iridium to our laboratory where the data agreed with the data recorded internally in Spray. The PIES data message has embedded checksums and from which it was determined that the data received acoustically contained 2 single-bit errors. Spray then performed a dive to 100 meters during which it interrogated the PIES during ascent. This data was relayed to shore via Iridium, along with a CTD profile and GPS fix, once Spray reached the surface. The relayed data contained no errors and once again the Iridium data agreed with data stored in Spray. An attempt to establish communications at a horizontal distance failed; acoustic ray-tracing indicated no paths connecting the PIES to the glider depth.

The limited testing to date is little more than a check against significant errors and there is substantial software work needed to integrate acoustic communications into the mix of Spray operations. However, we have met the major milestone of a freely diving glider establishing communication with a PIES on the seafloor, downloading its data acoustically, and then relaying the PIES data to shore once at the surface. More is shown under task B.

Task B: Moorings and PIES in Boundary Current Observing Systems
(U.Send)

The main goal in the reporting period was the development and initial testing of the fixed instrumentation needed needed to implement the proposed boundary current observing system. After researching the available options and choosing an acoustic modem type (Teledyne Benthos ATM-885), several of these modems were purchased, with and without pressure case (OEM version), for attachment to an inverted echosounder with pressure sensor (PIES) and to the moorings, and also for incorporation into a glider (see task A).

A hierarchy of modifications of the PIES instrument was designed and agreed on with the manufacturer (Univ. of Rhode Island, URI), for attaching and later incorporating the acoustic modems to/into the PIES. This requires diverting some of the internal data streams to an extra line/port going to the acoustic modem, and the first stage of this was also implemented with the manufacturer. The present configuration of the modified PIES with an external modem attached, is shown in the foto in figure 4.

Figure 4: *Assembly of the modified PIES (white sphere) with an external modem (black cylinder), mounted onto a*

stable bottom tripod (together with extra buoyancy, yellow sphere).
After testing the modem extensively in the lab, measuring the power consumption and the communication capabilities (see technical annex in previous year report), the system was deployed in 900m of water depth off San Diego in October 2007, on the inshore end of the CalCOFI line 93, see figure 5 (the real implementation in year 3 will take place offshore on line 90). Communication was then established from the boat to the modem-PIES assembly, by lowering a second modem over the side to a depth of a few meters. Successful communication was possible to a distance of about 6km, see figure 6 showing the SNR ratio as a function of distance. Beyond 6km, a shadow zone exists at the surface (see figure 7), and we believe longer ranges will be possible at larger depths.

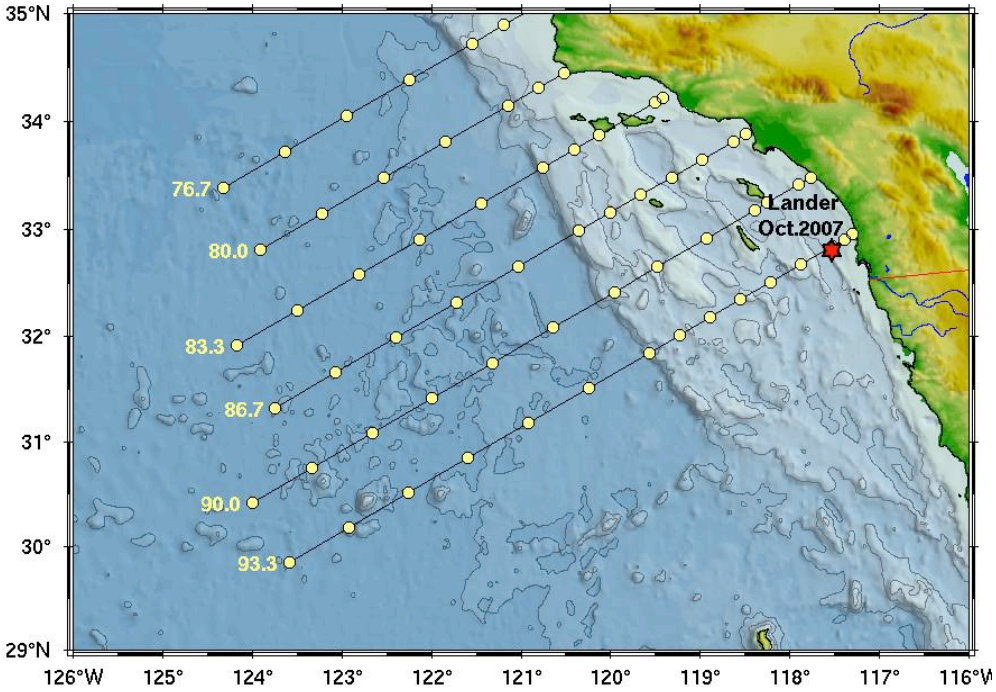


Figure 5: *Location of the test deployment of the modem-PIES assembly off San Diego, in 900m water depth (red asterisk). Also indicated for reference is the CalCOFI sampling grid, from line 93 (south) to line 76 (north).*

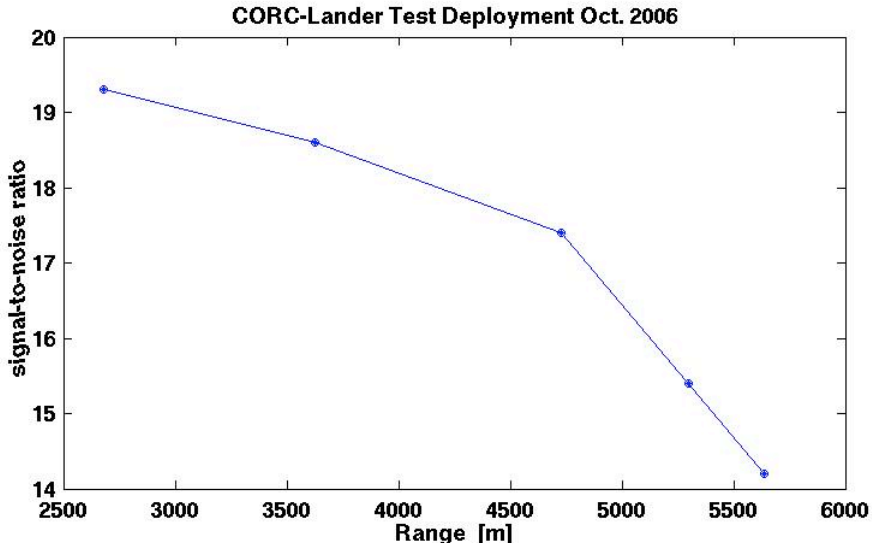


Figure 6: *Signal-to-Noise ratio measured with the modem during test transmissions between the boat and thePIES modem. A range of close to 6km was achieved.*

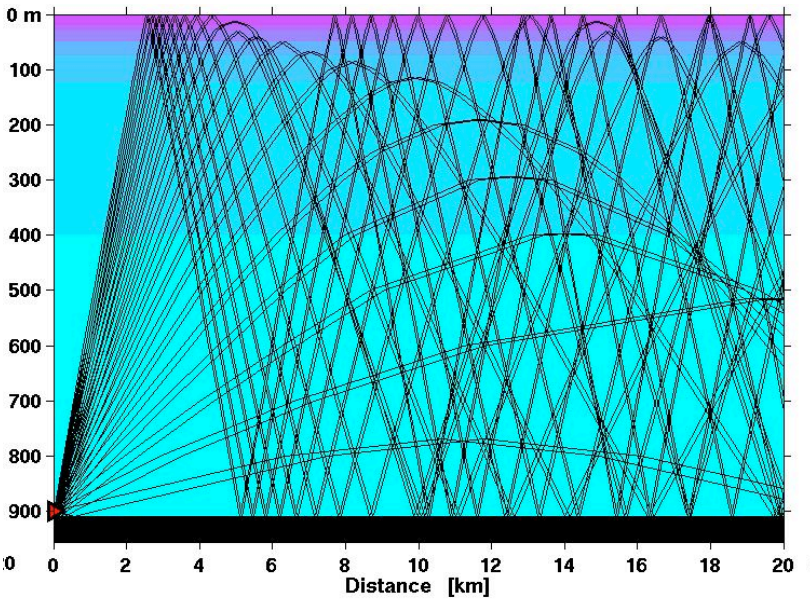


Figure 7: *Raytrace calculation for acoustic propagation paths emanating from the PIES on the bottom. Beyond about 6km distance there are no more paths to the surface, i.e. a shadow zone exists (color shows sound the speed stratification).*

In mid-November, first tests with the glider were carried out to communicate acoustically with the bottom-mounted PIES deployed at the above location. By that time, the PIES had accumulated 5 weeks of daily average traveltimes and bottom pressure values (future versions of the CORC PIES will telemeter single ensembles of these measurements as well). Figure 8 shows the transponding glider prior to the dive (described under task A), figure 9 shows a short water column heat content timeseries derived from the telemetered traveltime data.

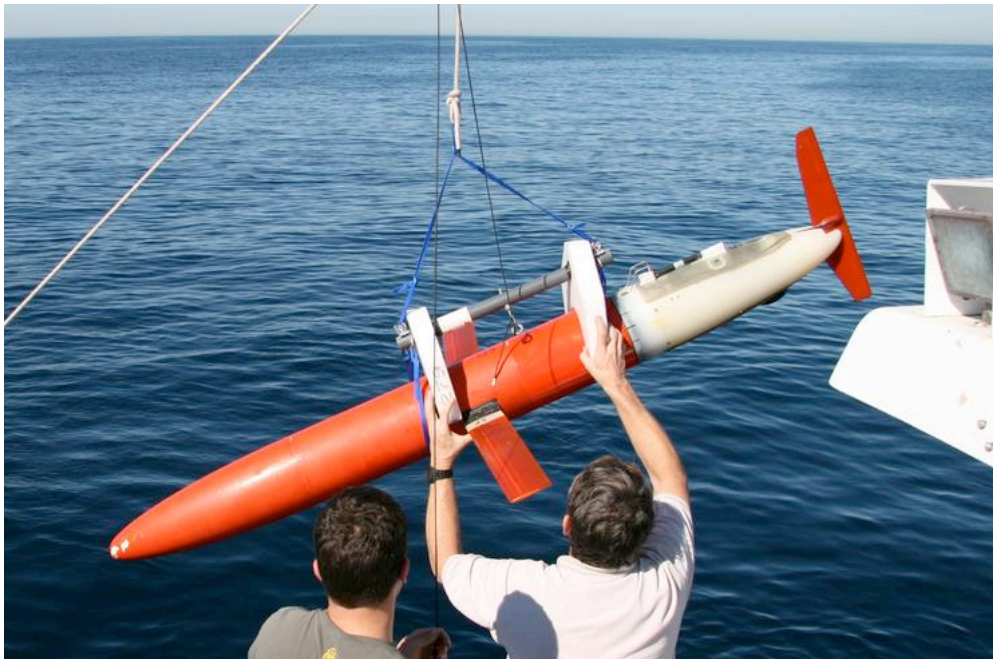


Figure 8: *The first CORC Spray glider equipped with the acoustic modem (transducer mounted in the white rear section) prior to test deployment near the bottom-mounted PIES.*

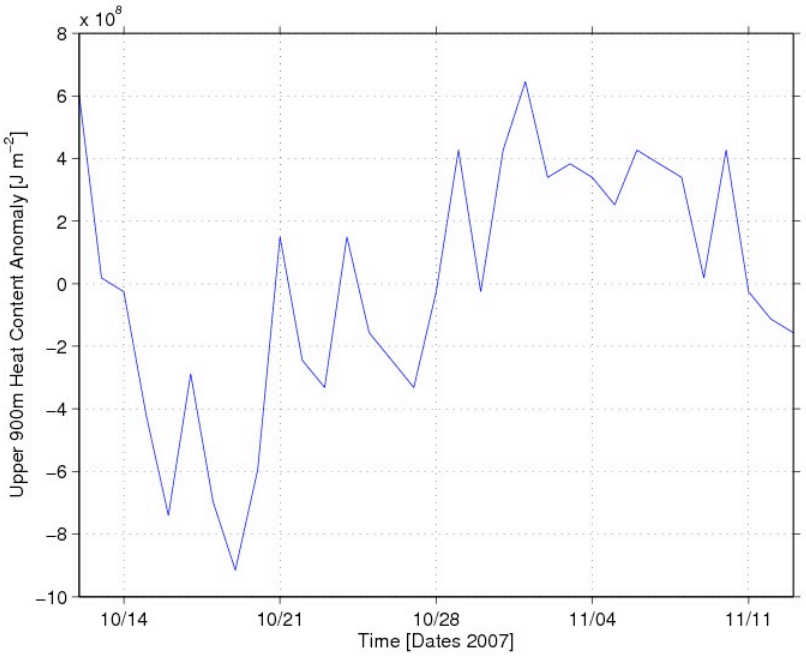


Figure 9: *Vertical water-column heat content derived from the daily average acoustic traveltimes between the PIES and surface. This kind of data will be an important part of the CORC sampling strategy.*

Order for the final PIES have been placed now, which will bring the total number of CORC PIES with the modem capability to six. We will need to purchase additional modems now, after the successful tests, in order to have 6 functional PIES ready for deployment on CalCOFI line 90 for the coming year. In parallel, preparations are being finalized now for deployment of a test *mooring* in the vicinity of the PIES shown above. A controller is nearing completion, which will be installed in the mooring, collecting data inductively from T/S microcat sensors and passing these to a Benthos modem in the mooring, for telemetry to a glider. This mooring is planned to be deployed before the end of the year.

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

Main task: Analysis of High Resolution XBT transects in the California Current system

The High Resolution XBT Network (HRX) collects eddy-resolving temperature transects along commercial shipping routes. Most lines are sampled on a quarterly basis, with temperature profiles from 0-800 m at horizontal separations ranging from 50 km in mid-ocean to 10 km near ocean boundaries. Two HRX transects cross the California Current system (Fig 1). These are lines PX37 (San Francisco-to-Honolulu) and PX31 (Los Angeles-to-Fiji). The latter is in close proximity to CalCOFI Line 90. Line PX37 has been sampled continuously since 1992.

Analysis of HRX data from PX37 and PX31 (Fig 10), including temperature, salinity, and geostrophic velocity and transport, will allow the more intensive CORC measurement program along CalCOFI Line 90 to be placed in the context of the larger eastern subtropical North Pacific domain.

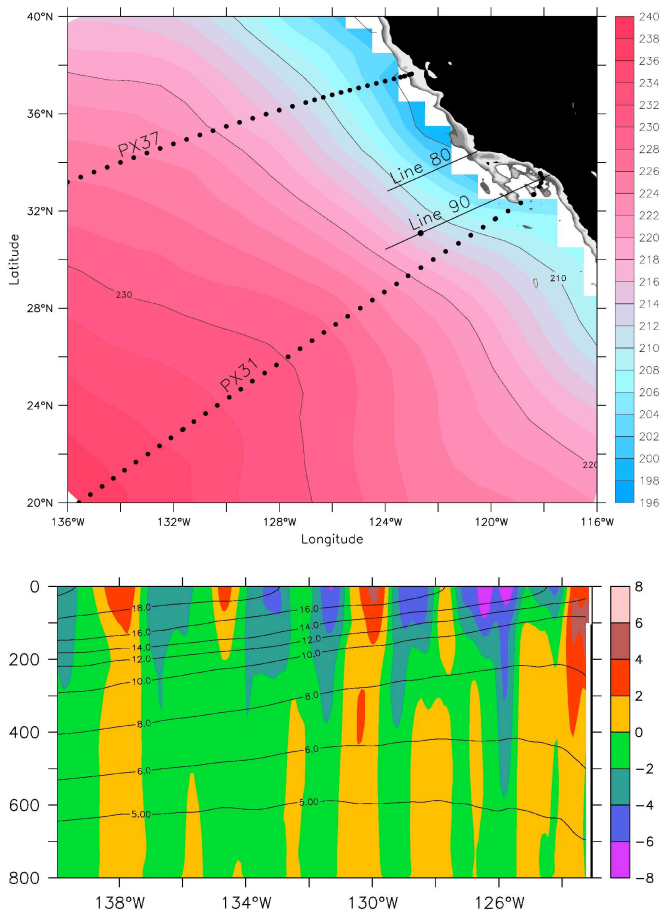


Figure 10:

(TOP) HRX Lines PX37 and PX31 are shown in relation to CalCOFI Lines 80 and 90, and to the mean dynamic height of the sea surface from Argo (0/2000 dbar, 2 dyn cm shaded intervals). Station 90.100 is marked as a dot on Line 90.

(BOTTOM) The 60-cruise (15-year) mean geostrophic velocity across HRX Line PX37.

Accomplishments:

Work began only recently on this project, and to date has consisted of organizing the individual datasets (HRX P37 and P31, CalCOFI Line 90, Argo), calculating geostrophic velocity and volume transport integrals. Fig 11 shows transport integrals from the shoreward-most station on CalCOFI Line 90 out to Station 80 and to Station 100 (see dot on Fig 10 Line 90). It is clear that substantial southward extends beyond Station 80 and that there is large variability in Line 90 transport.

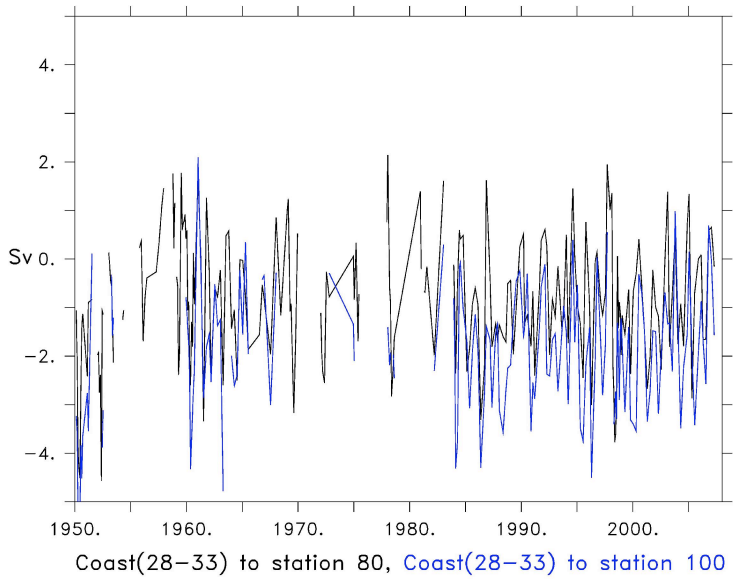


Figure 11: *Geostrophic transport (0-500 m) across CalCOFI Line 90, integrated from shore out to Station 90.80 (black) or 90.100 (blue)*

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

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

We planned to deploy approximately 240 LMP5-T1 probes, and to evaluate their potential for use in the HRX Network.

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

Accomplishments:

Development of the LMP5-T1 probe by Lockeed Martin has been delayed by integration of pressure point calibration circuitry into the instrument. We have elected not to take delivery of probes without the pressure point. The work will be initiated as soon as probes can be built. No new funds are requested.

Task D: Analysis of CALCOFI, Drifter and Altimeter Data for Climate Evolution Modes
(Peter Niiler and Yoo Yin Kim and Luca Centurioni)

The CalCOFI hydrographic grid off the southern California coast was sampled on a yearly to seasonal basis from 1949 to 2007. These data, when taken together with drifter (1985-2007) and altimeter data (1992-2007) can be used to define a variety of "interannual-to-decadal modes" of variability. For example, a "mode" of mass transport can be constructed from smoothing the data with several energy containing EOFs of the time average space correlation matrix of monthly anomalies of geostrophic velocity relative to 500m at Line#90. From this "smoothed" spatially coherent data of velocity, a climate mode of variability can be constructed by filtering the time series at each location.

The Schneider et al. (2005) used the CalCOFI Line #90, data from 1937-1999 to demonstrate the differences in the temperature and salinity modes of long time-scale variability. The temperature variability in and above the seasonal thermocline was largely related to ENSO. But the salinity variability, which could not be related directly to either ENSO or the PDO, was produced by time variations of long-term persistent transport features that advected anomalous water masses across Line #90. Since this calculation was made, there now are 8 more years of CalCOFI hydrographic data.

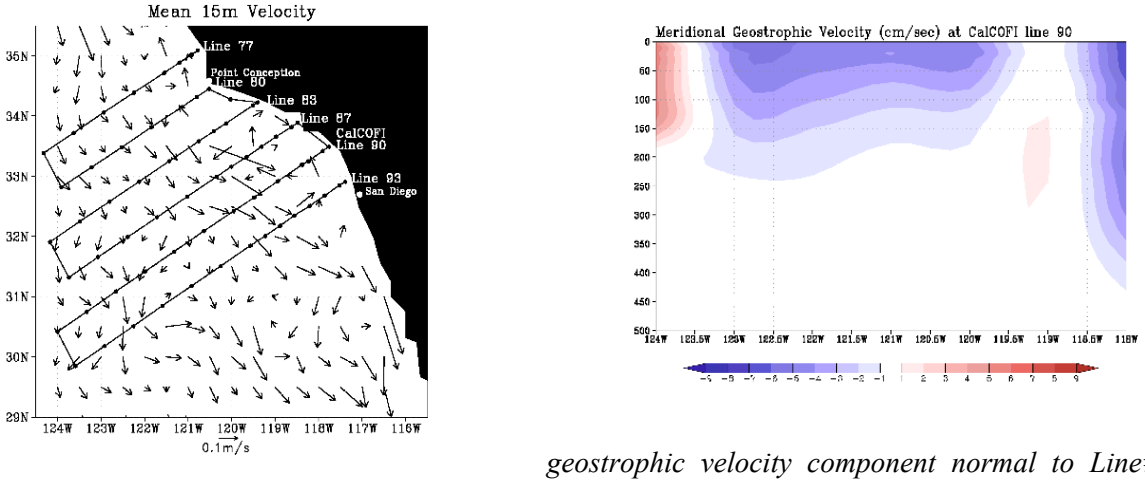
We propose to analyze the complete CalCOFI hydrographic data set for coherent patterns of relative geostrophic circulation from 1949-2007 and calculate how these relate to the altimeter (1992-2007) and drifter observations (1985-2007). The principal objective is to construct an interannual-to-decadal mass, thermal energy and property transport indices for the area that is to be sampled by the CORC moored/glider array and modeled by the CORC California Current climate model.

The following specific tasks form the initial basis of our analysis. Progress is noted in italics:

1. Organization of quality controlled data file. This task requires the organization of the historical CalCOFI hydrographic, the Global Drifter and the AVISO altimeter files. Most of these data are available on existing files but require additional quality control and assembly into joint files for analysis. ***This task has largely been completed for the hydrographic and drifter data sets in the 2006-2007 funding period (viz. Fig. 12).***

2. Computation of the principal, spatial coherent modes of variability. A variety of programs exist for this computation, especially when different engineering units are used designate the files (e.g. temperature, salinity, velocity, dynamic height, etc.). We will rely on the expertise of the CORC Investigators to recommend the appropriate analysis tools. ***This task has been initiated for hydrographic data but the velocity and sea level data has not been included because these are available over the past 13-15 years.***

Figure 12. *The 15m velocity derived from 0.5° ensemble averaged drifter data in the CalCOFI region (left panel; for methodology, viz. Niiler 2001) and the*



geostrophic velocity component normal to Line#90 as function of depth and longitude along Line#90 (right panel). Because significant differences exist at in these distributions at 15m depth along Line#90, the challenge is to determine how these two data, and others named above, can be used to derive the absolute, depth dependent circulation, and its variability, from the historical data in the CalCOFI area.

3. Release of SVP drifters on Quarterly CalCOFI cruises. Our proposal was to commence the releases in July 2007 with 7 SVP drifter deployments on each of the CalCOFI cruises. The velocity observations from these will be used to aid in the definition of the circulation patterns in the area of the CORC CCS monitoring. The Global Drifter Program will supported these releases as part of the global deployment of drifting buoys. ***The plan is to begin releases of drifters in the CalCOFI survey in winter of 2007-08.***

Add-Task: Development of Autonomous Deployment Pods for Drifters

The objective of this task is to design, test and deploy autonomous drifter release containers for sampling of ocean boundary current systems. A package, containing 5-10 drifters with borosilicate

glass floats would be placed on the ocean floor from which periodic releases to the surface would occur. The technology for the release mechanism has been designed, tested and deployed by several oceanographic laboratories (WHOI, U.R.I, etc). We anticipate adapting a 'burn wire' methodology, in which drifters are packed into and released from a cylindrical 35cm x 2m tube that rests vertically on the ocean floor. The principal technical issues are to construct the release mechanism that is fit into the tube on the bottom and to package the drifters into a compact form. For the latter purpose, the drogue shape will be altered into a truncated cylinder that allows the surface glass float and the coiled tether to nest in a vertical space that is about 50 cm in the vertical. In summer of 2008, the sea tests will commence in progressively deeper water, beginning in 15m water depth off the Scripps Pier (scuba diving depth) and culminating in 1000m in the San Diego trough in late 2008. Deployment in the CORCIII observation area and, anticipating future deployments in strong boundary currents, these drifters would be fixed with GPS and report the data through Argos system. Further tests in 2009 and initial deployments of pods would be made in the CORCIII California Current study area and, within three years, sampling in more remote western boundary currents is anticipated. ***This task was funded in September '07. The development engineer to accomplish the technical parts was hired on 15 November 2007. Progress will be reported in June 2008.***

References

Niiler, P. P.: The world ocean surface circulation In *Ocean Circulation and Climate*, edited by G. Siedler, J. Church and J. Gould, Academic Press, pp. 193-204. (2001)

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

We have been working on technical details necessary to enable the California Current System (CCS) state estimation for hindcasts. This is a challenging problem, due to the relatively low density of observations compared to space and time scales. We are finishing the conversion to a new version of the ECCO code (which is the assimilation package including the MITgcm). The new version has many new features, and some of our old procedures have to be changed to work in the new system.

For example, the new assimilation system uses a "bulk formula" approach in which the control variables are atmospheric fields (such as wind, surface temperature, incoming short wave, and precipitation) as opposed to the old forcing fields (such as wind stress and heat flux). The atmospheric fields are converted to forcing using bulk formulas, which can then include the effects of small-scale structure in the ocean sea surface temperature, for example.

We have also been assembling constraints for the model initial and boundary conditions. In the long runs (1 year or greater) that we have used in the past, the initial conditions are not important relative to the forcing fields. In shorter runs, which are expected to be necessary in the CCS, it is helpful to constrain the initial and boundary conditions to be consistent with prior observations, in particular T-S relations and quasi-geostrophic balance. The constraints are being constructed from prior observations, mainly CalCOFI and other historical stations in the region, but work still needs

to be done to make the constraints part of the assimilation system and ready for the adjoint compiler. This work will also help set error bars on observations and forcing fields which are needed for best performance of the state estimation.

Finally, statistical investigations into the relation between the CCS and climate indices (PDO, ENSO, NPI) has begun, using the Optimal Interpolation technique, which is the same as the linear inverse model (LIM) formalism used in linear climate forecasting. The sea surface height (SSH) dataset from AVISO is valuable for creating indices of eddy kinetic energy (EKE) and CCS strength to be used in combination with the global climate indices and the more local CCS measures like upwelling index.

High Resolution Climate Data From Research and Volunteer Observing Ships

Chris 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.

FY2007 ACCOMPLISHMENTS

For the *Ronald Brown* C-band and wind profiler radar project, routine maintenance was performed on the wind profiler at Charleston, SC, after the NOAA 2007 PNE/AMMA in May and June 2007.

ESRL completed two research cruises as planned: the Bob Molinari buoy deployment cruise in the Atlantic in the summer of 2007 (this is the *PNE/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/cruises .

A synthesis of the main results of the previous five years of strategic observations was produced in the form of three scientific publications (two appeared in print in 2006 and one is was accepted in 2007). The third paper (Fairall et al., 2007) 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. A second paper (Ghate et al., 2007) based on combining annual observations from the ESRL cruises to the WHOI buoy and radiative flux data from the buoy was submitted. A technique to derive stratocumulus cloud fraction using the WHOI observations was developed and applied to the buoy observations to give a five-year climatology (for 2001-2006). The results were compared with the satellite derived monthly cloud fraction and the ceilometer derived zenith cloud fraction (available during the maintenance cruises). The initial results and analysis show that the technique can be effectively applied to the longer datasets and the continuous observation from the WORS. Seasonal, inter-seasonal and average diurnal variations in cloud cover are obtained for five years of observations. The buoy-

derived cloud fractions were compared with ISSCP satellite-derived low-cloud and total cloud fractions. The satellite gets total cloud well, but is completely wrong on the partitioning between cloud heights.

Considerable progress was also made on developing the portable flux standard and implementing ship and buoy intercomparisons for quality assurance. Production of the roving flux standard is essentially complete. We 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 three parts: 1) convert from a network cabled sensors to wireless transmission and 2) improve the radiative flux and navigational measurements, 3) streamline the data acquisition and display processes. 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. Field tests were done on several cruises. Alternative wireless hardware was tested in 2007 and a number of problems (data dropouts) were solved.
*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 was field tested in on the October 2007 WHOI/stratocumulus cruise and it was a complete success.
*The portable standard will be deployed in spring of 2008.

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 2007)

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.* **111**, D23S20, doi:1029/2006JD007597.

Wolfe, D. E., C.W. Fairall, D.C. Welsh, M. Ratterree, A.W. Brewer, J.M. Intrieri, C.J. Senff, B.J. McCarty, S. Tucker, D.C. Law, A.B. White, and D.E. White, 2007: Shipboard multi-sensor merged wind profilers from NEAQS 2004: Radar wind profiler, high-resolution Doppler lidar, GPS rawinsonde, *J. Geophys. Res.*, **112**, D10S15, doi:10.1029/2006JD007344.

Fairall, C. W., J. E. Hare, T. Uttal, D. Hazen, Meghan Cronin, Nicholas A. Bond, and Dana Veron, 2007: A seven-cruise sample of clouds, radiation, and surface forcing in the Equatorial Eastern Pacific. *J. Clim*., to appear.

Kara, Birol, Alan J. Wallcraft, E. Joseph Metzger, Harley E. Hurlburt, and C. W. Fairall , 2007: Wind stress drag coefficient over the global ocean. *J. Clim.*, accepted.

Ghate, Virendra P., Bruce A. Albrecht, Christopher W. Fairall and Robert A. Weller, 2007: Climatology of marine stratocumulus cloud fraction in the South-East Pacific using surface longwave radiative flux observations. *J. Clim.*, submitted.

CONFERENCES (FY 2007)

28^{h} Session of the Joint Scientific Committee for the WCP, World Climate Research Program, Zanzibar, Tanzania, 26-30 March, 2007 Presentation: The WCRP Working Group on Surface Fluxes. [http://www.wmo.ch/pages/prog/wcrp/pdf/Doc%205.5%20WGSF%2015.02.pdf]

Office of Climate Observation 4th Annual System Review, NOAA, Silver Spring MD, 5-7 June 2007. Poster presented: *The SURFA Project: Reconciling in situ and Operational NWP Surface Fluxes*.

Papers are available as .pdf files from

ftp://ftp.etl.noaa.gov/user/cfairall/oceanobs/pubs

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

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

I. Project Summary

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

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

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

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

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

To create the most comprehensive Pacific raingauge database possible it is necessary to continue to work closely with the Pacific meteorological services to help them sustain high their quality gauge networks. One of our most successful efforts during 2007 was (and is) the implementation of a large network of new manual-read rain gauges and automatic data-logger equipped tipping bucket rain gauges located on various atolls and islands managed by the local Pacific meteorological services. A total of approximately 60 automatic, high quality tipping bucket gauges are being operated by various Pacific Island meteorological services. We currently are collecting the data in tip format and converting it to 1 minute resolution. Our Pacific educational program, SPaRCE (http://sparce.evac.ou.edu/) contributes in a direct way to the PACRAIN database through the contribution of Pacific schools taking manual read daily rain gauge measurements while learning about the importance of weather and climate. Underlying these projects is the long-term effort to help build the capacity of the all the PNMS to better serve their constituents. This will ultimately result in the PNMS being able to self-sustain their data networks. We continue to contribute to this effort by providing what we can in terms of needed supplies, education and communication infrastructure (e.g. involvement in the Radio/Internet; i.e. RANET project) until the PNMS become completely self-sustainable. We also work collaboratively with the Secretariat for Pacific Regional Environmental Programme (SPREP) which is located in Apia Samoa. SPREP acts as a communication conduit through which we communicate and collaborate with the different PNMS. This project is continually in the process of implementation with a portion of the total number of gauges on operational status, some currently being shipped to the Pacific and some needing maintenance. We work particularly close with the New Zealand Meteorological Service and the attached PI-GCOS Technical Support Project to accomplish the later objective.

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

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

II. Accomplishments

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

Rain rate measurements over open ocean regions are very important in the assessment of satellite rain 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 rain gauges tipping bucket gauges are equipped with data loggers and have been donated by the University of Oklahoma for this project. In turn, they have been given to the PI-GCOS Coordinator, headquartered at SPREP, for distribution to the various PNMS. We have deployed over 50 of these gauges throughout the Pacific region during 2007. We are currently receiving rainfall tip data back from many PNMS and these data are inserted into the PACRAIN database.

These data are particularly important in the understanding of basic tropical rain systems and consequently, more accurate global climate models. These data are all included in the PACRAIN database.

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

PI-GCOS Tipping Bucket Project Web site and related web sites:

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

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

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

http://www.pi-gcos.org/ (the P.I. initiated the PI-GCOS web site in collaboration with the GOSIC project at the University of Delaware. It now under the auspices of the NOAA National Climatic Data Center.

Figure 1 METONE Tipping Bucket Gauge at the Samoa (left) and Niue (right) Meteorological Services

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

EVAC maintains a database of selected high density raingauge network data for use in satellite rainfall algorithm assessment. Parts of our responsibilities include operating the Surface Reference Data Center (SRDC), which is associated with the Global Precipitation Climatology Project (GPCP). Our tasks in this capacity include identifying and collecting these data sets and making them available to researchers for this purpose. We also conduct studies on the errors involved when comparing satellite and rain gauge data. During 2007 we began research on the rain rate characteristics of tropical rainfall by developing a tropical point process model. The fit of the model at various temporal scales was tested using the data from the tipping bucket gauges.

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 data with some records beginning in 1874
- daily records begin in 1942

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

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

D. Current Status of PACRAIN Database

- From last year we have currently updated PACRAIN with 104,625 additional observations from a combination of existing data sets and newly installed instruments.
- The high resolution tipping bucket gauges incorporating data loggers which are now operational (since last year) are located in these countries:

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

- A total of 16 station-months of Tipping Bucket Gauge data received so far for FY2007
- New software (a Microsoft Excel add-in) has been developed for use by the individual meteorological services for easy download of tip data from these gauges.
- A new PACRAIN web interface is in development.

E. Survey of PACRAIN Usage

1. User Requests

We recently conducted a survey of the users of the PACRAIN database. We maintain query log on our server which goes back 26 months. In that time, 98 users (distinct e-mail addresses,

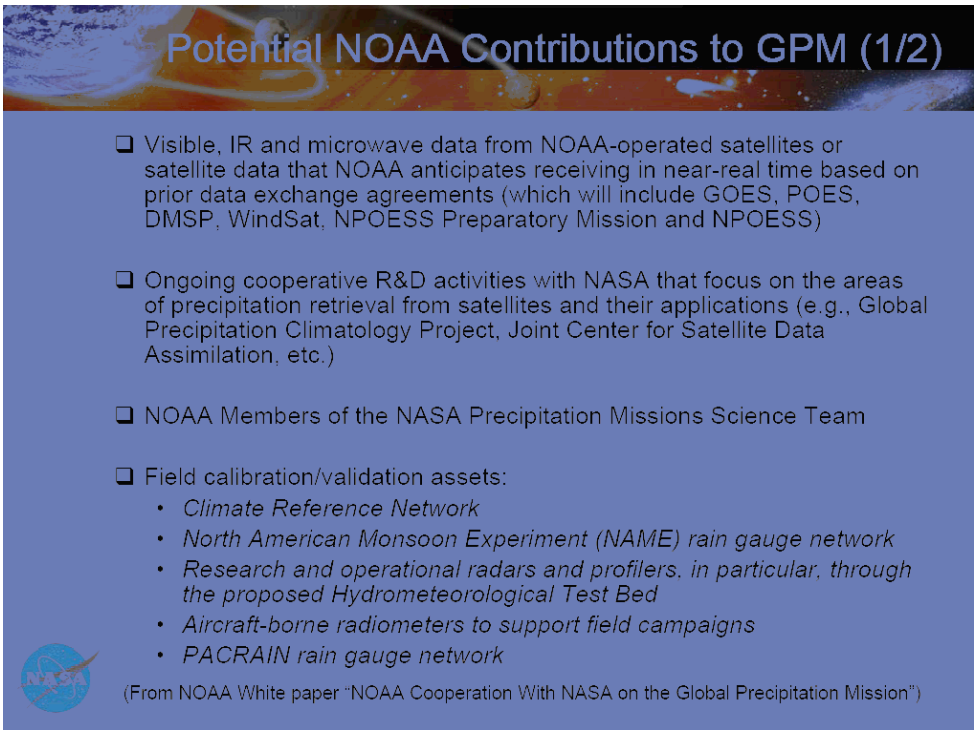
excluding us) have made 153 queries that returned 45 million records. Almost half of all queries return at least 1000 records. Most users are one-time visitors, and approximately 15% have made more than one query.

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

2. Institutional Usage

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

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



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

CMAP

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

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

3. Research Usage

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

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

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

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

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

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

Kidd, C. and G. McGregor, 2007: Observation and characterization of rainfall over Hawaii and surrounding region from the Tropical Rainfall Measuring Mission. *Int. J. Climatol.*, **27**, 541-553.

Delcroix, T., C. Henin, V. Porte and P. Arkin : Precipitation and sea-surface salinity in the tropical Pacific Ocean, Deep Sea Research I, Vol. 43, No. 7. pp. 1123-1141. 2006.

Brown, J. E. M., 2006: An analysis of the performance of hybrid infrared and microwave satellite precipitation estimates over India and adjacent regions. *Remote Sens. Environ.,* **101**, 63-81.

Matthews, A. J. and H. Y. Y. Li, 2005: Modulation of station rainfall over the western Pacific by the Madden-Julian oscillation. *Geophys. Res. Letters*, **14**.

Nicholson, S. E., B. Some, J. McCollum, et al., 2003: Validation of TRMM and other rainfall estimates with a high-density gauge dataset for West Africa. Part I: Validation of GPCC rainfall product and pre-TRMM satellite and blended products. *J. Appl. Meteor.,* **42**, 1337-1354.

Nicholson, S. E., B. Some, J. McCollum, et al., 2003: Validation of TRMM and other rainfall estimates with a high-density gauge dataset for West Africa. Part II: Validation of TRMM rainfall products. *J. Appl. Meteor.,* **42**, 1355-1368.

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

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

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

Kummerow, C., J. Simpson, O. Thiele, et al., 2000: The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. *J. Appl. Meteor.*, **39**, 1965-1982.

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

Zeng, X. B., 1999: The relationship among precipitation, cloud-top temperature, and precipitable water over the tropics. *J. Climate*, **12**, 2503-2514.

Chapman, T., 1998: Stochastic modelling of daily rainfall: the impact of joining wet days on the distribution of rainfall amounts. *Environ. Model. Softw.*, **13**, 317-324.

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

Waliser, D. E. and W. F. Zhou, 1997: Removing the satellite equatorial crossing time biases from the OLR and HRC datasets. *J. Climate*, **10**, 2125-2146.

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

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

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

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

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

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

4. Comments from Project Coordinators and PACRAIN USERS

a. From Dr. George Huffman, Mesoscale Atmospheric Processes Branch, NASA Goddard:

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

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

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

(attached; note Fig. 7 and Table 1). The Kwajalein Island radar and the TAO/TRITON buoys provide additional unique data, but they cover a different scale and region, respectively, and cannot replace PACRAIN or replicate its period of record.

It is important to our work that the PACRAIN data are maintained in a coherent, accessible Web location that minimizes the amount of time we spend dealing with obtaining such data. This allows

us to focus on our core activity - combining precipitation estimates from as many sensors as possible to establish a unified global record of precipitation.

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

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

b. From John Janowiak, Climate Prediction Center:

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

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

c. From Pingping Xie, NOAA's Climate Prediction Center

Hi, Mark,

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

Pingping Xie, CPC

d. Letter from Dr. Thomas Peterson, NOAA's NCDC

Dear Prof. Morrissey,

As you know, we were delighted to be able to incorporate your Pacific Island rainfall data set, PACRAIN, into the Global Historical Climatology Network (GHCN) version 2 precipitation data set. Scientists all over the world have been downloading GHCN precipitation data free of charge from http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/ and using the data for a wide variety of analyses.

I just discussed the plans for GHCN version 3 precipitation data set and confirmed that PACRAIN is an integral part of global precipitation data as it provides important observations across a wide expanse of the globe where other sources of in situ precipitation measurements are sparse. In addition to being used in the monthly version of GHCN, PACRAIN has been incorporated into GHCN daily which has been used to provide valuable information on changes in extremes. Both GHCN data sets, which means both daily and monthly versions of your PACRAIN data, were used in analyses presented in the Nobel Prize winning Intergovernmental Panel on Climate Change's Fourth Assessment Report.

Thank you for your valuable contribution to these endeavors.

Regards,
Thomas C. Peterson

F. Enhancement of Educational Outreach Component of the SPaRCE Program

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

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

III. Publications, Workshops, and Conference Presentations

Publications

<u>Book Chapter</u>

A Senior Author of the book "*Measuring Precipitation from Space - EURAINSAT and the future*" Levizzani, Vincenzo; Bauer, Peter; Turk, F. Joseph (editors), **2006**, Approx. 745 p., Hardcover ISBN: 978-1-4020-5834-9. Chapter Title: Ground Validation for the Global Precipitation Climatology Project, M. L. Morrissey and J.S. Greene. P. 381-392.

Journal Articles

Morrissey, ML., and J.S. Greene: "A Theoretical Framework for the Sampling Error Variance for Three Dimensional Climate Averages of ICOADS Monthly Ship Data", Submitted to Theoretical and Applied Climatology.

Greene, JS, B Paris, and M Morrissey, 2007, "Analysis of Historical Changes in Extreme Precipitation Events in the Tropical Pacific", Climate Research, 34, 1-14.

Greene, JS, M Klatt M Morrissey, and S Postawko, "The Comprehensive Pacific Rainfall Database: An enhanced tool for research and education", Journal of Atmospheric and Oceanic Technology (published in January, 2008).

Workshops

"Progress on PI-GCOS Pacrain tipping bucket gauge project", Mark Morrissey, 12th RMSD in the Cook Islands, July 2007.

Conference Presentations

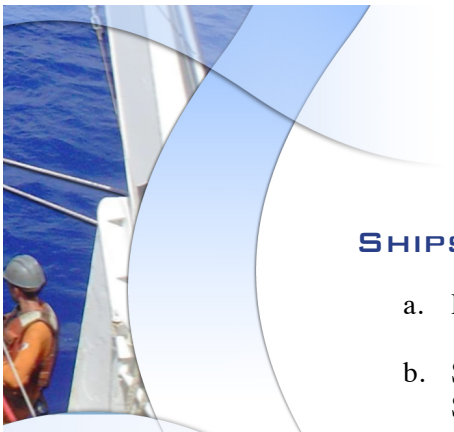
Morrissey, M. and S. Postawko, "Schools of the Pacific Rainfall Climate Experiment: The Benefits and Challenges of Student Participation in Scientific Research" presented at the AGU Annual Meeting, December 2005

M.D. Klatt, J.S. Green, S.E. Postawko, and M.L. Morrissey. "The Pacrain Database". Presented at the 86th AMS Annual Meeting in Atlanta, GA, January 2006

Morrissey, M.L., D. Solofa, R. Pulehetoa, J. Napat, 'O. Faanunu, and S. Postawko, "Pacific Island Global Climate Observing System basic instrument project: High quality tipping bucket rain gauges" presented at the 86th AMS Annual Meeting in Atlanta, GA, January 2006

S. Postawko, "Update of SPaRCE Activities" presented at the 11th Regional Meteorological Service Directors meeting in Noumea, New Caledonia, July 2006

Klatt, M., M. Morrissey, and J. Greene, "The PACRAIN/PI-GCOS automated rain gauge initiative", presented at the 87th AMS Annual Meeting in San Antonio, TX, January 2007



Ships of Opportunity

a. High Resolution XBT Transects

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

c. Ships of Opportunity

High Resolution XBT Transects

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

Project Summary

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

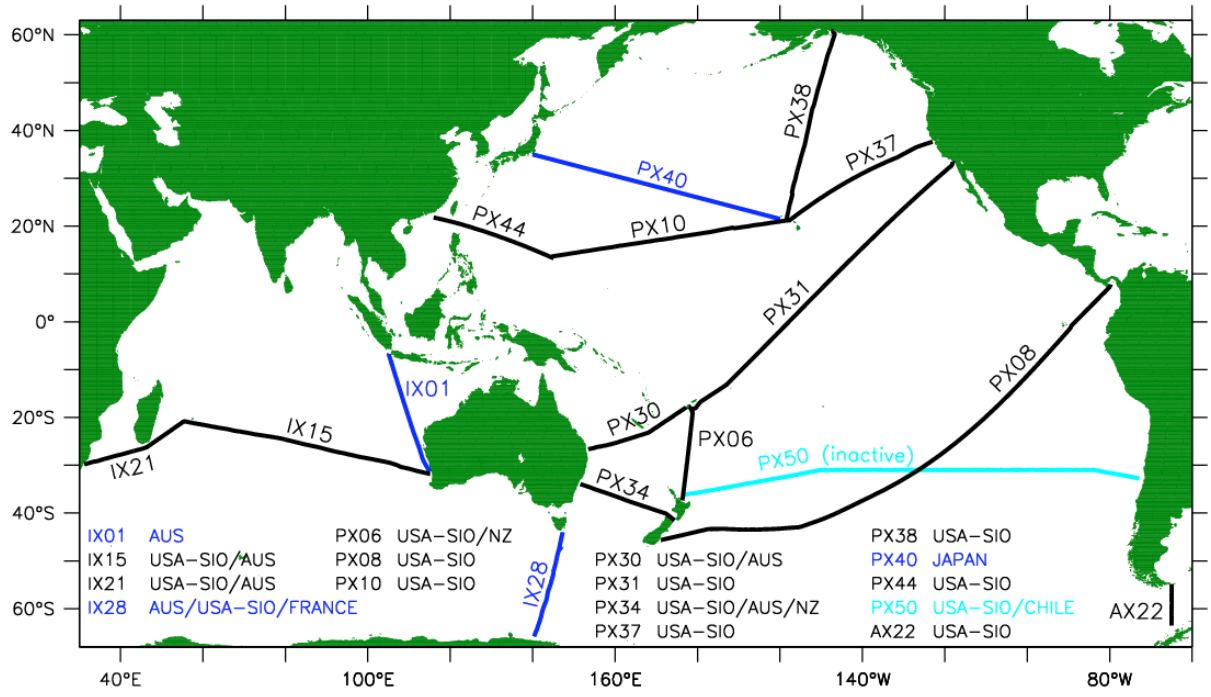


Fig 1: The HRX Network in the Pacific and Indian Ocean. International partnerships are indicated in the notes on the bottom of the figure.

Scientific Objectives-

A primary scientific goal of the HR-XBT network is to determine whether interannual variability in the transport of heat by ocean currents is a major contributor to the heat budget of the ocean

and hence to air-sea interactions and feedbacks in the climate system. Specific scientific objectives of the HR-XBT program are to:

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

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

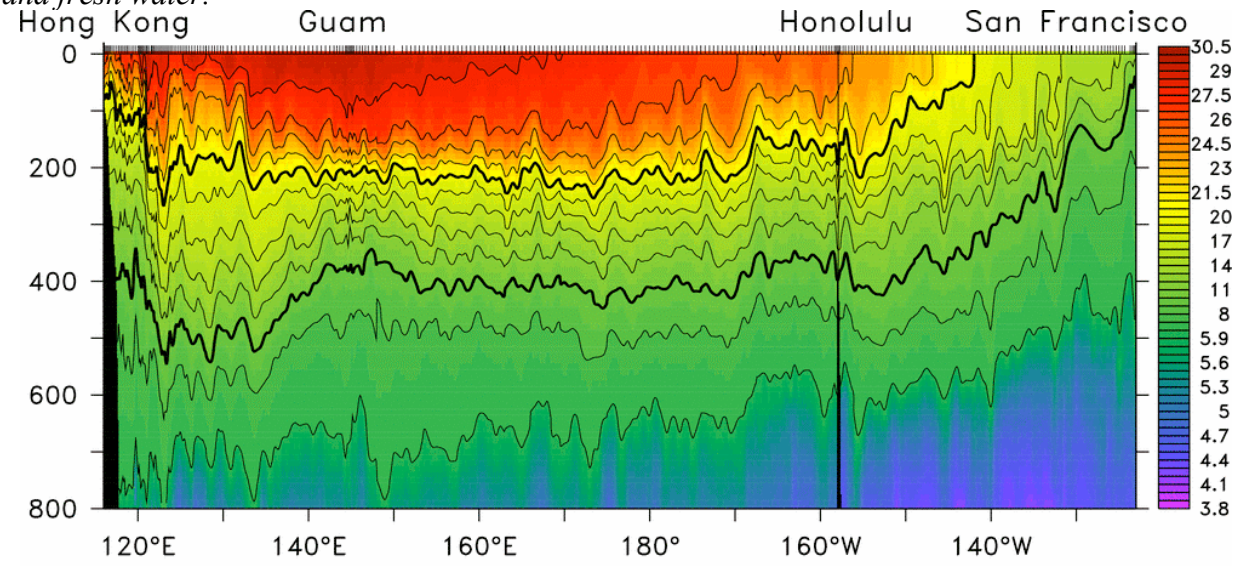


Fig 2. Example of a single temperature transect using 321 XBT profiles along PX37/10/44.

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.

FY2007 Accomplishments: October 2006 – September 2007.

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, including yearly sums for total XBT drops and good XBT drops:

PX37/10/44 (North Pacific - San Francisco to Hawaii to Guam to Hong Kong)
4 transects: Nov 2006, Feb 2007, May 2007, July 2007 (1223 good/1253 total drops)

PX38 (North Pacific – Hawaii to Alaska)
2 transects: Dec 2006, July 2007 (211 good/224 total drops)

PX08 (South Pacific – New Zealand to Panama)
4 transects: Dec 2006, March 2007, May 2007, July 2007 (997 good/1018 total drops)

PX06/31 (Central Pacific – New Zealand to Fiji to Los Angeles)
3 transects – Feb 2007, June 2007, Sep 2007 (760 good/806 total drops)

PX30 (South Pacific – Brisbane to Fiji, collaborative with Australia)
3 transects – January 2007, April 2007, July 2007 (338 good/360 total drops)

IX21 (South Indian – Durban to Mauritius)
3 transects – Feb 2007, April 2007, July 2007 (249 good/261 total drops)
+ 2 IX06 Mauritius to Strait of Malacca, April 2007, July 2007 (131 good/133 total drops)

IX15 (South Indian – Mauritius to Fremantle or Bass Strait)
3 transects – Oct 2006, Jan 2007, July 2007 (599 good/615 total drops)

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 (480 probes per year are as part of our collaboration with CSIRO) for:

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

Logistics -

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

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

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

Development and technical issues –

The most substantial XBT technical issue of the past year has been the identification of a (warm) temperature bias due to variations over time of XBT fall-rate. Work is ongoing to estimate the time history of fall-rate corrections and to apply this correction to historical data:
Wijffels, S. and 7 co-authors: Changing eXpendable Bathythermograph Fall-rates and their Impact on Estimates of Thermosteric Sea Level Rise, In preparation.
Our role in this work is through providing datasets, suggestions, and ancillary calculations.

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

Analysis and research highlights -

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

- There is now a 20-year time-series of HRX measurements along PX06 (Auckland-Suva). The PX06 long time-series has revealed permanent small-scale features of the circulation, shown interannual and decadal variability in transport, closed mass and heat budgets of the "Tasman Box" region, and provided a valuable dataset for ocean data assimilation modeling.
- E. M. Douglass is completing her PhD thesis in which HRX data are analyzed in combination with other datasets and results from the ECCO Ocean Data Assimilation model (Douglass, 2007, Douglass et. al., 2007). North Pacific HRX transects are a key dataset in this work, providing strong tests of the ODA model to correctly represent geostrophic velocity and ocean heat transport.
- In other work on Ocean Data Assimilation modeling, I. Hoteit and B. Cornuelle are using a regional eddy-permitting ($1/3^o$) model of the tropical Pacific (Hoteit *et al.*, 2006), to explore the capabilities and sensitivities of the ECCO model in the tropical domain. Again, HRX transects are a key dataset for challenging the capability of ODA models.
- J. Gilson is pursuing accuracy and consistency issues for both HRX and Argo datasets (e.g. Willis et al., 2007). Objectives are to identify and remove systematic errors in both

of these global datasets to enable the XBT and Argo records to be combined with one another as well as with other historical and ongoing data collections.

Refereed publications –

Hoteit, I., B.D. Cornuelle, A. Köhl and D. Stammer, 2006. "Treating strong adjoint sensitivities in tropical eddy-permitting variational data assimilation," *Quarterly Journal of the Royal Meteorological Society*, **131**, 3659-3682, doi:10.1256/qj.05.97.

Uehara, H., S. Kizu, K. Hanawa, Y. Yoshikawa, and D. Roemmich, 2007. Estimation of heat and freshwater transports in the North Pacific using the high resolution XBT data. Accepted by *J. Geophys. Res.*

Ueno, H., E. Oka, T. Suga, H. Onishi and D. Roemmich, 2007. Formation and variation of temperature inversions in the eastern subarctic North Pacific. *Geophys. Res Lett., 34,* L05603, doi:10.1029/2006GL028715.

Willis, J., J. Lyman, G. Johnson, and J. Gilson, 2007. In situ data biases and recent ocean heat content variability. Submitted to *Geophys. Res. Lett.*

Douglass, E. M., D. Roemmich, and D. Stammer, 2007. North Pacific variability from a data-assimilating model. In preparation.

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

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.

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

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.

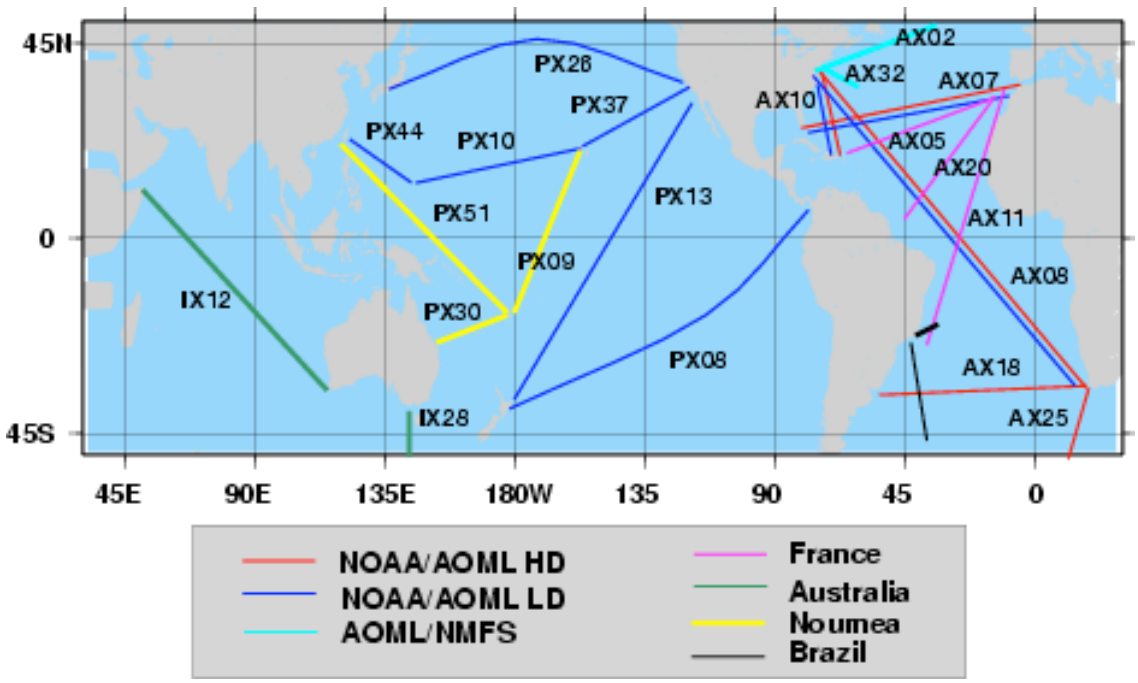


Figure 1. Map showing the network of XBT transects maintained by NOAA/AOML and by NOAA/AOML in collaboration with international partners.

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.

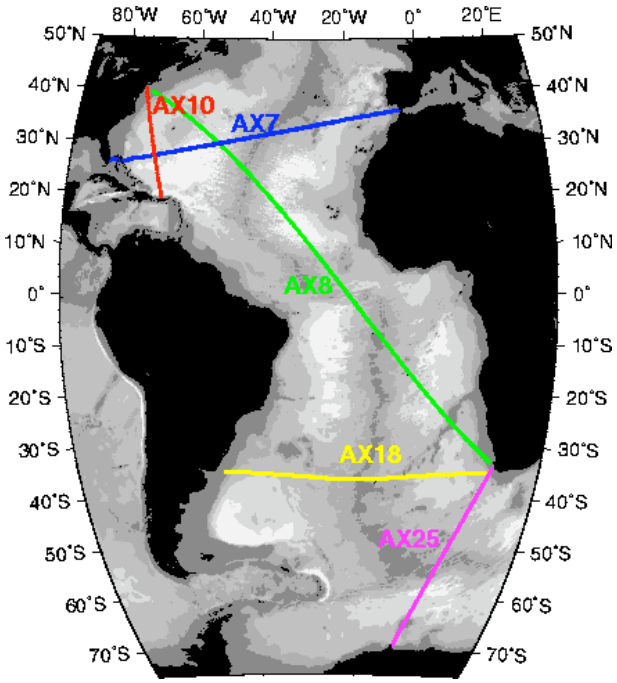


Figure 2. Location of the five high density XBT lines (AX07, AX08, AX10, AX18, and AX25) maintained by NOAA/AOML.

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 2007 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. 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.

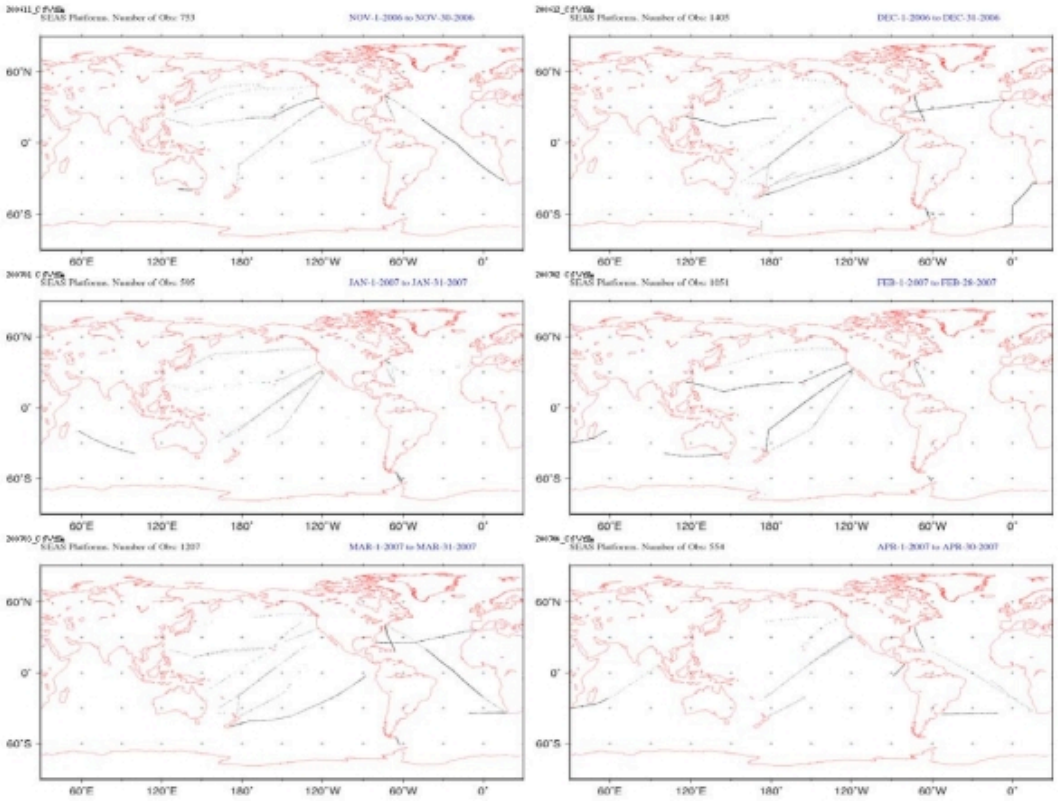


Figure 3b. XBT observations transmitted through the SEAS system for the first six months of FY2007.

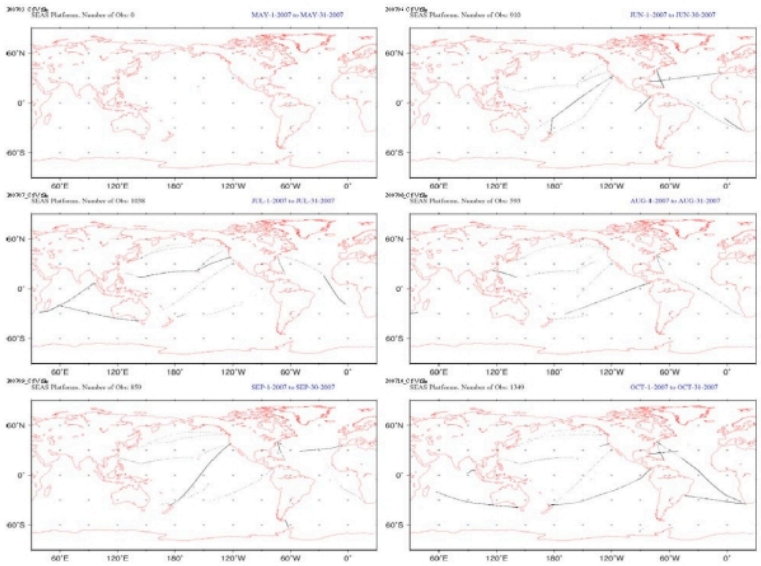


Figure 3b. XBT observations transmitted through the SEAS system for the second six months of FY2007.

1. Meteorological System (VOS ships) and SEAS software

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.

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 and is being updated to collects data from the SCS system using socket transfer. Transferring these data into the Automated MET capability of SEAS 2K 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. Seas 2000 was interfaced to the OMAO SCS system to retrieve weather data through sockets. The software retrieves the data and emulates an Auto Imet system to minimize the impact on SEAS 2K. Modifications were made to allow the new MK21 data acquisition card.

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.

XBT profiles can now be sent through the Thrane standard C units as well as through Iridium using a direct Internet connection and SMTP e-mail.

SEAS XBT Tracking- NRT XBT SEAS data arrives routinely to AOML for QC. Profiles passing the QC and VQC are subsequently distributed to the user community through the GTS. The XBT group at AOML has developed procedures to detect and identify data gaps and errors affecting prompt data availability at different stages of the collecting, processing and distribution chain. Within this context, we have developed a web page to monitor and evaluate the performance of the whole system on a daily basis. Through this web page, SEAS personnel can supervise the system's performance at different sections of the processing sequence: profiles arriving to AOML for QC, selected for VQC, going to the GTS, arriving through the GTS, etc. The information collected is presented both in tabular format and graphically using monthly charts.

SEAS NRT – AOML provides web resources to access NRT SEAS and non-SEAS XBT information. Local databases allow users to display the geographic distribution of XBT measurements at regional and global scales, subset by ship ID and date range, etc. A similar interface was developed for the meteorological measurements from the SEAS system.

Metadata - AOML participates in the META-T Pilot Project, collaborating in describing and developing a list and categorization of metadata fields. These guidelines will create a collaborative functional model between data centers and users, defining interaction models, establishing common practices and developing a robust data and metadata integration scheme.

BUFR project implementation plan- Following the SOOPIP recommendations, AOML was selected as a showcase facility to design, implement and test the BUFR format for the XBT and TSG operational data streams. At this point, field XBT&TSG incoming measurements can be encoded and decoded in BUFR, following ad-hoc templates developed at AOML. All the applications were developed using an Open Source model and can be easily modified and expanded to accommodate other data and metadata requirements, quality control procedures and different operational requirements in general. We look forward to test the whole BUFR data distribution schema with NOAA/NCEP during the next FY.

Google Earth interface- AOML has developed a GE application that greatly improves the visualization of the different in-situ observing systems, including SEAS. Using as background the global daily SST fields obtained from microwave radiometers, the interface also allows to overlay the location of drifters, Argo profilers, moorings, etc. The timebar feature on GE provides control over the time referenced datasets and permits to animate the data collection processes for each dataset.

EAS Master Ship List – The list containing the information about the ships that participate in the SEAS program is kept updated at the local AOML IDS database. Each time a new ship reports a raw SEAS report, a file is submitted to AOML with the Ship ID and the Lloyds number. Here, those fields are used to extract the ship's name, and the database is upgraded with the new records.

SEAS4 GTS - We submitted SEAS4 formatted data to the GTS without passing for the automatic QC, using a program developed at AOML for reading that format and formats the JJVV message accordingly. We developed a similar program to read the SEAS2K message but as actually there are programs performing those tasks on the NOS side, I don't ellaborate on this. This item should be removed.

3. Thermosalingraph (TSG) System

The TSG transmission system was tested on the Cap Victor in September 2006. During this fiscal year the TSG transmission system was successfully tested in the M/V Explorer and on the Oleander. The SEAS 2000 software was implemented for easy setup and to require no user input once started. The TSG computer resides in the engine room and collects data from the TSG junction box and time/position stamps the TSG data. The TSG Server can read GPS data in two possible ways either from the Time Server or from the TSG junction box. If the TSG module collects GPS data from the junction box it can pass on this GPS data to the Time Server for use by SEAS2K if necessary. The TSG data is transferred to the bridge over the ship intranet and can then be transmitted. TSG collection and transmission was added as a standalone component interfacing to the SEAS 2K Time/Position Server.

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. A full report of the XBT deployments by line is shown at: **http://www.aoml.noaa.gov/phod/goos/ldenxbt/index.php**. For the lines maintained exclusively by NOAA/AOML, the deployments are shown in Table I.

	XBT transmissions	
Line	AOML transects FY06 *	AOML XBTs FY06*

AX10	7	843
AX07	12	772
AX08	4	1349
PX13	10	427
PX37-PX10-PX44	16	1901
PX26	17	508
PX08	9	1395

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

This year LD sampling maintained the reduced levels of the previous year, FRX lines already begun were continued. 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.

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 number of XBT deployed in each line is shown in Table I.

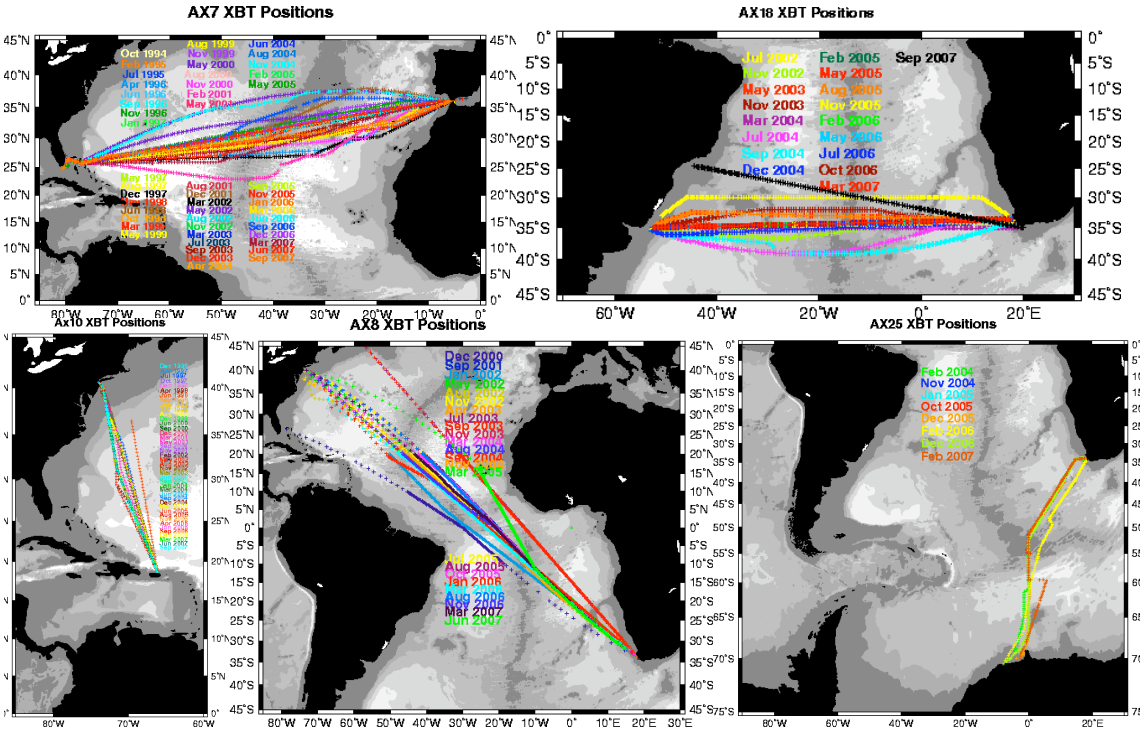


Figure 4. Location of XBT deployments for XBT lines AX07(top left), AX18 (top right), AX10 (bottom left), AX8 (bottom middle), and AX25 (bottom right) from the high-density XBT web

High-density XBT Observations

XBT deployments along HD lines proceeded as planned in previous years for most sections: 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 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. In fiscal year 2006 three

cruises of data were received from our collaborators 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

Line Designation	# Sections FY07	# XBTs	Avg # XBTs	Percentage Good	ARGO deployed	Drifters deployed
AX7	4	779	194.8	96.1	12	2
AX10	4	438	109.5	93.2	2	1
AX8	4	1036	259.0	94.8	15	20
AX18	3	533	177.7	95.7	8	2
AX25	2	355	177.5	98.0	0	6
Total	17	3141		95.4	37	31

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

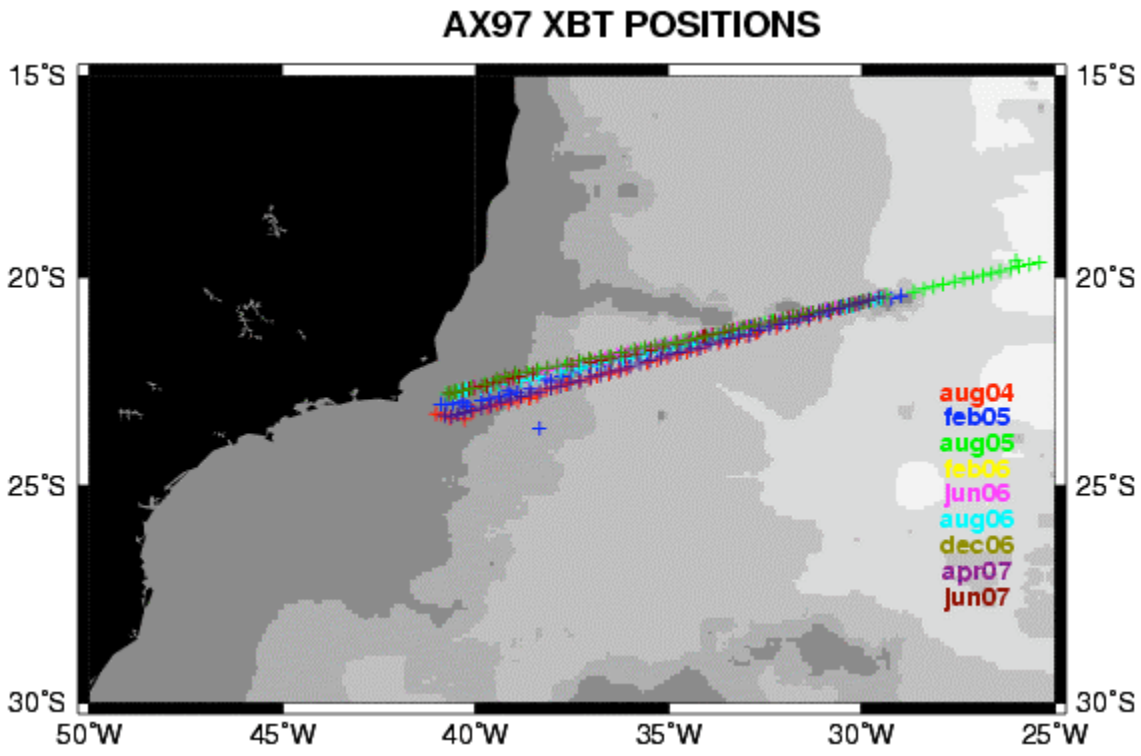


Figure 5. Deployment locations of XBTs on the line AX97 located off the coast of Brazil.

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
South African Institute for Aquatic Biodiversity, 0.3 pallets

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
South Africa : Mozambique Channel

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.

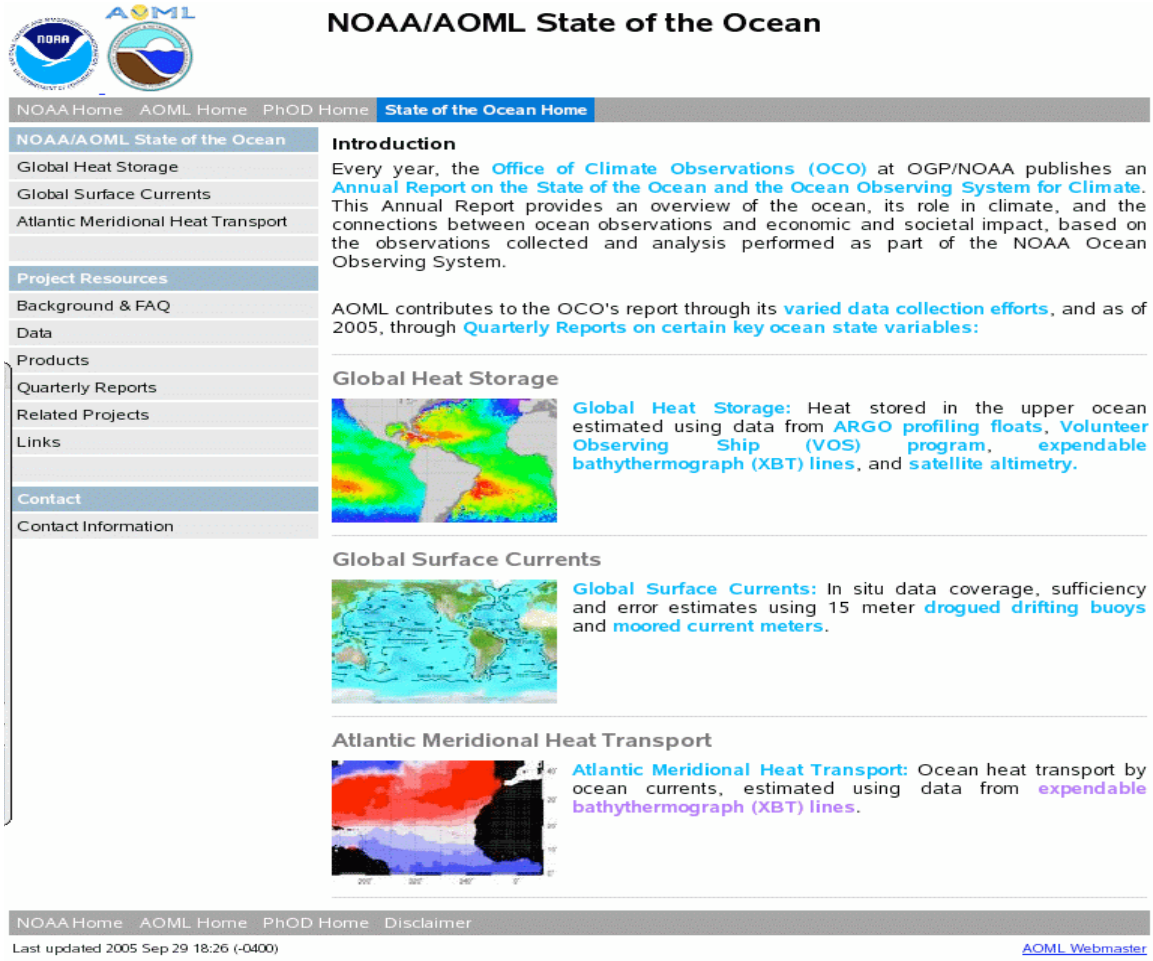


Figure 6: Main title page developed for the dissemination of products developed to provide input into the state of the ocean reports for NOAA's Office of Climate Observations.

2. Antarctic Circumpolar Current: Temperature profiles obtained from AX25 transects are being used to monitor the spatial and temporal variability of the Polar Front south of South Africa. These data have been used together with altimetry fields to derive a methodology to monitor the frontal variability.

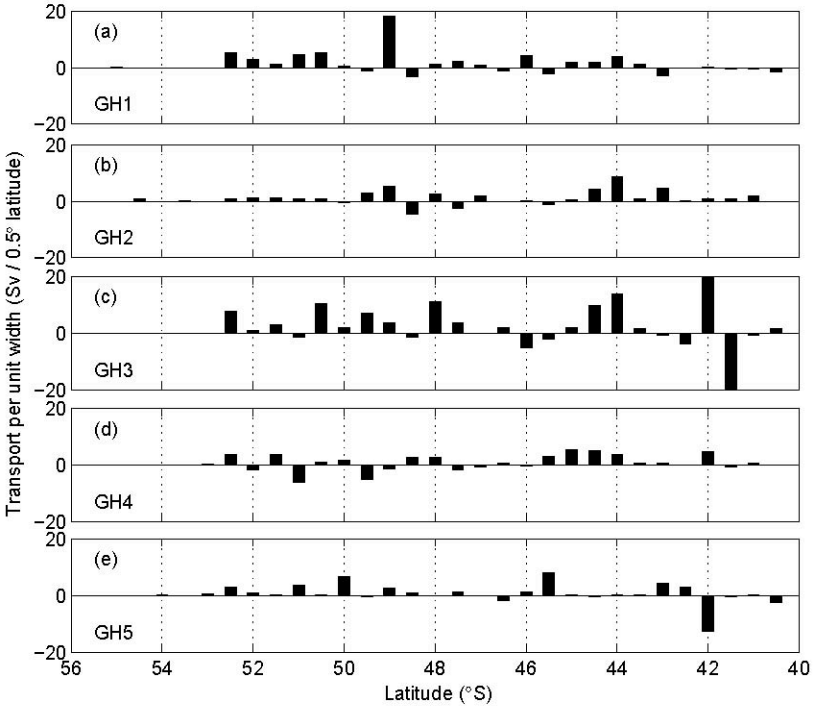


Figure 7: Baroclinic transport across the first five AX25 sections (known as GoodHope, GH, transects) per half degree latitude. Eastward flow is positive.

3. Baringer and Garzoli (2007 and Garzoli and Baringer (2007) determined the heat transport across the high density line AX18 using first fourteen sections collected between July 2002 and May 2006 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 7). 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. This work resulted in two publications in FY2006.

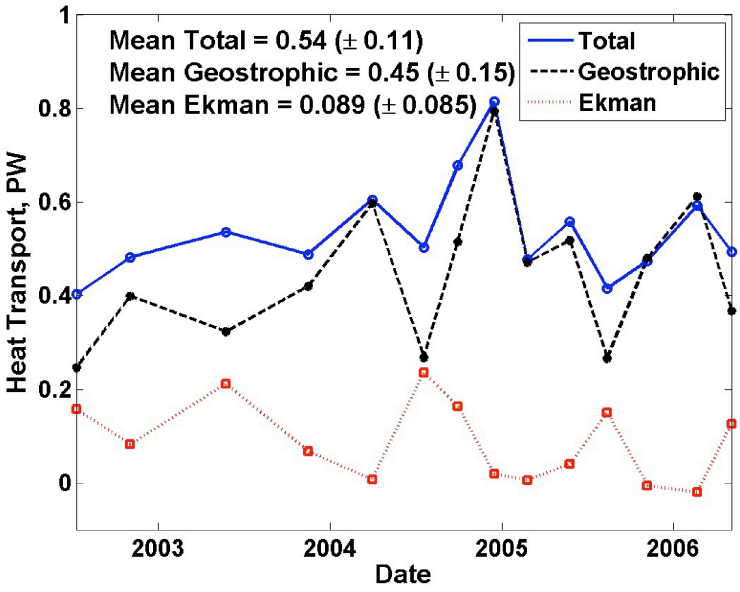


Figure 7: Variability with latitude of the computed total (red) and geostrophic (blue) fluxes. The lines are the linear fit between the total heat transport (red) and geostrophic heat transport (blue) with latitude.

Publications:

Peer-reviewed:

1. Thacker, W.C., 2007. Estimating salinity to complement observed temperature, Part 1: Gulf of Mexico. *Journal of Marine Systems*, 65 (1-4), 224-248.
2. Thacker, W. C. and L. R. Sindlinger, 2007. Estimating salinity to complement observed temperature, Part 2: Northwestern Atlantic. *Journal of Marine Systems*, 65 (1-4), 249-267.
3. Baringer, Molly O. and Silvia L. Garzoli, 2007. Meridional Heat Transport using Expendable Bathythermographs. Part I: Error Estimates from model and hydrographic data, *Deep Sea Research, (Part 1)*, DOI information doi:10.1016/j/dsr.2007.03.011.
4. Garzoli, Silvia L. and Molly O. Baringer, 2007. Meridional Heat Transport using Expandable Bathythermographs Part II: South Atlantic Transport. *Deep Sea Research (Part 1)*, DOI information doi:10.1016/j.dsr.2007.04.013.
5. Baringer, M. O. and C. S. Meinen, 2007. Thermohaline Circulation *in* Supplement to State of the Climate in 2006, A.Arguez, ed., *Bulletin of the American Meteorological Society:* Vol. 88, No. 6, pp. s1–s135, doi: 10.1175/BAMS-88-6-State of the Climate.
6. Transport and variability of the Antarctic Circumpolar Current south of Africa. S. Swart, S. Speich, I. Ansorge, G. Goni, S. Gladyshev, J. Lutjeharms, J. Geophys. Res., 2007 (in press).
7. Application of oceanic heat content estimation to operational forecasting of recent Atlantic category 5 hurricanes. Weather and Forecasting, Mainelli, M., DeMaria, M., Shay, L., Goni, G., 2007 (in press).

Presentations:

G. Goni, M. Baringer, and D. Snowden, NOAA XBT Operations, Ship of Opportunity Team Meeting, Geneva, Switzerland, 16-21 April, 2007.

G. Goni, D. Snowden, NOAA TSG Operations, Ship of Opportunity Team Meeting, Geneva, Switzerland, 16-21 April, 2007.

Evaluation of the observing system for heat content and surface currents, G. Goni, P. DiNezio, C. Schmid, and R. Lumpkin, Ocean Surface Topography Science Team Meeting, Hobart, March 12-15, 2007.

Worshops:
NOAA/AOML SEAS, XBT, and TSG Operations. Miami, Florida, 25-27 June, 2007.

8. A monitoring system for heat and mass transport in the South Atlantic as a component of the Meridional Overturning Circulation, Buenos Aires, May 8-10, 2007:

Ships of Opportunity

Robert A. Weller and Albert J. Plueddemann
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 Air-Sea Interaction Meteorology (ASIMET) system developed at WHOI. 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 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 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 efforts to get 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

VOS Field Operations

The implementation of the ASIMET hardware on the VOS is the AutoIMET. AutoIMET was developed at WHOI to meet the need for improved marine weather and climate forecasting. It is a wireless, high time resolution system for making systematic, climate quality measurements of surface meteorology. The AutoIMET system interfaces to the NOAA SEAS 2000 (Shipboard Environmental (Data) Acquisition System) that automatically receives the meteorological data and sends in hourly reports via Inmarsat C.

The basic deliverable is the data, supported by the appropriate metadata. Descriptions, technical information and raw data from the several VOS being serviced is posted on our VOS website: http://kuvasz.whoi.edu/vos. Data (plots) are presented for all ship sets. Quality controlled data files are available for the VOS Enterprise for April 2002 through May 2006. Data from other cruises are available by request from Frank Bahr (fbahr@whoi.edu). Instrument design questions can be addressed to Dave Hosom (dhosom@whoi.edu). Data from transects of the Atlantic ship Merkur passing near the NTAS buoy have been processed and used in evaluation of spatial variability. In an effort to obtain quality meteorological data in closer proximity to the NTAS site, we have also begun processing of shipboard data from the NTAS-1 through 6 mooring service cruises.

We have typically supported ASIMET installations on two ships. A first-order challenge is the short lifetime of a given ship on a given route. Our longest running vessel has been the Horizon Enterprise, doing the Oakland -Hawaii-Guam-Taiwan-Tacoma run (Fig. 1). The second VOS was an Atlantic ship (originally the SeaLand Express and then the Merkur during 2004-2005). In February 2006, the Atlantic ship was sold. We are waiting for colleagues at AOML to initiate a new Atlantic ship for XBT sampling and plan to re-install the ASIMET hardware on that ship. At present we are maintaining two Pacific installations, the Horizon Enterprise and the Horizon Hawk. The Enterprise stopped going all the way across the Pacific, and now runs between the West Coast and Hawaii (Fig. 2). A new installation on the Horizon Hawk is evaluating this ship as an alternated trans-Pacific installation, as the Horizon Hawk runs from the west coast to Hawaii, Guam, Taiwan, Hong Kong, and back to the west coast (Fig. 2). The Field

Operations effort carries out two turnarounds per year for each ship that we have systems installed on. This includes the preparation and calibration of the systems, and recovery of the raw data as well as the ancillary time series of ships' position and velocity.

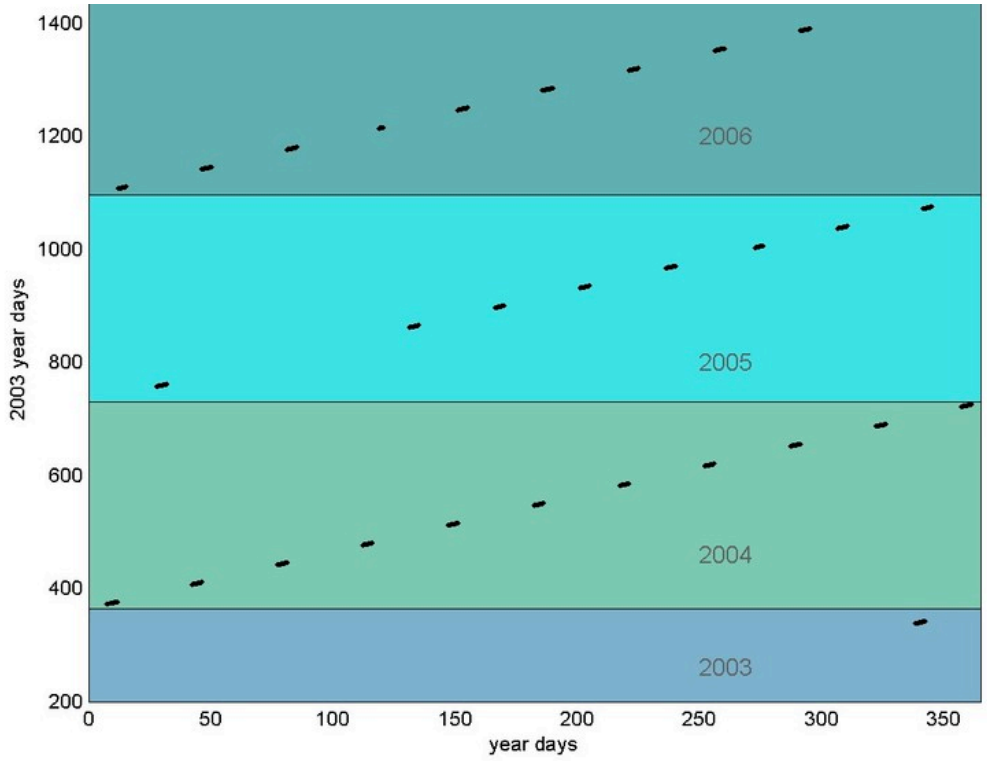
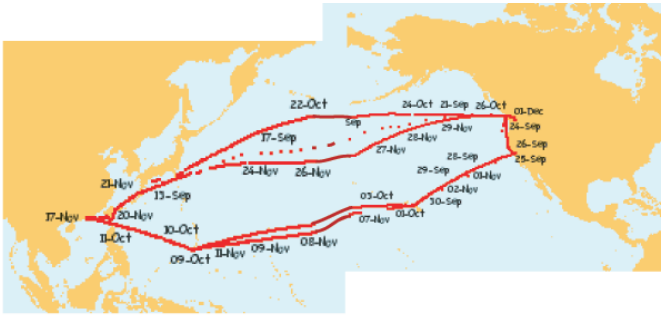


Figure 1. Season vs. year breakdown of twenty nine VOS Horizon Enterprise transects between Oakland CA and Honolulu for the period 2003 – 2006. These data were used to evaluate spatial variability in the ECMWF fields.

Ship selection in the Atlantic and our interface to the NOAA SEAS system is via AOML (Atlantic Oceanographic and Meteorological Laboratory, Miami, Florida). In the Pacific there is ongoing cooperation with Scripps Institution of Oceanography via the CORC (Consortium for Ocean Climate Research) program on Pacific ship scheduling and support. Some logistical support is provided by the Southern California Marine Institute on ship turnarounds. There is also ongoing cooperation with many sensor manufacturers and the VOS people at the German Weather Service (Deutsch Wetter Dienst) in Hamburg Germany.

Horizon Enterprise



Horizon Hawk

Figure 2. Recent routes for the Horizon Enterprise (left) and Horizon Hawk (right).

Specific activities relating to supporting the VOS Horizon Enterprise and Horizon Hawk during the reporting period are listed below.

May 2006; Tacoma, WA: Horizon Enterprise. AutoIMET sensor turn-around.
Nov 2006; Tacoma, WA: Horizon Enterprise. AutoIMET sensor turn-around.
Apr 2007; Oakland, CA: Horizon Enterprise. AutoIMET sensor turn-around.
Jun 2007; Honolulu, HI: Horizon Enterprise. Address problem with air temperature (AT) and humidity (HRH) readings.
Jul 2007; Oakland, CA: Horizon Hawk. Inspection of vessel in preparation for AutoIMET installation.

For now, the availability of two systems while we await selection of a new Atlantic ship, together with the proven performance of the Horizon Enterprise, has argued for continuing on the Enterprise, even though she only goes from the west coast to Hawaii and back. The push this year has been to instrument the Horizon Hawk to evaluate the possibility of focusing on this ship (rather than the Enterprise) to maintain a trans-Pacific route. 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. We continue to need to upgrade the hardware to address lessons learned, and we also continue 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.

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 found that some of the components in our ASIMET circuit boards are no longer available or soon to be obsolete, including the digital memory cards used to log the data. 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. Prototype new sensor modules were built and tested at WHOI and in the field.

Data Analysis

Work under this task is yielding information about the spatial variability and coherence of the surface meteorological fields by examining data from VOS track lines. Initial effort in the Atlantic was focused on tracks from the R/V Merkur that passed within 500 km of the NTAS Ocean Reference Station (Fig. 3). Auto-correlation functions for ship and buoy showed that typical de-correlation times are from 3 to 6 h (Fig. 4). Cross-correlation between ship and buoy indicated that spatial correlation scales are < 200 km on short (< 20 h) time scales. Barometric pressure, dominated by the semidiurnal atmospheric tide, and shortwave radiation, dominated by the diurnal cycle, showed the most coherence between ship and buoy.

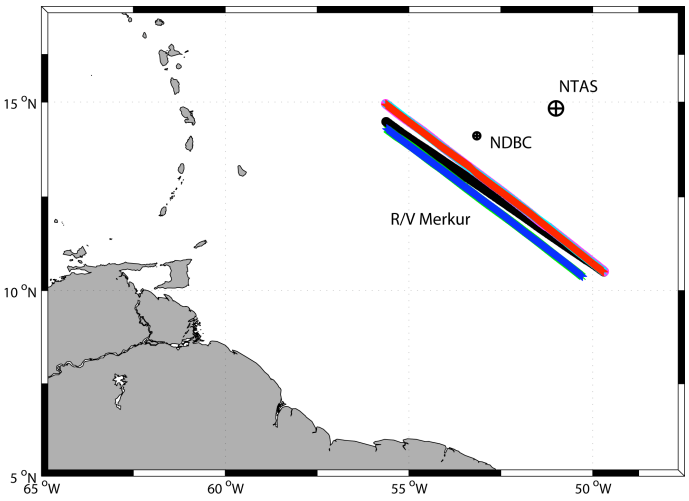


Figure 3. Ship tracks (color) for six "encounters" of the R/V Merkur passing within 50 km of the NTAS buoy. The NDBC 41041 station is also shown.

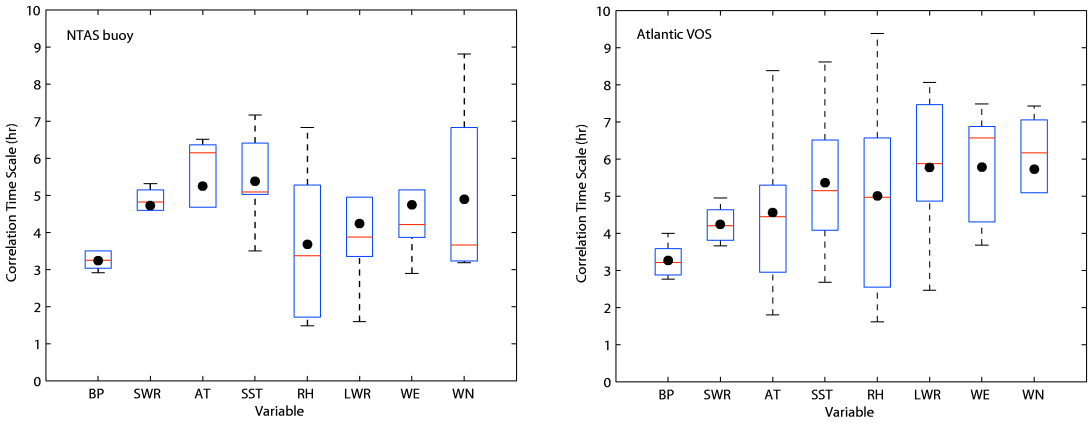


Figure 4. Auto-correlation time scale (hours) for meteorological variables observed on the NTAS buoy (left) and the Atlantic VOS (right). Box plots show the mean (dots), median (red line), upper and lower quartile values (blue box) and extent of data within 1.5 times the inter-quartile range (dashed whiskers).

The second investigation used repeat transects of the Enterprise between Oakland and Honolulu between 2003 and 2006 (Fig. 1). In this study, we compared spatial variability in the VOS records with that of the ECMWF model output along the ship track (Fig. 5). VOS data were averaged to 1 hr and compared with ECMWF data for the

appropriate grid cell during each ~6 day transit. Most variables showed good agreement in the mean, but notable discrepancies were found on short spatial scales.

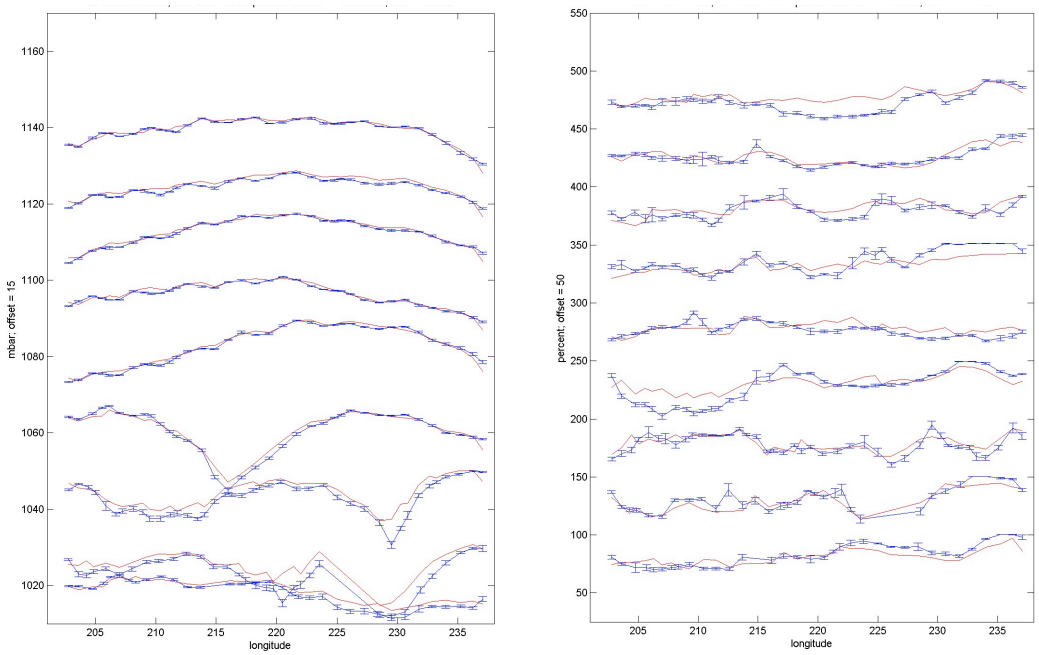


Figure 5. Comparison of hourly averaged BP (left) and RH (right) from the Enterprise VOS (blue, with error bars) and ECMWF (red) for a subset of Oakland-Honolulu transits. Each transit spans about 6 days in time, and is plotted vs. longitude. The first transit of the group is shown at the bottom; an offset has been applied for successive records.

Publications and Reports

Plueddemann, A., F. Bahr, D. Hosom and R. Weller, 2007. Spatial Variability in Surface Meteorology from a VOS and the ECMWF model, NOAA Office of Climate Observation Annual System Review, Silver Spring, MD (poster).

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.

Argo Profiling Floats

a. The Argo Project: Global Observations for Understanding and Prediction of Climate Variability

The Argo Project: Global Observations for Understanding and Prediction of Climate Variability

Dean H. Roemmich[1], Russ E. Davis[1], Stephen C. Riser[2], W. Brechner Owens[3], Silvia L. Garzoli[4], Gregory C. Johnson[5]

[1] Scripps Institution of Oceanography, La Jolla CA
[2] School of Oceanography, University of Washington, Seattle WA
[3] Woods Hole Oceanographic Institution, Woods Hole MA
[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), a global array of autonomous profiling floats, is implemented through this award. The present report covers Year 1 of the 5-year "sustained phase" of the project, which builds on progress made under previous awards (Phases 1,2 and 3) for pilot float arrays, data system development, and global implementation.

As of November 1, 2007, the international Argo Project, including the US contribution, has met its goal of building a global array of 3000 active profiling CTD floats (Roemmich and Owens, 2000, Roemmich et al, 2001, 2002, Gould et al., 2004), and established a data system to meet the needs of both operational and scientific users for data delivery in real time and delayed mode. In order to maintain the Argo array, it is necessary to replace over 25% (800) instruments every year. Argo is a major initiative in oceanography, with research and operational objectives, providing a global dataset for climate science and other applications. It is a pilot project of the Global Ocean Observing System (GOOS).

Phase 1 (9/99 – 9/02) and Phase 2 (7/00 – 6/02) of US Argo provided regional arrays of CTD profiling floats to demonstrate technological capabilities for fabrication and for deployment of float arrays in remote ocean locations (Phase 1) and to demonstrate the capability for manufacture and deployment of large float arrays (Phase 2). Development of the U.S. Argo Data System was carried out to make Argo data publicly available within a day of collection, to apply automated quality control procedures consistent with international Argo practices, and to provide research-quality data in delayed-mode.

Phase 3 of US Argo was a 5-year project (8/01 – 6/06) aimed at full implementation of the US component of Argo. Float deployment rates were increased to more than 400 per year beginning in CY 2004 (Fig. 1). Objectives were to achieve 1500 active US Argo floats (50% of the global array), to improve the spatial distribution of floats toward the target of uniform 3° spacing, to increase the mean lifetime of floats to 4 years, to operate the near-real time and delayed-mode data systems consistent with international agreements, and to provide substantial leadership and coordination roles for international Argo.

Phase 4 of US Argo is a follow-on 5-year project (7/06 – 6/11) aimed at improving and sustaining the US component of Argo. Float deployment rates should continue at about 400 per year. Objectives are to complete and sustain the array of 1500 active US Argo floats, to further improve the spatial distribution of floats through targeted deployments, to further increase the mean lifetime of floats beyond 4 years, to continue to improve and operate the near-real time and delayed-mode data systems

consistent with international agreements, and to provide substantial leadership and coordination roles for international Argo.

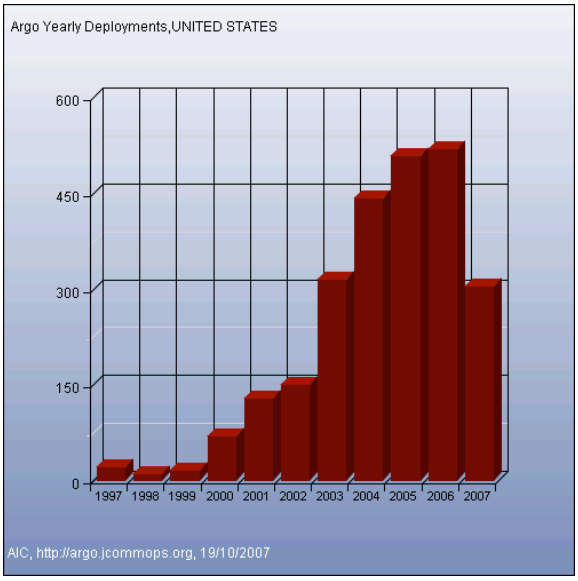


Figure 1: *Yearly deployments of United States Argo floats through 19 October 2007(including Argo-equivalent), and growth in the number of active US floats. (Source:AIC)*

Float production and deployment are accomplished by four facilities – SIO (production and deployment), WHOI (production)/AOML (deployment), UW (assembly and deployment), and PMEL (thorough testing and deployment of commercially manufactured floats). This distributed effort has been designed to safeguard the US contribution to the Argo project from unforeseen problems at any one of the partner institutions. It also makes Argo success independent of the participation of any individual PI and institution or of any single float design. It allows the large amount of effort to be shared. It encourages individual, technical innovation and enhancement. While the initial focus has been on improving float technical performance, attention of the PIs will increasingly focus on demonstrating the scientific value of Argo.

The data system is also distributed. AOML is the US Argo Data Assembly Center (DAC), responsible for acquiring the float data received by satellite communications, for carrying out real-time quality control, and for distribution of data via the GTS and to the Global Argo Data Assembly Centers. The second step in data management is a semi-automated drift-adjustment of the salinity sensor carried out by each float-providing PI, using nearby high quality CTD data for comparison with float temperature/salinity data (Wong et al, 2003). The final step is individual examination of all profiles by the float-providing PIs, in order to provide high-quality data suitable for research applications.

All Argo data are freely available within about 24 hours of collection, and can be accessed from the GTS or internet (http://www.usgodae.org/, or http://www.ifremer.fr/coriolis/cdc/argo.htm).

ACCOMPLISHMENTS

The goal of 1500 active US Argo floats has been achieved (Fig. 2). As of 30 September 2007 there are 1521 active US Argo floats, plus 88 US Argo-equivalent instruments that also feed data to the US Argo DAC. Float deployments have continued at 400 per year through the first year of Phase 4.

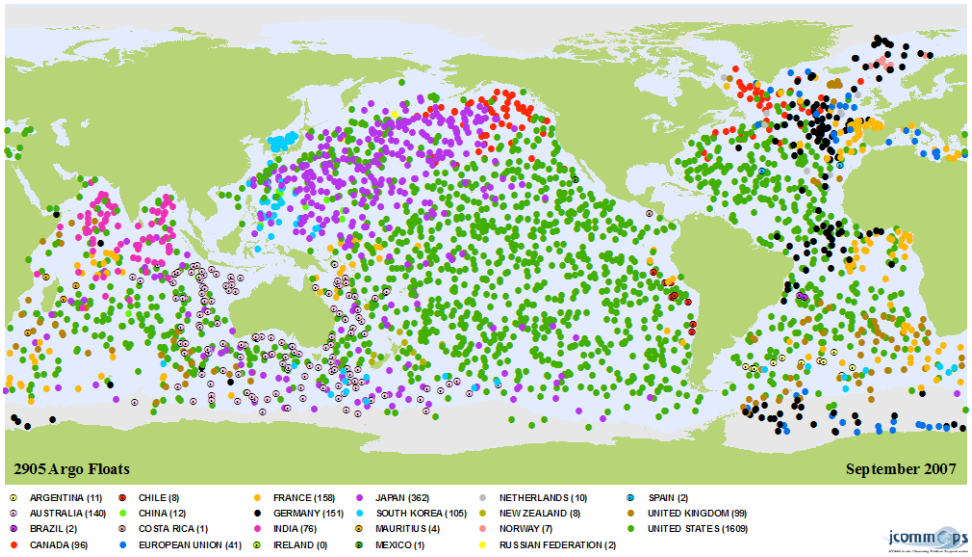


Figure 2*: The Argo Array as of 30 September 2007. The 1609 active US floats (Green), included 1521 floats funded via US Argo, and 88 other US (Argo-equivalent) floats whose data are released by the PIs via the US Argo Data Assembly Center.*

944 of the 1521 active US Argo floats are in the Southern Hemisphere, reflecting the US commitment to eliminate the northern bias of the international Argo array and achieve uniform global coverage. A notable effort has been the collaboration between US Argo and NIWA (Argo-New Zealand), resulting in more than 450 deployments since 2004 in remote ocean locations by NIWA's R/V Kaharoa. Funding shortfalls may decrease the level of this work in future.

Good progress has been made in increasing float lifetimes (Fig. 3). For floats deployed in 2004, about 75% remain active after 130 cycles. Nearly 90% of 2005 deployments remain active after 100 cycles. It is likely that the goal of a 4-year mean lifetime has been met for both APEX and SOLO designs. The re-design of the SOLO float (SIO) is nearly complete for increased lifetime and capabilities. Prototypes will be deployed in the coming year. The US is the technology leader in profiling floats and about 90% of floats in the international array are made in the US.

The Argo data system continues to operate well, with the AOML DAC providing near-real time data to the GDACs in NetCDF format consistent with international specifications. Improvements in procedures continue to be implemented as required by the International Argo Data Management Team. A backlog in processing of research-quality delayed-mode data has been substantially reduced and will be eliminated in the coming year. A pressure-offset error was detected in some WHOI floats this year and corrective steps have been taken (http://www-argo.ucsd.edu/Acpres_offset2.html). Procedures are being considered for more effective detection of systematic data errors.

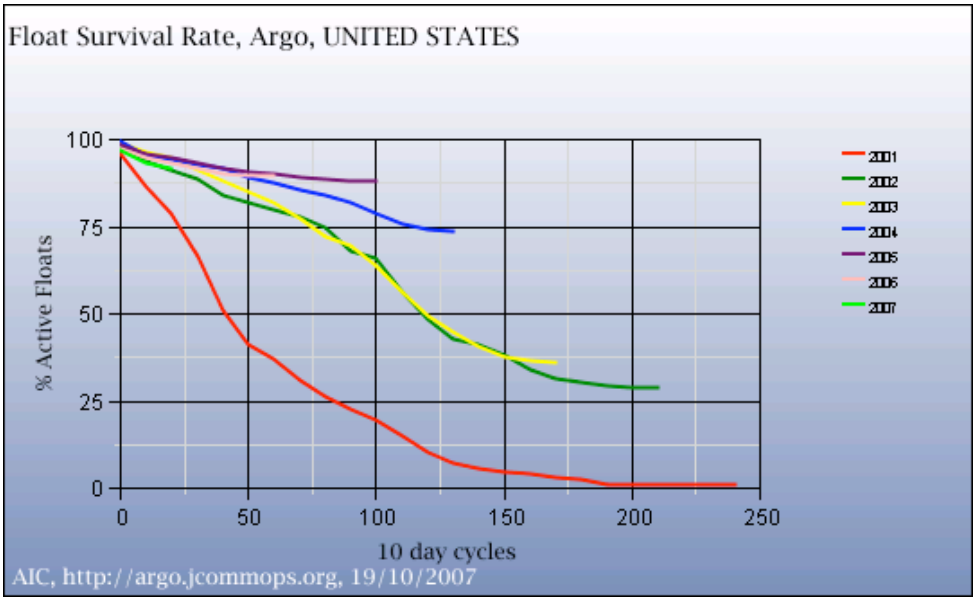


Figure 3: *Float reliability. Note that the percentage of floats surviving for at least 100 cycles increased from about 65% for 2002/03 deployments to about 90% for 2005 deployments.*

The US Argo consortium plays strong leadership roles in the international Argo project. This includes the international Argo Steering Team Co-Chairman (Dean Roemmich, SIO) and the international Argo Data Management Team Co-Chairman (Mark Ignaszewski, FNMOC) as well as many international panel memberships. US partners provide international leadership in float technology and data management techniques through workshops and training of international colleagues. US partners provide coordination for deployment planning activities in the Pacific, Atlantic, and Southern Oceans. The US is also a leader in utilization of Argo data, organizing international symposia such as the Argo session at the 2007 IUGG conference, and through sharing of research results and operational capabilities.

The Argo array is providing unprecedented views of the evolving physical state of the ocean. It reveals the physical processes that balance the large-scale heat and freshwater budgets of the ocean and provides a crucial dataset for initialization of and assimilation in seasonal-to-decadal forecast models.

About 300 research publications have resulted so far from Argo data, including 132 in 2006-2007 (to date). These publications span a wide variety of research topics from small spatial-scale/short time-scale phenomena such tropical cyclone intensification, to studies of mesoscale eddies, to large-scale phenomena such as water mass variability and basin-scale ocean circulation. Almost none of this work would have been possible without the contributions of US Argo to building, sustaining, and utilizing the array.

A sparse global Argo array was achieved in 2004, and so there are now nearly 4 years of continuous global coverage. The 4-year global dataset provides a baseline of the present climate-state of the oceans (Fig. 4), against which future variability can be observed by a sustained Argo array. It also provides a comparison point for past datasets to describe decadal change in the oceans. With 4-years of data we have, for the first time, a stable estimate of the mean and annual cycle of the global ocean over a fixed period of time (Fig. 5).

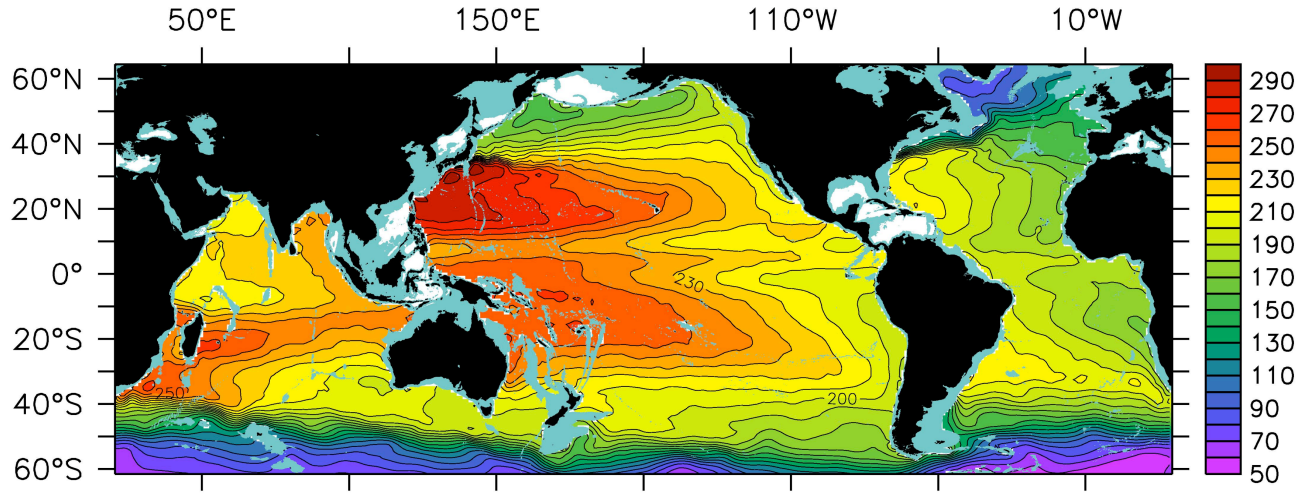


Figure 4: *Argo observes the mean state of the oceans, 2004 – 2006: mean dynamic height of the sea surface relative to 2000 dbar (dyn-cm).*

At least 13 operational centers around the world are using Argo data on a routine basis (http://www.argo.ucsd.edu/FrUse_by_Operational.html). Operational applications include ocean state estimation, short-term ocean forecasting, atmosphere/ocean seasonal-to-interannual prediction, and coupled climate modeling. Ocean state estimation has an increasing number of valuable uses including climate monitoring, forecast initialization, fisheries and ecosystem modeling, provision of boundary conditions for regional and coastal modeling, and others. At the most recent Argo Steering Team meeting, operational centers reported on their use of Argo data, and noted positive impacts in all the above applications.

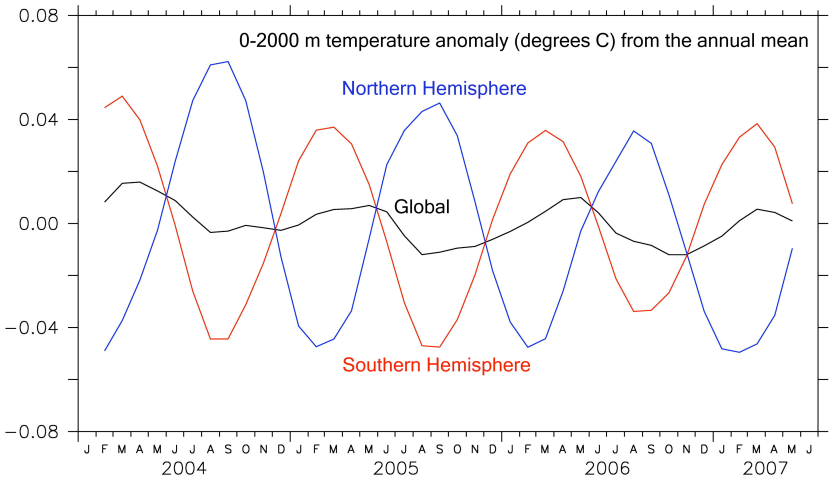


Figure 5: *Argo takes the ocean's "pulse": Time-series of global (black), Southern Hemisphere (red) and Northern Hemisphere (blue) averaged ocean temperature (anomaly from the annual mean), 0-2000 m, from Argo data.*

US Argo Consortium relevant web sites:

Argo Steering Team home page http://www-argo.ucsd.edu
Argo Information Center http://argo.jcommops.org
Scripps Institution of Oceanography http://sio-argo.ucsd.edu
Woods Hole Oceanographic Institution http://ursa.whoi.edu/~argo/
University of Washington http://flux.ocean.washington.edu/argo/

NOAA PMEL http://floats.pmel.noaa.gov
NOAA AOML(US DAC and South Atlantic Argo Regional Center)
http://www.aoml.noaa.gov/phod/argo/index.php

US GDAC http://www.usgodae.org

REFEREED PUBLICATIONS:

Papers Published in FY 2007:

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

Baringer, M.O., S.L. Garzoli, 2007: Meridional heat transport determined with expendable bathythermographs – Part 1: Error estimates from model and hydrographic data. Deep-Sea Research Part I – Oceanographic Research Papers 54(8): 1390-1401.

Garzoli, S.L., M.O. Baringer, 2007: Meridional heat transport determined with expendable bathythermographs – Part II: South Atlantic transport. Deep-Sea Research Part I – Oceanographic Research Papers 54(8): 1402-1420.

Johnson, G. C., J. M. Toole, and N. G. Larson, 2007: Sensor corrections for Sea-Bird SBE-41CP and SBE-41 CTDs. Journal of Atmospheric and Oceanic Technology, 24, 1117-1130.

Johnson, G.C., and J.M. Lyman, 2007: Global Oceans: Sea Surface Salinity. In State of the Climate in 2006, A. Arguez, Ed., Bulletin of the American Meteorological Society, 88, 6, S34-S35.

Johnson, G.C., J.M. Lyman and J.K. Willis, 2007: Global Oceans: Heat Content. In State of the Climate in 2006, A. Arguez, Ed., Bulletin of the American Meteorological Society, 88, 6, S31-S33.

Johnson, K., J. Needoba, S. Riser, and W. Showers (2007) Chemical sensor networks for the aquatic environment. *Chemical Reviews*, 107, 623-640.

Korotaev, G., T. Oguz, S. Riser, 2006: Intermediate and deep currents of the Black Sea, obtained from autonomous profiling floats. Deep-Sea Res Pt II 53(17-19): 1901-1910

Roemmich, D., 2007. Super spin in the southern seas. *Nature, 449,* 34-35.

Roemmich, D., J. Gilson, R. Davis, P. Sutton, S. Wijffels, & S. Riser, 2007: Decadal spinup of the South Pacific subtropical gyre. Journal of Physical Oceanography, 37 (2), 162-173.

Schmid, C., R.L. Molinari, R. Sabina, Y-H. Daneshzadeh, X. Xia, E. Forteza, and H. Yang , 2007: The real-time data management system for Argo profiling float observations. Journal of Atmospheric and Oceanic Technology 24 (9): 1608-1628.

Ueno, H., E. Oka, T. Suga, H. Onishi, D. Roemmich, 2007: Formation and variation of temperature inversions in the eastern subarctic North Pacific. Geophysical Research Letters 34 (5): Art. No. L05603.

Willis, J. K., J. M. Lyman, G. C. Johnson, and J. Gilson. 2007. Correction to "Recent cooling of the upper ocean". Geophysical Research Letters, 34, L16601, doi:10.1029/2007GL030323.

Papers Submitted In FY 2007:

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

Freeland, H., D. Roemmich, W.J. Gould, and M. Belbeoch, 2007. Argo ? a global ocean observing system for the 21st Century. In: The Full Picture, Paris, Group on Earth Observations (GEO). Edited by the GEO Secretariat, pp 67-71.

Gourdeau, L., W.S. Kessler, R.E. Davis, et al, 2008: Zonal Jets Entering the Coral Sea. Journal of Physical Oceanography, 3, 715-725.

Lyman, J. M, and G. C. Johnson. 2008. Estimating global upper ocean heat content despite irregular sampling. Journal of Climate, in press.

Owens, W.B. and A. P. S. Wong, 2008. An Improved Calibration Method for the Drift of the Conductivity Sensor on Autonomous CTD Profiling Float by theta-S Climatology. Deep Sea Research, in press.

Riser, S.C. and K.S. Johnson, 2008: Net production of oxygen in the subtropical ocean. Nature, 451, 323-326. doi:10.1038/nature06441.

Riser, S.C., L. Ren, and A. Wong (2008) Salinity in Argo: a modern view of a changing ocean. *Oceanography*, **21**, 56-67.

Roemmich D. and J. Gilson, 2008. The 2004 ? 2007 mean and annual cycle of temperature, salinity and steric height in the global ocean from the Argo Program. Submitted to *Progress in Oceanography*.

See http://www.argo.ucsd.edu/FrBibliography.html .

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REFERENCES

Argo Science Team, 2001. Argo: The global array of profiling floats. From: *Observing the Oceans in the 21st Century*. C. Koblinsky and N. Smith eds, Melbourne, Bureau of Meteorology.

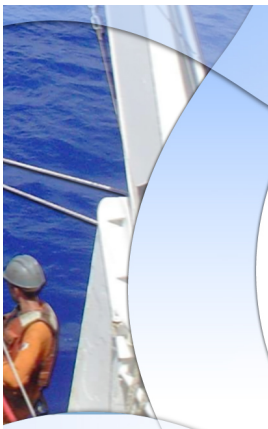
Gould, J., and the Argo Science Team, 2004. Argo Profiling Floats Bring New Era of In Situ Ocean Observations. EoS, Transactions of the American Geophysical Union, 85(19), 11 May 2004.

Levitus, S. and 5 co-authors, 2001. Anthropogenic warming of the Earth's climate system. Science, 292, 267 – 270.

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.

Roemmich, D. and W. B. Owens, 2000. The Argo Project: Global ocean observations for understanding and prediction of climate variability. Oceanography, 13, No. 2 (NOPP Special Issue), 45-50.

Wong, A., G. Johnson and W.B. Owens, 2003. Delayed-Mode Calibration of Autonomous CTD Profiling Float Salinity Data by θ–S Climatology. Journal of Atmospheric and Oceanic Technology, 20, 308 – 318.



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 CO2 Measurements aboard the RVIB Palmer and Data Management of the Global VOS Program

c. High-Resolution Ocean and Atmosphere pCO2 Time-Series Measurements

d. Optimal Network Design to Detect Spatial Patterns and Variability of Ocean Carbon Sources and Sinks from Underway Surface pCO2 Measurements

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

Richard A. Feely[1], Rik Wanninkhof[2], Christopher Sabine[1], Gregory C. Johnson[1], Molly Baringer[2], John Bullister[1], Calvin W. Mordy[3], Jia-Zhong Zhang[2]

[1] NOAA Pacific Marine Environmental Laboratory, Seattle WA

[2] Atlantic Oceanographic and Meteorological Laboratory, Miami FL

[3] Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, WA

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.

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.

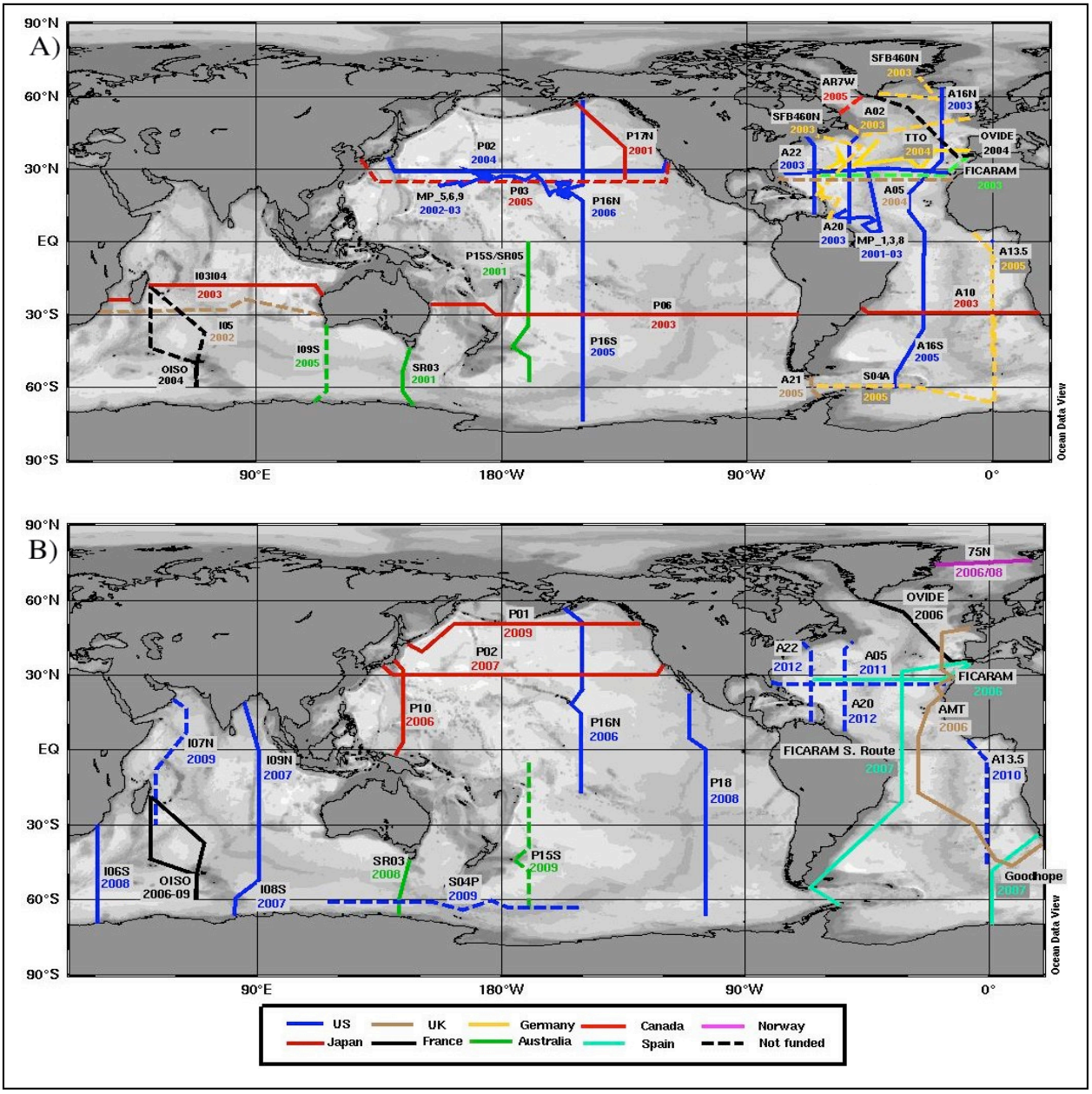


Figure 1. Global map of completed (A) and planned (B) Repeat Hydrography CO_2/tracer Program hydrographic sections with carbon system measurements. Solid lines indicate funded lines. Dashed lines indicate planned lines that are not fully funded at this time. The U.S. cruises are designated with blue lines. Solid lines are funded cruises.

Table 1. Sequence of Repeat Hydrography CO_2/tracer completed and planned cruises in the oceans - from 2003 to 2014.

Schedule of US CO2/CLIVAR Hydrography Lines (as of 8/31/07)						
Dates	**Cruise**	**Days**	**Ports**	**Year**	**Contact/Chief Scientist overall coordinator: Jim Swift, SIO**	**Ship**
06/19/03-7/10/2003	A16N, leg 1 Planning Cruise results	22	Reykjavik-Madeira	1	Bullister, PMEL	Ron Brown
07/15/03-8/11/2003	A16N, leg 2 Planning Cruise results	28	Madeira - Natal, Brazil	1	Bullister, PMEL	Ron Brown
09/15/03-10/13/2003	A20 Cruise results	29	WHOI - Port Of Spain	1	Toole, WHOI	Knorr
10/16/03-11/7/2003	A22 Cruise results	21	Port Of Spain - WHOI	1	Joyce, WHOI	Knorr
06/15/04-7/25/2004	P2, leg 1 Cruise results	41	Yokohama-Honolulu	2	Robbins, SIO	Melville
07/28/04-8/27/2004	P2, leg 2 Cruise results	32	Honolulu - San Diego	2	Swift, SIO	Melville
01/09/05-2/22/2005	P16S Cruise results	45	Wellington-Tahiti	3	Sloyan/Swift, WHOI/SIO	Revelle
01/11/05-2/26/2005	A16S Planning Cruise results	48	Punta Arenas - Fortaleza	3	Wanninkhof,Doney; NOAA/AOML,WHOI	Ron Brown
02/13/06-3/3/2006	P16N, leg 1 Planning	18	Tahiti-Honolulu	4	Sabine; NOAA/PMEL	Thompson Schedule
03/10/06-3/30/2006	P16N, leg 2 Planning	21	Honolulu-Kodiak	4	Feely; NOAA/PMEL	Thompson Schedule
02/04/07-3/17/2007	I8S	38	Dunedin, NZ-Perth	5	Swift, SIO	Revelle
03/22/07-5/2/2007	I9N	38	Perth-Colombo, Sri Lanka	5	Sprintall, SIO	Revelle
02/04/08-3/17/2008	I6S	43	Cape Town	6	Speer, FSU	Revelle
12/06/07-1/16/2008	P18, Leg 1	32	San Diego-Easter Island	6	Johnson, Bullister, PMEL	Ron Brown
01/19/08-2/23/2008	P18, Leg 2	35	Easter Island- Punta Arenas	6	Johnson, Bullister, PMEL	Ron Brown
austral summer early 2008	S4P/P16S Leg 1	25.5	Wellington-Perth	6		?

austral summer early 2008	S4P/P16S Leg 2	25.5	Wellington-Perth	6		?
2009	A13.5	40	Abidjan-Cape Town	7	future planning	NOAA
2009	I7N	47	Port Louis/Muscat		future planning	UNOLS
2010	A10	29	Rio de Janeiro-Cape Town	8	future planning	NOAA
2010	I5	43	Perth - Durban		future planning	UNOLS
2011	A5	30	Tenerife-Miami	9	future planning	NOAA
2011	A20/A22	29	Woods Hole-Port of Spain-Woods Hole		future planning	UNOLS
2012	A16N	29		10	future planning	NOAA
2012	P06				future planning	UNOLS
2013	A16S			11	future planning	NOAA
2013	P02				future planning	UNOLS
2014	P16N			12	future planning	NOAA
2014	P16S				future planning	UNOLS

The Repeat Hydrography CO_2/tracer Program is being implemented to maintain decadal time-scale sampling of ocean transports and inventories of climatically significant parameters in support of 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; 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.

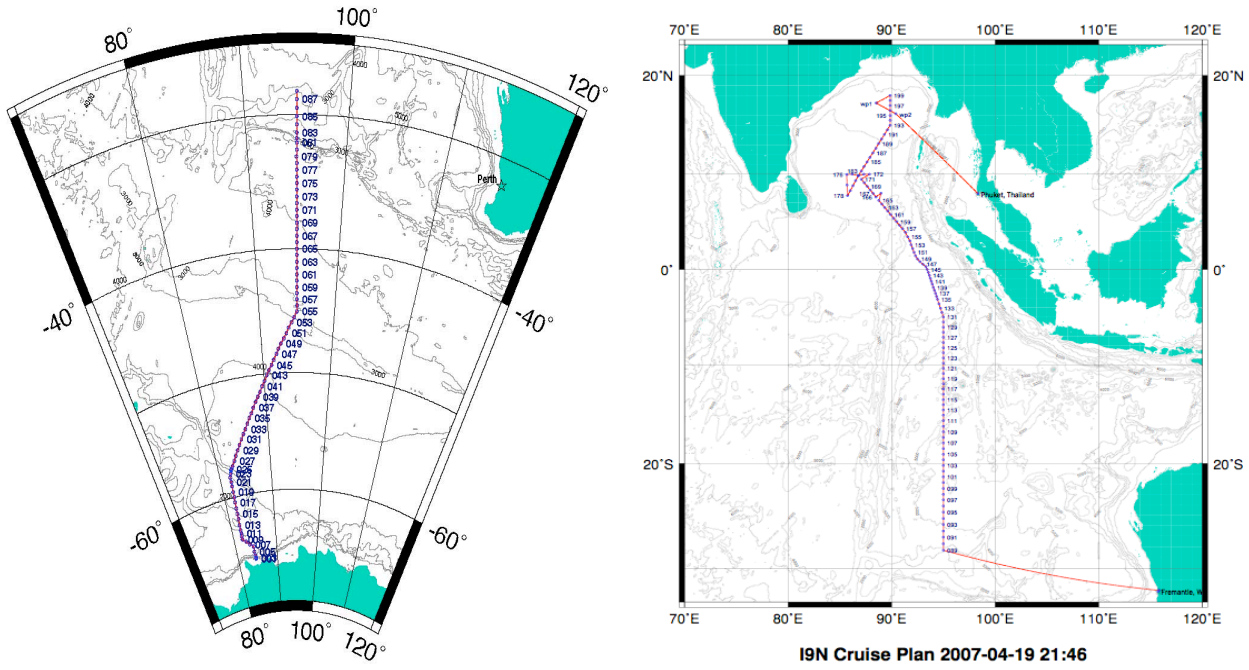


Figure 2. Cruise Tracks of Repeat Hydrography I8S and I9N during Feb – May 2007 in the Indian Ocean.

The scientific objectives are important both for the CLIVAR and the OCCC programs, and for operational activities such as Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). In mid-2001 the US scientific steering committees of CLIVAR (www.clivar.org) and the Carbon Cycle Science Program, (CCSP; www.carboncyclescience.gov) proposed the creation of a joint working group to make recommendations on a national program of observations to be integrated with international plans. Several community outreach efforts have been implemented to provide information about the program, such as a web site with interactive forum (http://ushydro.ucsd.edu/index.html), articles in EOS (Sabine and Hood, 2003) and the JGOFS newsletter, as well as AGU and Ocean Science meeting forums. The Repeat HydrographyCO_2/tracer Program addresses the need, as discussed by the First International Conference on Global Observations for Climate (St. Raphael, France; October 1999), that one component of a global observing system for the physical climate/CO_2 system should include periodic observations of hydrographic variables, CO_2 system parameters and other tracers throughout the water column (Smith and Koblinsky, 2000); (Fine et al., 2001). The large-scale observation component of the OCCC has also defined a need for systematic observations of the invasion of anthropogenic carbon in the ocean superimposed on a variable natural background (Doney et al., 2004). The CCSP has identified the critical need for the federal government to begin delivering regular reports documenting the present state of the climate system components. Through this plan NOAA 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 Global Carbon Project (GCP; http://www.globalcarbonproject.org/) has initiated the International Ocean Carbon Coordination Project (IOCCP; http://www.ioc.unesco.org/ioccp/) to: (1) gather information about on-going and planned ocean carbon research and observation activities, (2) identify gaps and duplications in ocean carbon observations, (3) produce recommendations that optimize resources for international ocean carbon research and the potential scientific benefits of a coordinated observation strategy, and (4) promote the integration of ocean carbon research with appropriate atmospheric and terrestrial carbon activities. It is through the workings of the IOCCP and international CLIVAR that international coordination of data management, data synthesis and scientific interpretation of the global repeat sections results will be implemented. In addition, the

Repeat Hydrography CO_2/tracer Program is being managed in accordance with the COSP Ten Climate Monitoring Principals.

2.0 FY 2007 PROGRESS REPORT AND ACCOMPLISHMENTS

2.1.1 I8S Cruise Results

A hydrographic survey consisting of LADCP/CTD/rosette sections, bio-optical casts, trace metals rosette sections, underway shipboard ADCP, float deployments in the southern Indian Ocean was carried out in February and March 2007. The R/V Revelle departed Dunedin, New Zealand on 4 February 2007. A total of 88 stations were occupied. Eighty-eight LADCP/CTD/Rosette casts, 39 Trace metals Rosette casts, 25 bio-optical casts were made, and 14 ARGO floats were deployed from 15 February to 14 March. Water samples (up to 36) and CTD data were collected on each LADCP/CTD/rosette coast in most cases to within 10-20 meters of the bottom. Salinity, dissolved oxygen and nutrient samples were analyzed for up to 36 water samples from each cast of the principal LADCP/CTD/Rosette program. Water samples were also measured for Total DIC, Total Alkalinity, CCs and CDOM, and samples were collected for DOC, POC, Helium/Tritium, and C13. Underway surface pCO_2, temperature, conductivity, dissolved oxygen, fluorometer, meteorological and multi-beam acoustical bathymetric measurements were made. The cruise ended in Fremantle, Australia on 17 March 2007.

2.1.2 I9N Cruise Results

The R/V Roger Revelle completed a hydrographic survey of CLIVAR/CO_2 section I9N in the Indian Ocean, nominally along 95°E (between 28°S and 4°S) and up into the Bay of Bengal, from 22 March to 01 May 2007. The 41 day cruise began at 0800 22 March 2007 from Fremantle, Western Australia and ended at 0800 01 Mary 2007 in Phuket Thailand.

A total of 111 stations were occupied. The station numbers were consecutive with those from the I8S cruise (Chief Scientist Jim Swift) that was occupied just prior to I9N from 2 February to 17 March 2007. The first cast of I9N, Station 89, was a reoccupation of the I8S Station 88. Station spacing was nominally 30 nm apart, except at the equator where station spacing was 20 nm. Stations 89 through 147 are exact repeats of the 1995 WOCE I9N Stations 155 to 212. Our transect then deviated slightly westwards from WOCE I9N to avoid the Indonesian EEZ, before angling northwestward up into the Bay of Bengal. Stations 172 through 176 are reoccupations of 1995 WOCE I1E Stations 991, 990, 989 (also WOCE I9N Station 268), 987, and 986. Stations 178 through 193 followed the original WOCE I9N section Station 260 to 271 across the north-eastward central axis of the Bay of Bengal. Station 182 repeated station 174 as well as the corresponding WOCE I1 (989) and WOCE I9N (268) stations. After a short northward section from Station 193, our station sampling ended at Station 199 in ~2000 m water depth.

Each station consisted of a CTD/LADCP/rosette cast to within 10-15 m of the bottom. Water samples (usually 36 bottles) at each station were analyzed for salinity, nutrients, dissolved oxygen, dissolved inorganic carbon, total alkalinity, dissolved organic matter, colored dissolved organic matter, chlorofluorocarbons, helium/tritium, particulate organic carbon, carbon-14, bacteria and chlorophyll. Trace metal casts to 1000 m were conducted at approximately every other station for a total of 49 trace metal casts. The trace metal casts were conducted near the same locations as the CTD profiles and were either before or after the full-depth casts depending on time of day. Optical profiles were collected once each day when on station, generally near 12:00 – 14:00 local time. Argo floats were deployed at 14 locations upon departure from a

station. Underway surface pCO_2, temperature, conductivity, dissolved oxygen, fluorometer, meteorological, aerosol and multi-beam acoustical bathymetric measurements were also made along the cruise track. No major problems were encountered on the cruise and all major cruise objectives were achieved.

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

While analyses of repeat hydrographic data are not funded through this proposal, they are vital to the use of these data, and our efforts in this regard in FY2007 are summarized here. Our analysis of subpolar mode water variability using the 2003 A16N data (Johnson and Gruber, 2007) was published. Our submitted analyses of repeat hydrographic section data also demonstrated significant AABW warming in the western basins of the S. Atlantic Ocean (Meredith et al., 2007) and the main deep basins of the Pacific Ocean (Johnson et al., 2007). Analysis of bottom water variability in the eastern Indian Ocean by comparing the 2007 repeat of I8S/19N to the 1994-1995 section data along the same track is in progress. While there is no apparent warming north of the Southeast Indian Ridge crossed at about 45 °S by this section, there is a warming of roughly 0.1 °C below about 3500 m, again in the Antarctic Bottom Water (AABW; Fig. 3). Together, the results in the S. Atlantic, the Pacific, and the S. Indian Oceans suggest the possibility of a global pattern of AABW warming in the past decade, which could constitute an important mode of climate variability, and a significant contribution to the global heat budget. Finally, given the potential importance of global AABW variations mentioned above, we have worked to quantify its relative volume compared with North Atlantic Deep Water (Johnson, 2007).

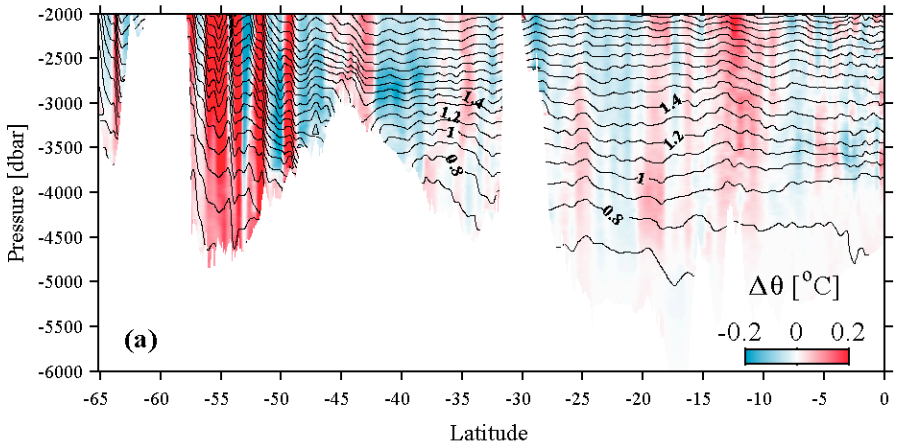


Figure 3. Difference of deep potential temperature, Δθ [°C], along WOCE Section I08S/I09N in the eastern Indian Ocean resulting from subtracting the 1994/5 data from the 2007 data. Red areas indicate warming and blue areas cooling with color saturation at ±0.2°C. Mean potential temperatures from all the data (black lines) are contoured at 0.1 °C intervals.

In FY 2007 the PMEL CTD group supported the coastal carbon survey cruise from Newport, Oregon to San Diego, California on the R/V Wecoma. We assembled the necessary CTD/O_2 equipment and arranged for pre- and post-cruise calibrations of all CTD/O_2 sensors. We purchased required supplies and equipment and shipped it to Newport and back from San Diego for the cruise. Our lead CTD/O_2 data processor participated on the cruise. We have now completed the final calibration of the cruise CTD/O_2 data.

During FY2007 the PMEL CTD group also began preparations for the FY2008 reoccupation of WOCE section P18. This repeat hydrography cruise will consist of a 42- and a 36-day leg, the former from San Diego to Easter Island, and the later from Easter Island to Punta Arenas. We have already bought long lead-time items like standard seawater and worked on building and readying equipment like frames and Niskin bottles. Dr. Johnson will serve as chief scientist for the second leg of P18 and has been involved in the planning.

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

I8S

Samples for DIC measurements were drawn according to procedures outlined in the Handbook of Methods for CO_2 analysis (DOE, 1994) from 10.4-L Niskin bottles (except Niskin 34, 9.6L) into cleaned 300-mL glass bottles. Over 2500 samples were analyzed for discrete DIC; full profiles were completed on odd numbered stations, with replicate samples taken from the surface, oxygen minimum, salinity maximum, and bottom Niskin-type bottles. On the even numbered stations, samples were drawn throughout the water column with focus on the upper 1000 m. The replicate samples were interspersed throughout the station analysis for quality assurance of the integrity of the coulometer cell solutions. No systematic differences between the replicates were observed.

I9N

Samples for DIC measurements were collected at every degree from 36 depths with three replicate samples. Some samples were also collected at every half-degree. The replicate seawater samples were taken from the surface, 1000 m, and bottom Niskin bottles and run at different times during the cell. No systematic difference between the replicates was observed. A total of 2526 samples for DIC were collected and analyzed during the cruise. The coulometers were calibrated by injecting aliquots of pure CO_2 (99.995%) by means of an 8-port valve outfitted with two sample loops with known gas volumes bracketing the amount of CO_2 extracted from the water samples for the two PMEL systems.

The stability of each coulometer cell solution was confirmed three different ways: the Certified Reference Material (CRM), Batch 78, supplied by Dr. A. Dickson of SIO, was measured at the beginning, gas loops in the beginning and at the end, and the duplicate samples at the beginning, middle, and end of each cell solution. The coulometer cell solution was replaced after 25 mg of carbon was titrated, typically after 9-12 hours of continuous use.

Calculation of the amount of CO_2 injected was according to the CO_2 handbook (DOE, 1994). The concentration of CO_2 ($[CO_2]$) in the samples was determined according to:

$$[CO_2] = Cal.factor * \frac{(Counts - Blank * Run\ Time) * K\ \mu mol/count}{Pipette\ volume * density\ of\ sample}$$

where Cal. Factor is the calibration factor, Counts is the instrument reading at the end of the analysis, Blank is the counts/minute determined from blank runs performed at least once for each cell solution, Run Time is the length of coulometric titration (in minutes), and K is the conversion factor from counts to µmol.

The instrument has a salinity sensor, but all DIC values were recalculated to a molar weight (µmol/kg) using density obtained from the CTD's salinity sensor. The results underwent initial quality control on the ship using property plots: DIC-depth, DIC-potential temperature, DIC-salinity and DIC-LAT-depth contour plots were used to analyze the quality of the data (Figure 4). The difference plot indicates DIC anomalies ranging from 5-55 µmol/kg in the upper

1000 m of the water column. These anomalies are due to uptake of anthropogenic CO_2, changes in mixing and ventilation of the water masses, and changes in biogeochemical processes. Our synthesis project will determine the relative contributions of each process to the total change in DIC over the 12-year interval.

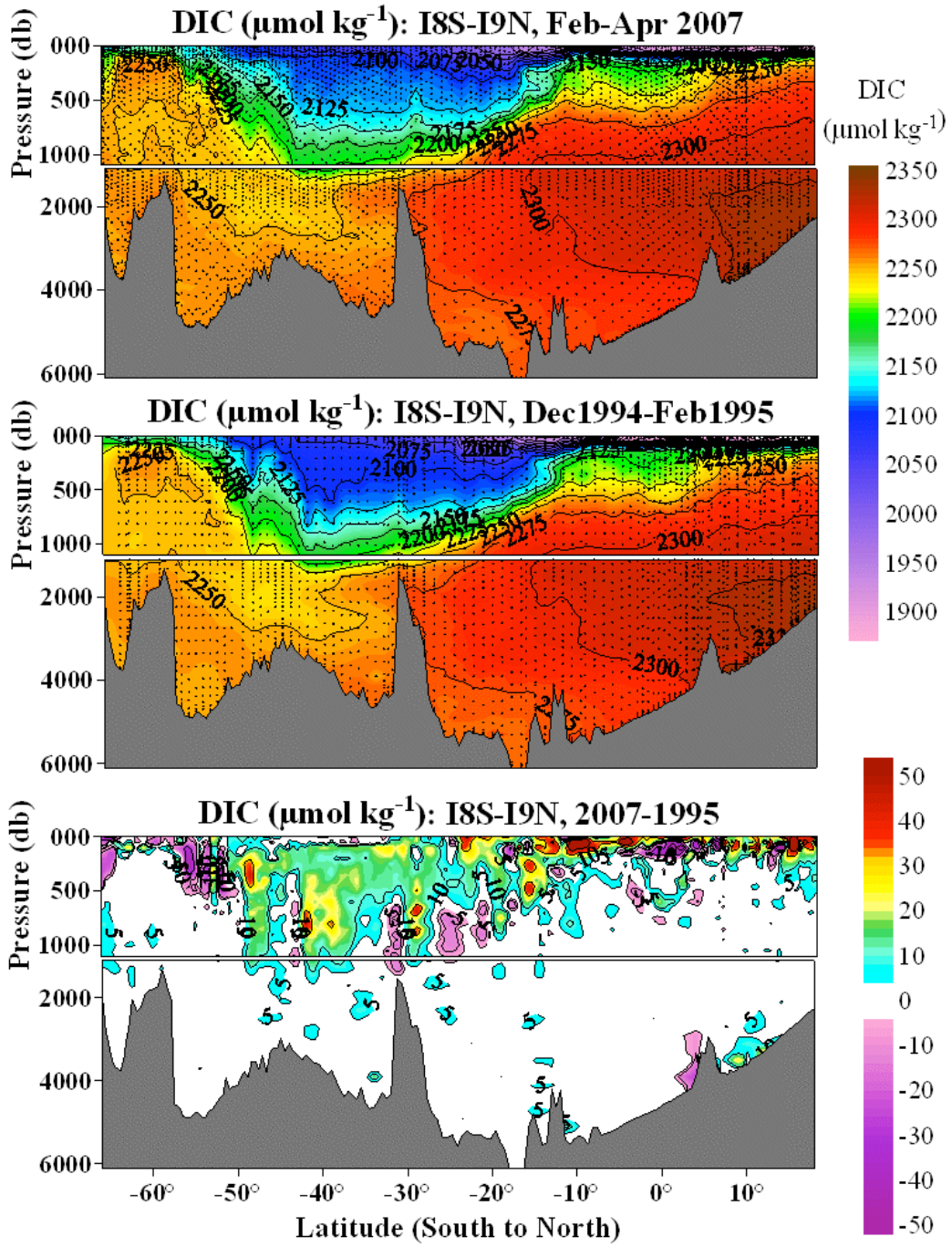


Figure 4. DIC in µmol kg^{-1} along the I8S and I9N section in the Indian Ocean along 95 °E. The gridded difference plot is shown on the bottom panel. The increases in DIC are the result of a combination of processes including anthropogenic CO_2 invasion and changes in circulation and biogeochemistry.

2.4 Discrete pCO_2 (Wanninkhof)

Underway pCO_2 measurements for I8 S and I9 N

Underway pCO_2 measurements were made on the R/V *Revelle* along the entire cruise track from Dunelin, New Zealand (46 ˚S, 170 ˚E) to the Northern end of the Bay of Bengal (17 ˚N, 90 ˚W). A total of 14942 surface water samples and 5600 air samples were taken. Sampling and data reduction followed standard protocol as outlined in (Pierrot et al., 2007). No major problems were encountered except that the water intake of the R/V *Revelle* occasionally breached the surface entraining bubbles and affecting the surface temperature measurements from the thermosalinograph. This occurred primarily during maneuvering while on station and is the cause of the spikes in the values shown in Figure 5.

The transit from New Zealand to the start of the hydrographic section at 83 ˚E, 64 ˚S went along 64 ˚S from 135 ˚E to 83 ˚E, providing a unique dataset near the ice edge of the Southern Ocean. The partial pressure difference of CO_2 between water and air (ΔpCO_2) as compared to the climatological values for March (Takahashi et al., 2007) is shown in Figure 6. The observations show a very strong CO_2 sink ranging from -40 to -120 μatm along 64 ˚S. The lowest values correspond to elevated chlorophyll values as determined from the shipboard fluorometer indicating that this sink is in response to strong biological activity. The observed sink is much greater than shown in the climatology, clearly indicating the value of these measurements to improve our understanding of the air-sea CO_2 fluxes in this data sparse region.

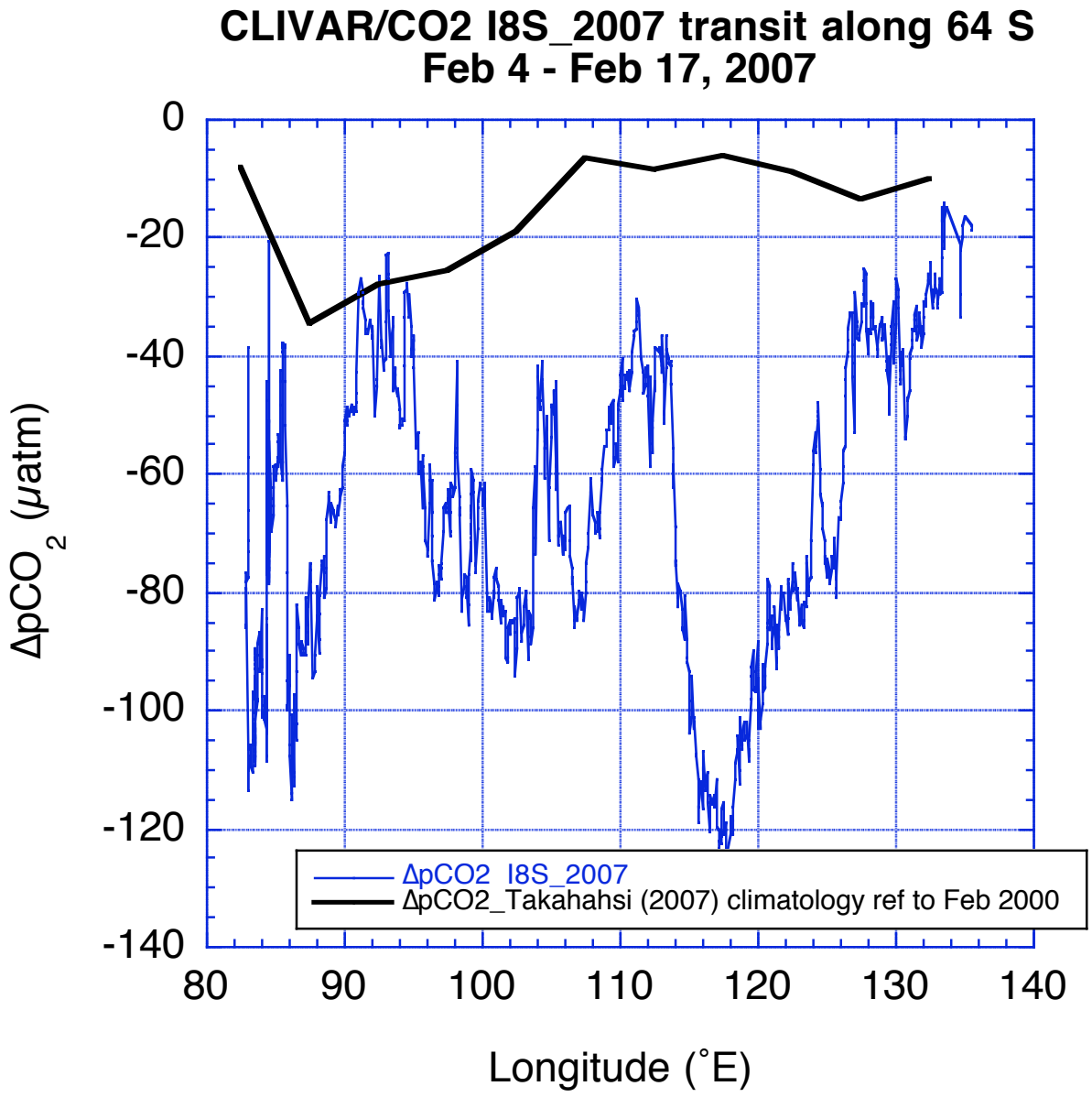


Figure 5. The ΔpCO_2 along zonal transect of 64 ˚S from February 4, 2007 to February 17, 2007 (thin line) compared to the climatology of Takahashi et al. (2007) (thick line) referenced to February 2000. The monthly climatological values are for a 4 by 5 ˚ grids centered on 64 ˚S.

The ΔpCO_2 observations along the hydrographic transect from 64 ˚S to 16 ˚N that occupied stations between 83 ˚E and 95 ˚E are shown in Figure 6. Going northward the ocean alternates from sink to source of CO_2 often delineated by gyre boundaries. The region turns from a sink in the polar region at 60 ˚S to a source in the sub-polar area at 50 ˚S and becomes a sink again at the boundary of the sub-polar and sub-tropical gyres around 40 ˚S. The subtropical gyre in the Austral summer is a weak source. There is a weak sink in the southern tropics. From 10 ˚S northward the region is a source of CO_2. Overall the pattern follows the climatology but measured ΔpCO_2 values on this cruise are slightly higher. The higher values from 55 ˚S to 40 S are in accord with the output of models as presented in Lovenduski et al., (2007) and Le Quere et al., (2007) that suggest that this is caused by increased upwelling of water with high CO_2 content in response to increasing westerly winds. The higher values observed in the north are associated

with higher salinities in the northern Bay of Bengal during the cruise compared to the cruises used in the climatology which are primarily those of the 1995 WOCE cruises in the Indian Ocean (Sabine et al., 2000).

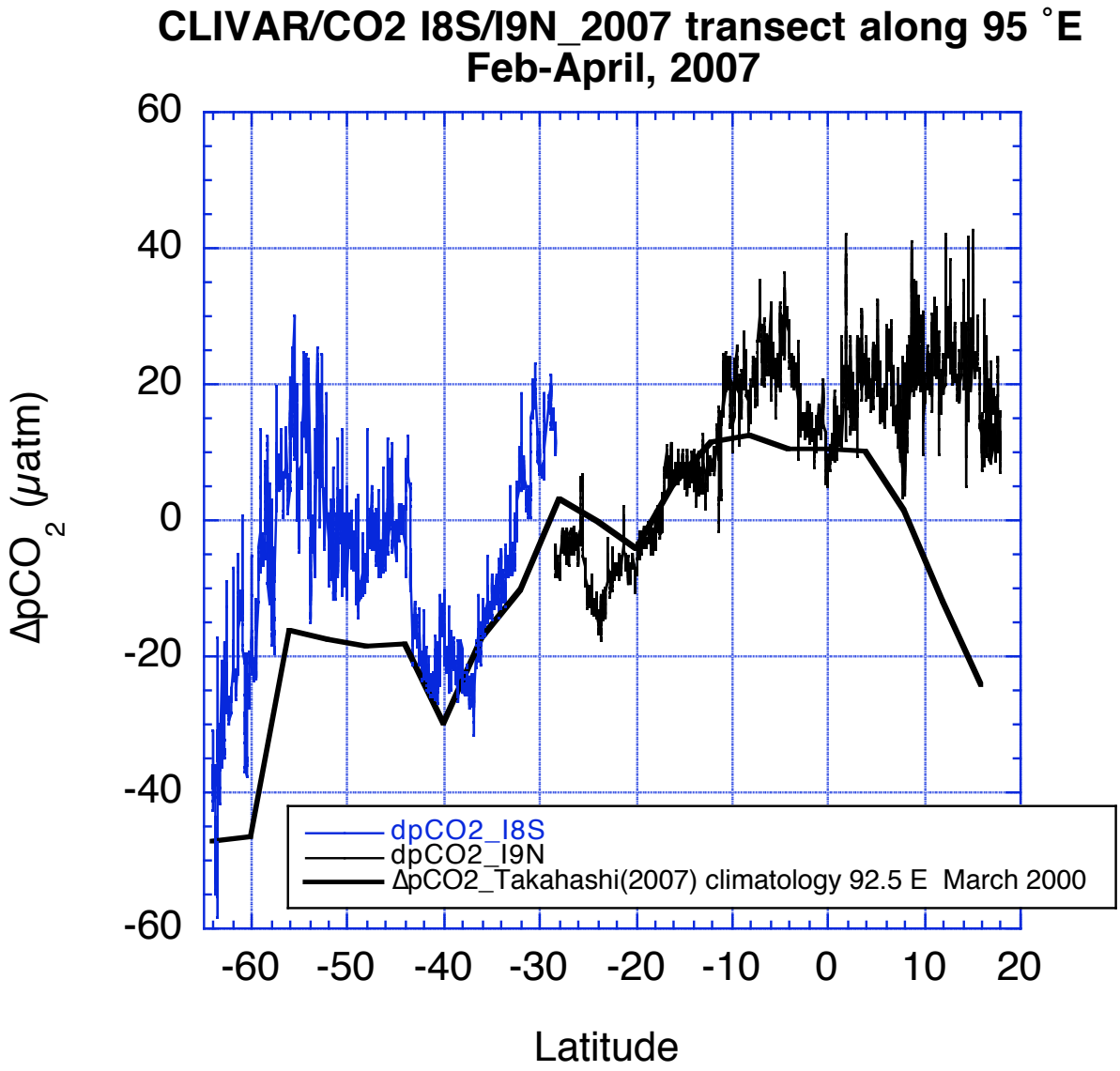


Figure 6. The ΔpCO2 along a quasi-meridional transect from 64 ˚S to 16 ˚N along a northward route between 82 and 95 ˚E from February to April 2007 (thin line) compared to the climatology of Takahashi et al. (2007) (thick line) referenced to March 2000. The monthly climatological values are on 4 by 5 ˚ grids centered on 92.5 ˚E.

2.5 Nutrients (Zhang)

In FY 2007 we developed Labview-based software for the auto-analyzer and made preparations for the P18 cruise which is scheduled for late 2007.

1. Software development for autoanalyzer: To obtain high quality nutrient data we need a data acquisition software that can correct for refractive index and background nutrients in low nutrient seawater that is routinely used as a matrix in preparing standard and used as wash solution in

seawater analysis using an autoanalyzer. We cannot use commercial autoanlyzer software which is designed for freshwater analysis and the correction for seawater is not available. Currently we are using a half-constructed and problematic "twinpeak" software that was constructed by several programmers over years but none of them had time or resources to finish it. Dr. Natchanon Amornthammarong has examined the current version of software and made significant modifications. We have added a user-friendly data reduction routine. We have also selected two suitable autosamplers, "Westco Scientific CS9000" and "CETAC ASX 520HS". These samplers can supply a large sample volume (25-50 ml) for simultaneous analysis of five nutrient constituents (nitrate, nitrite, ammonium, phosphate and silicate). Computer programs have been written to interface both autosamplers. A fully developed software will be shared with the PMEL nutrient group and other nutrient labs participating the Repeat Hydrography program. This is a key step toward a unified instrumentation for shipboard nutrient analysis in long-term ocean observation program.

2. We have participated in the international inter-comparison for nutrient in seawater organized by Dr. Aoyama of the Japanese Meteorological Research Institute who is also responsible for nutrient measurements in the Repeat Hydrography Program sponsored by the Japanese government. A total of 55 laboratories from 15 counties have participated in this exercise, including our Repeat Hydrography Program partner, the nutrient lab at Scripps Institution of Oceanography. Our measurements have provided high quality data to the inter-comparison as evidenced by high precision and the degree of agreement to the consensus values.

3. Preparation for P18 cruises: We have prepared chemical reagents, standard solutions and instruments for the P18 cruises. We have compared our nutrient standards with our previous standards and with standards from the Japanese Meteorological Research Institute.

2.6 Discrete Oxygen (Baringer and Langdon)

This year, support was provided for the maintenance of the existing photometric O_2 titration equipment, completion of the building of four new amperometric titration systems (three built last FY, one to be completed this FY), and training for all technicians on the use of the new systems. AOML/CIMAS will further prepare for P18 cruises including the pre-purchase of chemical reagents for the cruise. The group will also participate in the at-sea collection of discrete O_2 by contributing one technician working a twelve-hour daily shift on the east and west coast CO_2 surveys, including initial data reduction, and purchasing of all chemical reagents and supplies.

For the two cruises conducted in FY2007, samples were drawn from Niskin bottles into calibrated 140 ml iodine titration flasks using Tygon tubing with a Silicone adapted 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 mmol 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.

On the West Coast CO_2 cruise, 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 (1965a) with modifications by Culberson et al. (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.

On the Gulf of Mexico East Coast Carbon Cruise (GOMECC, see AOML Hydrography Group Type) twenty-four dissolved oxygen samples plus two duplicates were drawn from each station except the shallow costal stations where fewer samples were drawn depending on the depth. Total number of samples collected was 1247. A total of 133 sets of duplicates were run. The difference between replicates averaged 1.3 umol kg^{-1} for stations 1-45. The mixing time between additions by the titrator was increased from 4 to 8 s. This improved the reproducibility significantly. The difference between replicates for stations 46-90 averaged 0.4 umol kg^{-1}. The total number of samples flagged after initial shipboard reduction of quality control: Questionable (QC=34): Not reported (QC=1).

Additional oxygen samples were drawn from the ship's uncontaminated seawater line for comparison for the purpose of checking the calibration of the UNH Aanderra Optode oxygen sensor and for comparison with the oxygen sensor on the UGA CO_2 buoy.

Dissolved oxygen analyses were performed with an automated oxygen titrator using amperometric end-point detection (Culberson and Huang, 1987). This was the first full cruise performed by AOML using this system. The titration of the samples and the data logging and graphical display was performed on a PC running a program written by Ulises Rivero of AOML. The titrations were preformed in a climate controlled lab at 18.5°C - 20°C. Thiosulfate was dispensed by a 2 ml Gilmont syringe driven with a stepper motor controlled by the titrator. Tests in the lab were performed to confirm that the precision and accuracy of the volume dispensed were comparable or superior to the Dosimat 665. The whole-bottle titration technique of (Carpenter, 1965b) with modifications by (Culberson and Knapp, 1991) was used. Four replicate 10 ml iodate standards were run every 24 hours. The reagent blank determined as the difference between V1 and V2, the volumes of thiosulfate required to titrate 1 ml aliquots of the iodate standard, was determined at the beginning and end of the cruise. This method was found during pre-cruise testing to produce a more reproducible blank value than the value determined as the intercept of a standard curve. The temperature corrected molarity of the thiosulfate titrant was determined as given in (Dickson, 1994).

2.7 Chlorofluorocarbons (Bullister)

Samples for the analysis of dissolved CFC-11 and CFC-12 were drawn from ~ 4100 of the water samples collected during the I8S/I9N expedition. As a pilot study, the PMEL CFC analytical system was modified for the I8S/I9N expedition to allow analysis of ultra-trace levels of sulfur hexafluoride (SF_6) along with CFCs from the same water sample. Efforts were made to sample CFCs and SF_6 (CFCs/SF_6) from the same bottles sampled for carbon parameters (DIC, alkalinity, pCO_2 and pH) and other tracers. Specially designed water sampling bottles were used on the cruise to minimize CFC/SF_6 contamination. When taken, water samples for CFCs/SF_6 analysis were the first samples drawn from the sample bottles. Care was taken to coordinate the sampling of CFCs/SF_6 with other samples to minimize the time between the initial opening of each bottle and the completion of sample drawing. In most cases, CFCs/SF_6, helium-3, dissolved oxygen, DIC, alkalinity and pH samples were collected within several minutes of the initial opening of each bottle. To minimize contact with air, the CFCs/SF_6 samples were drawn directly through the stopcocks of the 12-liter bottles into 250 cc 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, CFC-12 and SF_6 in air samples, seawater and gas standards were measured by shipboard electron capture gas chromatography (EC-GC) using techniques modified from those described by (Bullister and Weiss, 1988) and (Bullister and Wisegarver, 2007). For seawater analyses, an aliquot of ~ 200 cc of seawater was transferred from a 250 cc glass syringe to a large volume glass sparging chamber. The dissolved gases in the seawater sample were extracted by passing a supply of CFCs/SF_6-free purge gas through the sparging chamber and were concentrated on a cold-trap. The trap was then heated and its contents injected onto series of pre-columns and into the main analytical columns. The analytical system was calibrated frequently using a standard gas of known CFCs/SF_6 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 CFCs/SF_6-free gas) were injected and analyzed in a similar manner. The typical analysis time for seawater, air, standard or blank samples was ~12 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 of the SF_6 in air, seawater samples and gas standards are reported relative to the NOAA-GMD calibration scale (Bullister et al., 2006). Concentrations in air and standard gas are reported in units of mole fraction CFC/SF_6 in dry gas, and are typically in the parts per trillion (ppt) range. Dissolved CFC concentrations are given in units of picomoles per kilogram seawater (pmol kg^{-1}). Dissolved SF_6 concentrations are given in units of femtomoles per kilogram seawater (fmol kg^{-1}). CFC/SF_6 concentrations in air and seawater samples were determined by fitting their chromatographic peak areas to multi-point calibration curves, generated by injecting multiple sample loops of gas from a working standard. The response of the detector to the range of moles of CFC-12, CFC-11 and SF_6 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, 0.56% for CFC-11 and 1.2% for SF_6.

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 <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, 547.2 +/- 5.0 ppt for CFC-12 and 6.1 ppt =/- 0.1 for SF_6.

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

Table 2. Summary of number of CFC-11 samples taken and the estimated precision for the I8SI9N cruise

	CFC-11
Number of samples	4118
Number of replicates	293
Average standard deviation)	0.003 pmol kg^{-1} (or 1.0%), whichever is greater

Table 3. Summary of number of CFC-12 samples taken and the estimated precision for the I8SI9N cruise

	CFC-12
Number of samples	4118
Number of replicates	297
Average standard deviation)	0.003 pmol kg^{-1} (or 1%), whichever is greater

Table 4. Summary of number of SF6 samples taken and the estimated precision for the I8SI9N cruise

	SF6
Number of samples	4118
Number of replicates	234
Average standard deviation)	0.02 fmol kg^{-1} (or 2.0%), whichever is greater

A small number of water samples had anomalously high CFC/SF_6 concentrations relative to adjacent samples. These samples occurred sporadically during the cruise and were not clearly associated with other features in the water column (e.g. anomalous dissolved oxygen, salinity or temperature features). This suggests that these samples were probably contaminated with CFCs and/or SF_6 during the sampling or analysis processes. Measured concentrations for these anomalous samples are included in the 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 section of CFC-12 concentrations along I8S/I9N in 2007 is shown in Figure 7. The strong latitudinal gradient in surface concentrations primarily reflects the latitudinal gradient in surface temperature, since the solubility of CFCs is greater at cold temperatures. CFC-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 abyssal, mode and intermediate waters in the southern hemisphere south of 40 ^{o}S, indicating the potential of this region to take up atmospheric gases, including CO_2.

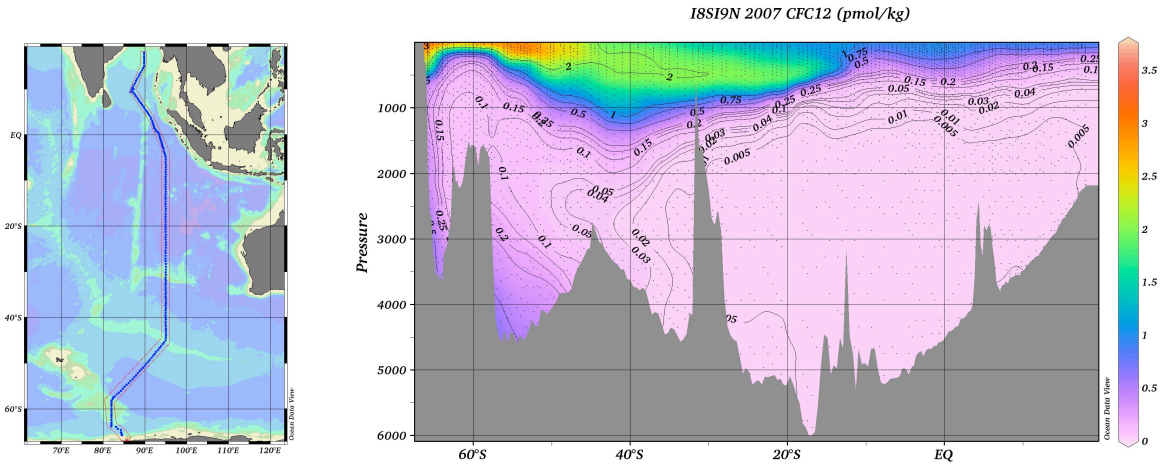


Figure 7. CFC-12 concentrations along I8S/I9N.

Figure 8 shows the concentration of dissolved sulfur hexafluoride (SF_6) along I8SI9N in 2007. The spatial resolution for SF_6 measurements was essentially the same as that for CFC-11 and CFC-12, with at total of ~ 4,100 SF_6 samples analyzed during the expedition.

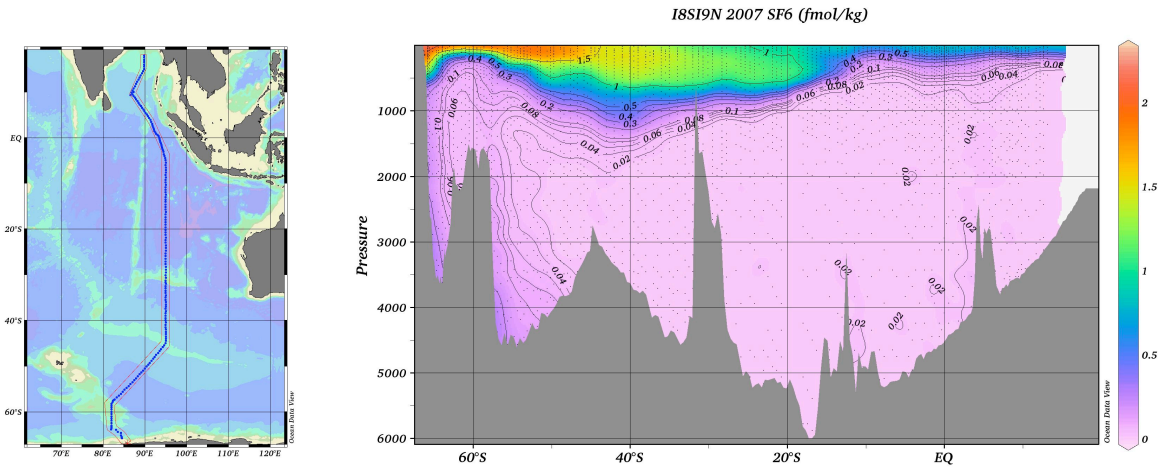


Figure 8. SF6 concentrations along I8S/I9N**.**

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.

3.0 PUBLICATIONS AND REPORTS

FY2007 Publications:

Berelson, W.M., W.M. Balch, R. Najjar, R.A. Feely, C. Sabine, and K. Lee (2007): Relating estimates of $CaCO_3$ production, export, and dissolution in the water column to measurements of $CaCO_3$ rain into sediment traps and dissolution on the sea floor: A revised global carbonate budget. Global Biogeochem. Cy., 21, GB1024, doi: 10.1029/2006GB002803.

Birdsey, R.A., R. Cook, S. Denning, P. Griffith, B.E. Law, J. Masek, A.M. Michalak, S. Ogle, D. Ojima, Y. Pan, C.L. Sabine, E. Sheffner, and E.T. Sundquist (2007): Investigators share improved understanding of the North American Carbon Cycle. Eos Trans. AGU, 88(24), doi: 10.1029/2007EO240004.

Bullister, J.L., and D.P. Wisegarver (2007): The shipboard analysis of trace levels of sulfur hexafluoride, CFC11 and CFC12, in seawater. Deep-Sea Res. [Submitted]

Caldeira, K., D. Archer, J.P. Barry, R.G.J. Bellerby, P.G. Brewer, L. Cao, A.G. Dickson, S.C. Doney, H. Elderfield, V.J. Fabry, R.A. Feely, J.-P. Gattuso, P.M. Haugan, O. Hoegh-Guldberg, A.K. Jain, J.A. Kleypas, C. Langdon, J.C. Orr, A. Ridgwell, C.L. Sabine, B.A. Seibel, Y. Shirayama, C. Turley, A.J. Watson, and R.E. Zeebe (2007): Comment on "Modern-age buildup of CO_2 and its effects on seawater acidity and salinity" by Hugo A. Loáiciga. Geophys. Res. Lett., 34, L18608, doi: 10.1029/2006GL027288.

Chanson, M., F. J. Millero, and R. Wanninkhof (2007), Synthesis and analysis of the carbonate parameters in the Atlantic Ocean based on decadal repeat occupations of the meridional section A16, Global Biogeochemical Cycles, submitted.

Doney, S.C., N. Mahowald, I. Lima, R.A. Feely, F.T. Mackenzie, J.-F. Lamarque, and P.J. Rasch (2007): The impact of anthropogenic atmospheric nitrogen and sulfur deposition on ocean acidification and the inorganic carbon system. Proc. Nat. Acad. Sci., 104(37), 14,580–14,585.

Dugdale, R.C., F.P. Wilkerson, F. Chai, and R.A. Feely (2007): Size-fractionated nitrogen uptake measurements in the equatorial Pacific and confirmation of the low Si–high-nitrate low-chlorophyll condition. Global Biogeochem. Cy., 21, GB2005, doi: 10.1029/2006GB002722.

Feely, and R. Wanninkhof (2007): 3. Global Oceans; f. Global ocean carbon cycle — in *State of*

the Climate in 2006, A. Arguez (ed.).. Bull. Am. Meteorol. Soc., 88 (suppl.)(6), S40–S43.

Johnson, G. C. 2007. Quantifying Antarctic Bottom Water and North Atlantic Deep Water Volumes. *Journal of Geophysical Research*, submitted.

Johnson, G. C., and N. Gruber. 2007. Decadal water mass variations along 20°W in the northeastern Atlantic Ocean. *Progress in Oceanography*, **73**, 277-295, doi: 10.1016/j.pocean.2006.03.022.

Johnson, G. C., S. Mecking, B. M. Sloyan, and S. E. Wijffels. 2007. Recent bottom water warming in the Pacific Ocean. *Journal of Climate*, **20**, 5365-5375.

Kieke, D., M. Rhein, L. Stramma, W.M. Smethie, J.L. Bullister, and D.A. LeBel (2007): Changes in the pool of Labrador Sea Water in the subpolar North Atlantic. Geophys. Res. Lett., 34, 06605, doi: 10.1029/2006GL028959.

LeBel, D.A., W.M. Smethie, Jr., M. Rhein, D. Kieke, R.A. Fine, J.L. Bullister, D.-H. Min, W. Roether, R.F. Weiss, C. Andrie, D. Smyth-Wright, and P. Jones (2006): The distribution of CFC-11 in the north Atlantic during WOCE: Inventories and calculated water mass formation rates. Deep-Sea Res. [Submitted]

Lee, K., L.T. Tong, F.J. Millero, C.L. Sabine, A.G. Dickson, C. Goyet, G.-H. Park, R. Wanninkhof, R.A. Feely, and R.M. Key (2006): Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans. Geophys. Res. Lett., 33, L19605, doi: 10.1029/2006GL027207.

Levine, N., M, S. C. Doney, R. Wanninkhof, K. Lindsay, and I. Y. Fung 2007. The impact of ocean carbon system variability on the detection of temporal increases in anthropogenic CO_2, J Geophys. Res., in press.

McGillis (chair and ed.), W., R. Duce, D. Erickson, C. Fairall, D. Farmer, R. Feely, B. Huebert, W. Jenkins, W. Keene, R. Kiene, P. Matrai, K. Melville, W. Miller, R. Najjar, E. Saltzman, P. Schlosser, D. Siegel, W.-J. Cai, D. Ho, S. Doney, K. Johnson, C. McNeil, M.J. Perry, J. Prospero, O. Schofield, P. Shepson, D. Turk, and R. Wanninkhof (2006): The United States Surface Ocean—Lower Atmospheric Study (SOLAS), Science Implementation Strategy. Published in collaboration with the U.S. Ocean Carbon and Biogeochemistry (OCB) program and the International integrated Marine Biogeochemistry Ecosystem Research (IMBER) and SOLAS programs, 123 pp.

Meredith, M. P., A. C. N. Garabato, A. L. Gordon, and G. C. Johnson. 2007. Evolution of the deep and bottom waters of the Scotia Sea, Southern Ocean, during 1995-2005. *Journal of Climate*, submitted.

Peng, T.-H. and R. Wanninkhof, Increase of anthropogenic CO_2 in the Atlantic Ocean in last two decades. (in preparation)

Reay, D.S., C.L. Sabine, P. Smith, and G. Hymus (2007): Spring-time for sinks. Nature, 446(7137), doi: 10.1038/446727a, 727–728.

Reay, D.S., P. Smith, G. Hymus, and C. Sabine (2007): New Directions: The changing role of the terrestrial carbon sink in determining atmospheric CO_2 concentrations. Atmos. Environ.,

41(27), 5813–5815.

Sabine, C.L., and R.A. Feely (2007): The oceanic sink for carbon dioxide. In Greenhouse Gas Sinks, D. Reay, N. Hewitt, J. Grace, and K. Smith (eds.), CABI Publishing, Oxfordshire, UK.

Sabine, C.L., R.A. Feely, and R. Wanninkhof (2007): 3. Global Oceans; f. Global ocean carbon cycle - in State of the Climate in 2006, A. Arguez (ed.).. Bull. Am. Meteorol. Soc., 88 (suppl.)(6), S40–S43.

Sonnerup, R., J. Bullister, and S. Mecking (2007): Circulation rate changes in the eastern subtropical North Pacific based on chlorofluorocarbon ages. Geophys. Res. Lett., 34, L08605, doi: 10.1029/2006GL028813.

Sonnerup, R.E., A.P. McNichol, P.D. Quay, R.H. Gammon, J.L. Bullister, C.L. Sabine, and R.D. Slater (2007): Anthropogenic delta13C changes in the North Pacific Ocean reconstructed using a multiparameter mixing approach (MIX). Tellus, 59B, 303–317.

Steinfeldt, R., M. Rhein, and J.L. Bullister (2007): Inventory changes of anthropogenic carbon in the Atlantic between 1997 and 2003. Nature. [Submitted]

Wanninkhof, R. et al. Decadal changes in inorganic carbon along meridional section A16 in the Atlantic Ocean. (in preparation).

FY2007 Reports

Cronin, M.F., C. Meinig and C.L. Sabine (2006): Global Flux Mooring for the North Pacific's Western Boundary Current: Kuroshio Extension Observatory (KEO), *Annual Report on the State of the Ocean and the Ocean Observing System for Climat*e, Silver

Feely, R.A., R. Wanninkhof, C. Sabine, G. Johnson, M. Baringer, J. Bullister, C. Mordy and J.-Z. Zhang (2006): Global repeat hydrographic/CO_2/tracer surveys in support of CLIVAR and global carbon cycle objectives: Carbon inventories and fluxes, *Annual Report on the State of the Ocean and the Ocean Observing System for Climat*e, Silver Spring, MD.

Sabine, C.L. and F. Chavez (2006): High-resolution ocean and atmosphere pCO_2 Time-series measurements, *Annual Report on the State of the Ocean and the Ocean Observing System for Climat*e, Silver Spring, MD.

Sabine, C.L., R. Feely, S. Hankin, R. Wanninkhof, T.-H. Peng, A. Kozyr, R. Key, F. Millero and A. Dickson (2006): Global carbon data management and synthesis project, *Annual Report on the State of the Ocean and the Ocean Observing System for Climat*e, Silver Spring, MD.

Relevant Meetings and Presentations in FY07

Sabine:

1) Sustained Indian Ocean Biogeochemistry and Ecological Research (SIBER) Workshop, Goa, India, October 1-8, 2006 (invited talk: Inorganic Carbon Distributions and Air-Sea CO_2 Exchange in the Indian Ocean)
2) NOAA West Coast Synthesis Meeting, Seattle, WA, October 10-11, 2006 (co-organizer and discussion leader)
3) CLIVAR Global Synthesis and Observations Panel (GSOP-2) SSG meeting, La Jolla, CA, Dec. 8-9 (invited talk: Global Carbon and Synthesis needs)
4) AGU Fall Meeting, San Francisco, CA, Dec. 11-15 (invited talk in session: OS04: Variability in Ocean Interior Circulation and Biogeochemistry: Repeat Hydrography and Modeling Studies - Decadal Changes in Pacific Ocean Inorganic Carbon Inventory, coauthor on 5 other abstracts)
5) JAMSTEC 5-year review, Tokyo, Japan, January 17-19, 2007 (invited presentation: Role of IOCCP in international carbon coordination)
6) NACP PI meeting, Colorado Springs, CO, January 22-24, 2007 (invited talk: Carbon Exchanges between the Continental Margins and the Open Ocean; coauthor on 3 posters)
7) NACP SSG Meeting, Colorado Springs, CO, January 24, 2007
8) Joint Canada-US-Mexico NACP meeting, Colorado Springs, CO, January 25-26, 2007 (poster: High Frequency CO2 variability in North American coastal waters; breakout session leader for 2 sessions)
9) NOAA CO_2 Science Team Meeting, Miami, FL, February 4-7, 2007 (meeting organizer and discussion leader)
10) Marshall Islands Workshop, Seattle, WA, March 3, 2007 (participated in discussion of ocean acidification issues with Marshall Islanders).
11) Meeting with King County Executive Board, March 21, 2007 (discussed carbon programs in Puget Sound).
12) IOCCP SSG meeting, Paris, France, April 10, 2007 (chair of meeting)
13) Ocean Surface pCO_2 and Vulnerabilities Workshop, Paris, France, April 11-13, 2007 (invited talks: Moorings: New Results and New Technology Overview, Overview of Proxy Techniques for Data Extrapolation and Interpolation)
14) Anthropogenic Stresses on Ocean Ecosystems Workshop, Seattle, WA, April 23-24, 2007 (breakout discussion leader; invited talk: Existing Technology and Challenges for Monitoring the CO_2 System in Seawater)
15) Seminar to King County Department of Natural Resources and Parks, Seattle, WA, April 25, 2007 (Ocean Storage of Anthropogenic CO_2 and its Impact on Marine Ecosystems)
16) Guest Lecture for Edward S. Sarachik's IPCC fourth assessment report class at UW (taught chapter 7)
17) OCB scientific steering committee meeting, Washington DC, May 3-4, 2007.
18) West coast cruise, R/V Wecoma, Newport OR to San Diego CA May 11-June 14, 2007 (chief scientist).
19) OCB annual summer workshop, Woods Hole, MA, July 23-26, 2007 (discussion leader for day 2 theme on ocean acidification, organizer of day 3 talks and working group on coastal ocean theme).
20) OCB scientific steering committee meeting, Woods Hole, MA, July 27, 2007.
21) NASA ROSES Panel member, Washington DC, August 28-30, 2007.
22) NOAA GCC program PI meeting, Silver Spring MD, September 10-11, 2007 (invited talk on moored CO_2 observations).
23) Southern Ocean GASEX meeting, Silver Spring MD, September 12, 2007 (meeting organizer and convener).
24) Informal discussions about Hawaii mooring program, Honolulu HI, September 14, 2007.

Feely:

1) Byrne, R.H., X. Liu, S. Mecking, and R.A. Feely (2006): Acidification of the North Pacific Ocean: Direct Observations of pH in 1991 and 2006. *Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract* OS21C-1598.
2) Chanson, M, F.J. Millero, R.A. Feely, C.L. Sabine, and R. Wanninkhof (2006): Decadal Changes in the Carbon Dioxide Parameters in the Atlantic and Pacific Oceans: Anthropogenic, Physical and Biogeochemical Perturbations. *Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract* OS34B-01.
3) Cosca, C.E., R.A. Feely, B. Tilbrook, P.D. Quay, D. Wisegarver, and L. Juranek (2006): First underway fCO_2 observations from the VOS container ship Columbus Waikato in the tropical and subtropical Pacific. *Eos Trans. AGU, 87(36), Ocean Sci. Meet. Suppl., Abstract* OS34J-03.
4) De Carlo, E.H., R.F. Solomon, C. Ostrander, M. Chung, L.E. de Gelleke, M. Akiba, F. Paquay, K.E. Fagan, M.A. McManus, F.T. Mackenzie, C. Sabine, and R.A. Feely (2006): Impact of Short Term Climatic Forcing on Biogeochemical Processes and Gas Exchange between Southern Kaneohe Bay, Hawaii and the Atmosphere. *Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract* B41E-0227.
5) Dugdale, R., F. Chai, M. Brzezinski, F. Wilkerson, and R.A. Feely (2006): Low Silicate, the cause of the HNLC and High Surface pCO_2 Condition of the Eastern Equatorial Pacific. *Eos Trans. AGU, 87(36), Ocean Sci. Meet. Suppl., Abstract* OS42D-01
6) Feely, R.A., C.L. Sabine, R.H. Byrne, and D. Greeley (2006): Direct Evidence for Ocean Acidification of the North Pacific Ocean. *Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstrac*t OS12B-04.
7) Feely, R.A., T. Takahashi, R. Wanninkhof, C.E. Cosca, M.J. McPhaden, S.C. Sutherland, M.-E. Carr, and F. Chai (2006): Interannual and Decadal Variability of the Air-Sea CO_2 Fluxes in the Equatorial Pacific Ocean. *Eos Trans. AGU, 87(36), Ocean Sci. Meet. Suppl, Abstract* OS42D-03.
8) Lueger, H., R. Wanninkhof, R. Castle, R.A. Feely, C. Neill, A. Olsen, T. Johannessen, D. Pierrot, F. Millero, T. Steinhoff, D.R. Wallace, and A. Koertzinger (2006): Common Data Reduction Practices for Underway fCO_2 Measurements by Ships of Opportunity. *EOS Trans. AGU, 87(36), Ocean Sci. Meet Suppl., Abstract* OS34J-04.
9) Mecking, S., C. Langdon, C.A. Deutsch, R.A Feely, C.L. Sabine, J.H. Swift, D. Min, and P.E. Robbins (2006): Climate Variability in the North Pacific Thermocline Diagnosed from Oxygen Measurements: An Update Based on the U.S. CLIVAR/CO_2 Repeat Hydrography Cruises. *Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract* OS33D-06.
10) Parker, A.E., A. Marchi, V.E. Hogue, K. Lew, A. Lorenzi, D. Greeley, R A. Feely, F. Wilkerson, and R.C. Dugdale (2006): Nutrient Utilization and Phytoplankton Community Response During Enclosure Experiments Conducted in the Eastern Equatorial Pacific: Testing Fe vs. Si Limitation. *Eos Trans. AGU, 87(36), Ocean Sci. Meet. Suppl., Abstract* OS35F-08.
11) Rodgers, K.B., O. Aumont, J.L. Sarmiento, A. Jacobson, C. Crevoisier, R.A. Feely, C. Sabine (2006): A Modeling Study of Seasonal to Decadal Variabiltiy in the Uptake of Antrhopogenic CO_2 in the North Pacific. *Eos Trans. AGU, 87(36), Ocean Sci. Meet. Suppl., Abstract* OS52C-06.

12) Sabine, C.L., R.A. Feely, F.J. Millero, A. Dickson, S. Mecking, R. Wanninkhof, and D. Greeley (2006): Decadal Changes in Pacific Ocean Inorganic Carbon Inventory. *Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract* OS33D-05.

13) Solomon, R.F., C.E. Ostrander, M. Chung, F. Paquay, L. de Gelleke, M. Akiba, K.E. Fagan, E.H. De Carlo, F.T. Mackenzie, M.A. McManus, C.L. Sabine, and R.A. Feely (2006): The Effects of Storm Events on Carbon Dioxide Exchange in Southern Kaneohe Bay, Hawaii. *Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract* OS21A-1566.

14) Talley, L., N. Bindoff, C. LeQuere, R.A. Feely, G.C. Johnson, C. Sabine, S. Mecking, J. Swift, N. Gruber, C. Deutsch, and I. Yashayaev (2006): Overview of Decadal Variations in Salinity, Oxygen and Nutrients Based on Recent Repeat Hydrographic Sections. *Eos Trans. AGU, 87(52), Fall Meet.* Suppl*., Abstract* OS33D-01.
15) NOAA West Coast Synthesis Meeting, Seattle, WA, October 10-11, 2006 (co-organizer)
16) NOAA CO_2 Science Team Meeting, Miami, FL, February 4-7, 2007 (co-organizer)
17) Marshall Islands Workshop, Seattle, WA, March 3, 2007 (discussion leader on ocean acidification issues with Marshall Islanders).
18) Meeting with King County Executive Board, March 21, 2007 (discussed carbon programs in Puget Sound).
19) IOCCP SSG meeting, Paris, France, April 10, 2007 (co-organizer) Ocean Surface pCO_2 and Vulnerabilities Workshop, Paris, France, April 11-13,
20) Anthropogenic Stresses on Ocean Ecosystems Workshop, Seattle, WA, April 23-24, 2007 Co-organizer and Keynote speaker)
21) West coast cruise, R/V Wecoma, Newport OR to San Diego CA May 11-June 14, 2007 (chief scientist).
22) OCB annual summer workshop, Woods Hole, MA, July 23-26, 2007 OCB scientific steering committee meeting, Woods Hole, MA, July 27, 2007.
23) NOAA GCC program PI meeting, Silver Spring MD, September 10-11, 2007 (invited talk on ocean acidification).
24) Southern Ocean GASEX meeting, Silver Spring MD, September 12, 2007 (meeting organizer and presenter).
25) European Science Foundation, Barcelona Spain. Invited talk on ocean acidification. September, 26, 2007.

4.0 REFERENCES

Bullister, J.L. and Weiss, R.F., 1988. Determination of CC13F and CC12F2 seawater and air Deep-Sea Res, 25: 839-853.

Bullister, J.L. and Wisegarver, D.P., 2007. The shipboard analysis of trace levels of sulfur hexafluoride, CFC11 and CFC12, in seawater. Deep-Sea Res., submitted.

Bullister, J.L., Wisegarver, D.P. and Sonnerup, R.E., 2006. Sulfur hexafluoride as a transient tracer in the North Pacific Ocean. Geophys. Res. Lett.,(33).

Carpenter, J.H., 1965a. The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. Limnol. Oceanogr., 10: 141-143.

Carpenter, J.H., 1965b. The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. Limnology and Oceanography(10): 141-143.

Culberson, C.H. and Huang, S., 1987. Automated amperometric oxygen
titration. Deep-Sea Res.(34): 875-880.

Culberson, C.H. and Knapp, G., 1991. A comparison of methods for the determination of dissolved oxygen in seawater, WOCE Hydrographic Programme Office.

Culberson, C.H., Knapp, G., Stalcup, M., Williams, R.T. and Zemlyak, F., 1991. A comparison of methods for the determination of dissolved oxygen in seawater.

Dickson, A.G., 1994. Determination of dissolved oxygen in seawater by Winkler titration. WHP Operations and Methods.

DOE, 1994. Handbook of methods for the analysis of the various parameters of the carbon dioxide system in sea water (Version 2), ORNL/CDIAC-74.

Doney, S.C. et al., 2004. Ocean Carbon and Climate Change (OCCC): An Implementation Strategy for U. S. Ocean Carbon Cycle Science, UCAR, Boulder, CO.

Fine, R.A. et al., 2001. Observing Tracers and the Carbon Cycle. In: C.J. Koblinsky and N.R. Smith (Editors), Observing the Ocean in the 21st Century. GODAE Project Office and Bureau of Meteorology, Melbourne, Australia, pp. 361-375.

Johnson, G.C., 2007. Quantifying Antarctic Bottom Water and North Atlantic Deep Water Volumes. Journal of Geophysical Research, submitted.

Johnson, G.C. and Gruber, N., 2007. Decadal water mass variations along 20°W in the northeastern Atlantic Ocean. Progress in Oceanography, 73: 277-295.

Johnson, G.C., Mecking, S., Sloyan, B.M. and Wijffels, S.E., 2007. Recent bottom water warming in the Pacific Ocean. Journal of Climate, 20: 5365-5375.

Le Quere, C. et al., 2007. Saturation of the Southern ocean CO2 sink due to recent climate change. Science, DOI:10.1126/science.1136188.

Lovenduski, N.S., Gruber, N.N., Doney, S.C. and Lima, I.D., 2007. Enhanced CO_2 outgassing in the Southern Ocean from a positive phase of the Soutehrn Annular Mode. Global Biogeochemical Cycles, 21(GB2026): doi:2010.1029/2006GB002900.

Meredith, M.P., Garabato, A.C.N., Gordon, A.L. and Johnson, G.C., 2007. Evolution of the deep and bottom waters of the Scotia Sea, Southern Ocean, during 1995-2005. Journal of Climate, submitted.

Pierrot, D. et al., 2007. Recommendations for autonomous underway pCO_2 measuring systems and data reduction routines. Deep-Sea Res., submitted.

Prinn, R.G. et al., 2000. A history of chemically and radiatively important gases in air deduced from ALE/GAGE/ AGAGE. J. Geophys. Res, 105: 17751-17792.

Sabine, C., Wanninkhof, R., Key, R.M., Goyet, C. and Millero, F.J., 2000. Seasonal CO_2 fluxes in the tropical and subtropical Indian Ocean. Marine Chemistry, 72: 33-55.

Sabine, C.L. and Hood, M., 2003. Ocean carbon scientists organize to achieve better coordination, cooperation. Eos, Trans. AGU, 84(23): 218-220.

Smith, N. and Koblinsky, C., 2000. Ocean Obs Conference Statement, Ocean Observation 1999 Conference, St. Raphael, France.

Takahashi, T. et al., 2007. Climatological mean and decadal change in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. Deep-Sea Res., submitted.

Surface Water pCO_2 Measurements from Ships

Rik Wanninkhof[1], Richard A. Feely[2], Nicholas R. Bates[3], Frank J. Millero[4], Taro Takahashi[5], Gustavo Goni[1]

[1] NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

[2] NOAA Pacific Marine Environmental Laboratory, Seattle, WA

[3] Bermuda Institute of Ocean Studies, Bermuda

[4] RSMAS/MAC, University of Miami, Miami, FL

[5] Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY

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 Norway, 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 had pCO_2 systems on them during part or all of the performance period : NOAA ship *Ronald H. Brown*, NOAA ship *Ka'imimoana*, container ship *Albert* Rickmers, RVIB *Palmer*, cruise ship *Explorer of the Seas*, container ship Skogafoss container ship *Oleander*, and UNOLS research ship RV *Atlantic Explorer* (ship owned and operated by BIOS). As mentioned in the progress report and workplan several ships were taken off lines and several new ships were outfitted in the past year. 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 2007 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	8	34,583	96.0%
M/V Skogafoss	11	55,588	81.0%
Explorer of the Seas	48	72,918	79.0%
RVIB Palmer	3	48,524	98.0%
R/V Ka'imimoana	5	115,334	91.0%
R/V Atlantic Explorer	16 months	92,000	83.0%
M/V Albert Rickmers	1	7,571	91.0%
M/V Oleander	12 months	108,000	68.0%

Table 1:VOS Data Summary FY-2007.

* The values are to illustrate overall performance of the program. They should be used with caution when making ship to ship comparisons. The number of data points is a function of frequency of measurements, number of cruises and instrument malfunction that differ for each ship. Percent recovery has been determined in different fashion by each investigator ranging from number of data points that could have been obtained if the units had operated whenever the ship was at sea to number of acquired data points that were discarded during quality control.

Four other critical endeavors in support of determining regional fluxes have been completed during the performance period:

1. To assure uniformity in measurements and to expand the effort within NOAA OCO and beyond, a technology transfer has been done in which General Oceanics Inc. of Miami, FL is building the underway pCO_2 systems to our specifications. Substantial time and effort is involved by participants at AOML and RSMAS to assist in building, troubleshooting, improving instrument design and training customers on the operation of the system. Over

13 units have been produced and sold to customers around the world. So far, about 6 of these units have been purchased by participants of the NOAA program.

2. The GOOS/TSG (thermosalinograph) component lead by Gustavo Goni currently operates and maintains TSGs in four ships of the SOOP: Albert Rickmers, Explorer of the Seas, M/V Explorer and Oleander. The Explorer of the Seas operations is a joint collaboration between NOAA/AOML and the University of Miami (RSMAS). We have recently successfully tested real-time mode quality control procedures for TSG data obtained from these ships. Three of these ships (Rickmers, Oleander and M/V Explorer) operate with SEAS2000 software to acquire and transmit the data in real- and delayed-time modes ().

The operations in the Skogaffoss that transected between Boston and Iceland ended in May 2007, and its data were processed and transmitted until that date. Once the replacement for this ship is found and the new TSG installed, we will resume with the data transmission in this transect.

NOAA/AOML installed a TSG unit in the M/V Explorer of the Semester At Sea Program that is operated by the University of Virginia. The first phase of this operation has been finished with the complete installation. The second phase that involves the data transmission is under progress. This ship performs two around the world transects every year. This TSG unit will support a pCO2 unit that is anticipated on this same ship.

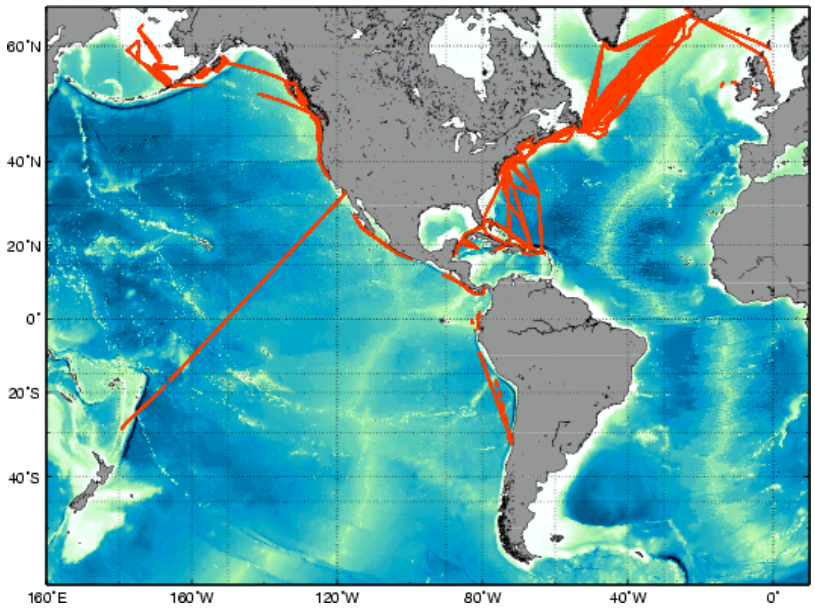


Figure 1: Location of real-time TSG transmissions into the GTS during FY 2007.

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, 2007). The comprehensive dataset that was used to create the global pCO_2 climatology comprised of 3.3 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 new data will be accessible only to the 25 co-authors of the paper until the paper in Deep-Sea Research is published , and will be released to the public after this period.

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.

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 (e.g Chierici et al., 2007) .

The AOML group also installed a pCO_2 system on the Chinese icebreaker *Snow Dragon (Xue Long)* as part of a collaboration with the Third Institute of Oceanography in the People's Republic of China. The data will be transmitted directly to AOML and posted in near-real time on the web.

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

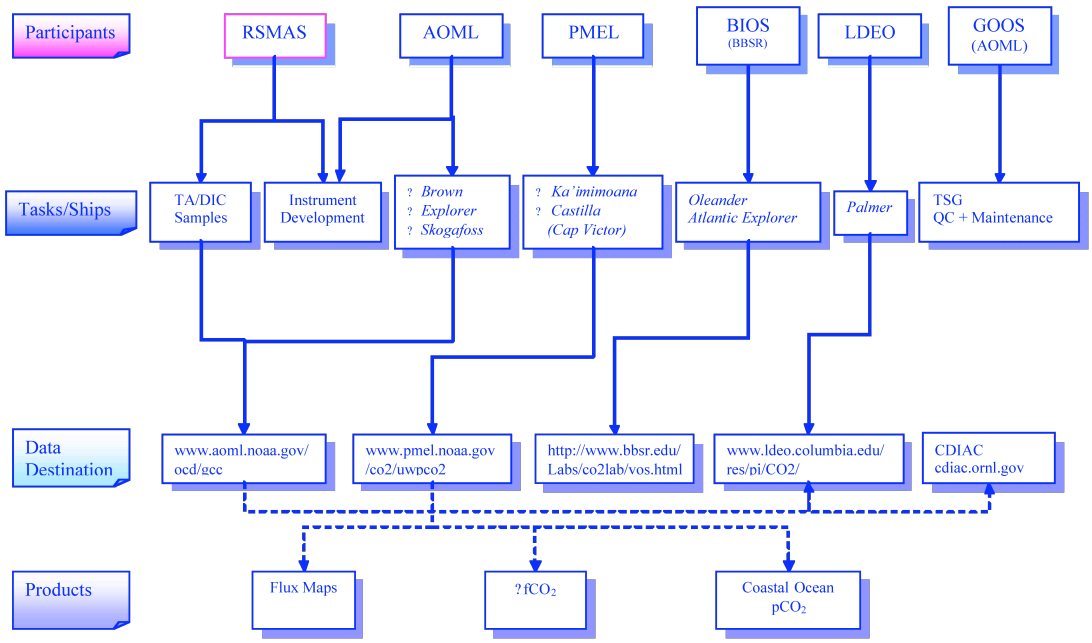


Figure 2: Organizational chart of the VOS project.

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 96 % data return. A trip had to be made to Puerto Rico to replace the computer and failure of the air pump caused a loss of atmospheric data over a short period of time. Overall returns from the ship continue to be excellent (see *Table **1***)

Description: The cruise tracks for each cruise of the *Brown* for FY 2006 and FY 2007 are shown at http://www.aoml.noaa.gov/ocd/gcc/rvbrown_data2006.php . The cruises include the Gulf of Mexico and East Coast Carbon (GOMECC) cruise, which is the first in a biennial series planned to study the coastal region along the Gulf of Mexico and eastern seabord of North America. *Figure* ***3*** shows the pCO_2 along the cruise. The goal of this program is to reduce the large uncertainties in the carbon flux of the coastal oceans.

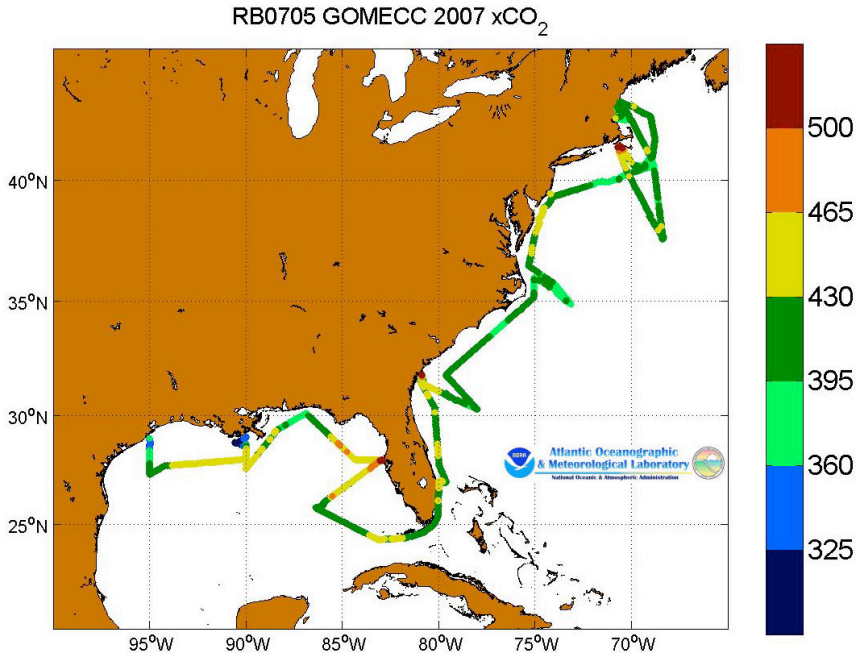


Figure 3: GOMECC cruise track and surface pCO_2 values.

NOAA ship *Ka'imimoana*- PMEL lead

Data Site: http://www.pmel.noaa.gov/co2/uwpCO2
Number of cruises: 5
Number of pCO_{2w} data points: 115334
% Data return: 91%.

Causes for non-return: The underway pCO_2 system on the *Ka'imimoana* yielded a 91 % data return during 2006-2007. There were problems associated with inadequate flushing

time prior to equilibrator measurements, resulting in rejection of a small fraction of the seawater pCO_2 values.

Description: During 2006-2007 the *Ka'imimoana* was involved in studies in the Equatorial Pacific between 95°W and 165°E (***Figure 4*****Error! Reference source not found.**). Prior to the 2006-2007 field season, the pCO_2 system was overhauled with updated software, pumps and filters. From April 2007 through September 2007, PMEL collected and processed 115,334 pCO_2 data values from the Ka'imimoana on 5 separate cruises in the equatorial Pacific. The cruise data can be obtained from our website located at**:** http://www.pmel.noaa.gov/co2/uwpco2. A summary of the cruise results from November 1997 through August 2007 is shown in ***Figure 6*****Error! Reference source not found.**. The results show weak seasonal and strong interannual variability of CO_2 fluxes from the oceans to the atmosphere. The following data files have been submitted to LDEO for contextual checks: KA0701, KA0702, KA0703, KA0704, KA0705, after which they will be submitted to CDIAC for archiving.

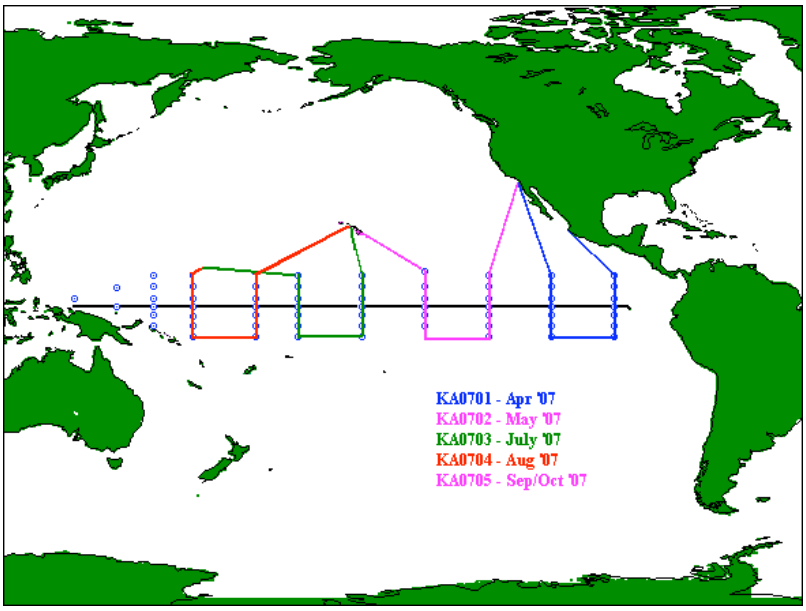


Figure 4: Ka'imimoana track lines occupied during FY 2007.

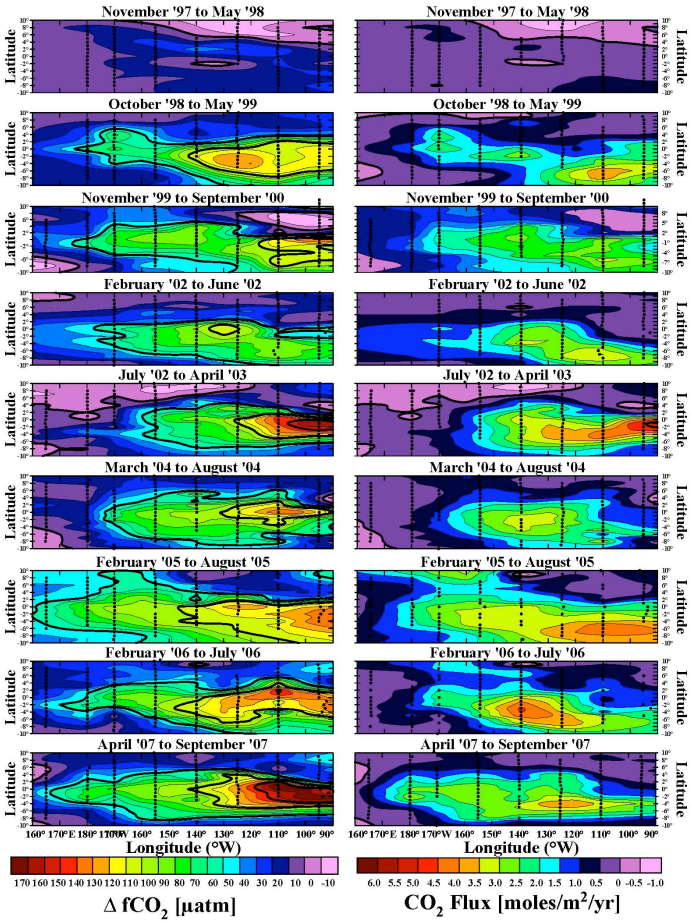


Figure 6: Time-Series of surface water pCO_2 levels in the tropical Pacific resulting from Ka'imimoana repeat observations from 1997 thru 2007.

Container ship *Albert Rickmers* - PMEL lead

Data Site: http://www.pmel.noaa.gov/co2/uwpCO2
Number of cruises: 1
Number of pCO_{2w} data points: 7571
% Data return: 91%.

Causes for non-return: The underway pCO_2 system on the *Albert Rickmers* resulted in a 91% data return during 2007. There were problems associated with inadequate flushing time prior to equilibrator measurements, resulting in rejection of a small fraction of the seawater pCO2 values.

Description: During the fall of 2007, a pCO_2 system was deployed on the container ship *Albert Rickmers*. The *Albert Rickmers* is involved in studies in the tropical and subtropical Pacific (**Error! Reference source not found.**). 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/uwpco2.

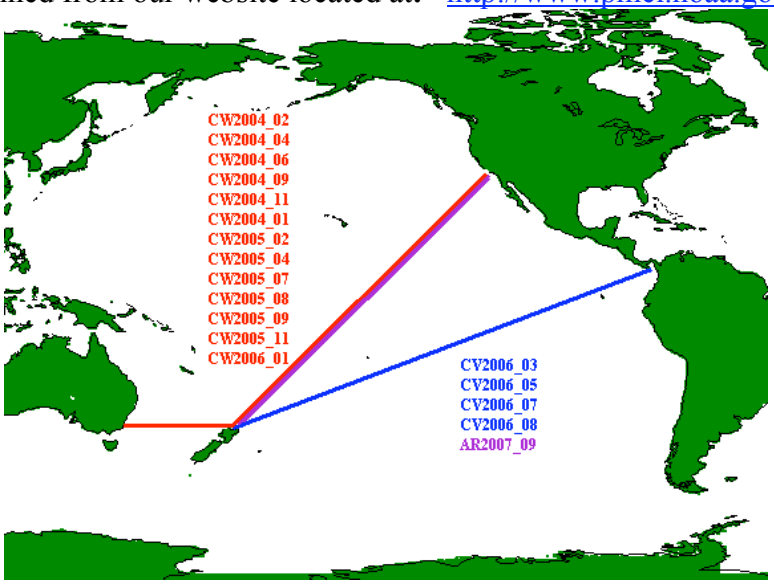


Figure 8:Cruise Tracks of the Columbus Waikato (red), Cap Victor (blue) and Albert Rickmers (purple) occupied during FY2004-2007.

A summary of the cruise results from Fall 2005 thru September 2007 is shown in *Figure 9* **Error! Reference source not found.**and *Figure 11***Error! Reference source not found.**. The results show strong seasonal variability of CO_2 fluxes in the southern and northern subtropic, but out of phase by 6 months. The most recent data shows high seawater pCO_2 values due to La Niña conditions in the equatorial Pacific. These results are described in the AGU/ASLO abstract by Cosca et al., (2008). The data will undergo further contextual checks by LDEO scientists before it is submitted to CDIAC for archiving.

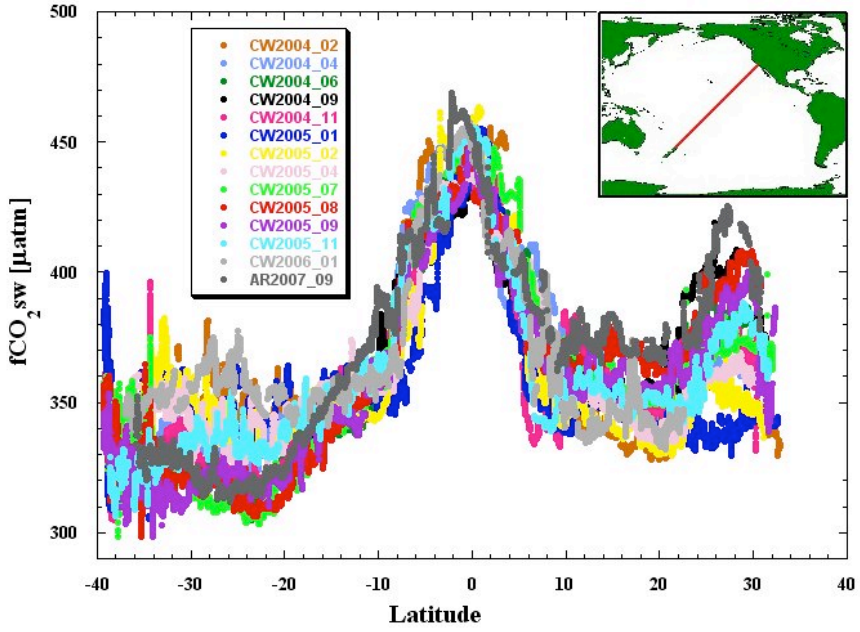


Figure 9:Time-Series of surface water pCO2 levels in the tropical and subtropical Pacific Resulting from Columbus Waikato and Albert Rickmers repeat observations from 2004 to 2007.

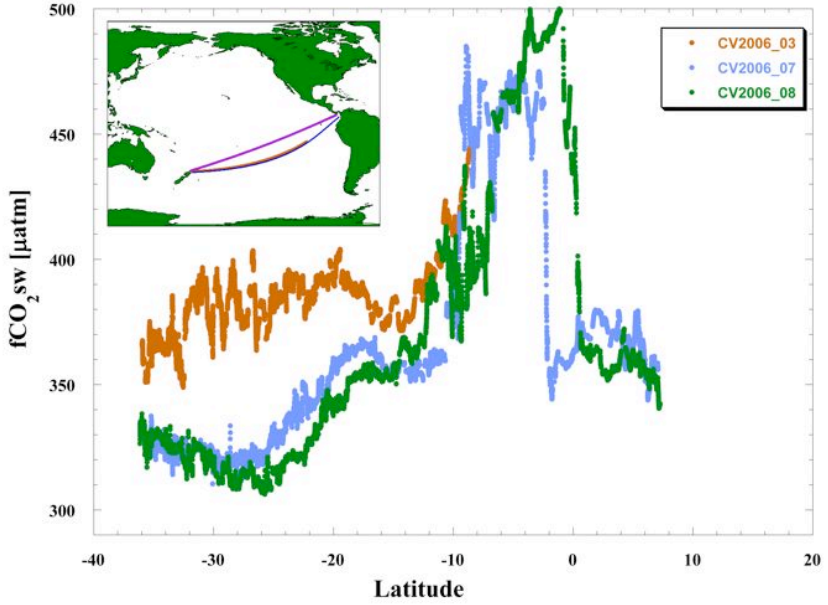


Figure 11:. Time-Series of surface water pCO2 levels in the tropical and subtropical Pacific Resulting from Cap Victor repeat observations in 2006.

RVIB *Palmer*- LDEO lead

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. Our pCO_2 system has been upgraded completely two years ago with the support from NOAA, and some new modifications are being added in order to make the system more stable and reliable. As the data are obtained, they are processed and added to our global database.

The locations of our data obtained since the beginning of this project in 2001 are shown in ***Figure 13***. The total number of surface water pCO_2 data obtained since January 2001 is 592,425. Approximately 48,524 measurements were added to the database during the calendar year 2007

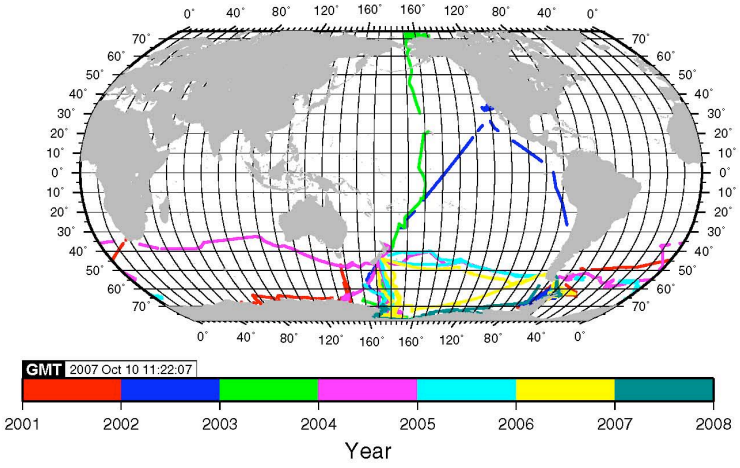


Figure 13: The locations of surface water pCO2 measurements made aboard the RVIB Palmer since 2001. The dark green lines indicate the observations made during the calendar year 2007, during which about 48,524 pCO2 measurements were obtained.

Cruise ship *Explorer of the Seas*-AOML lead

Causes for non-return: Some loss of data occurred because of a buildup of salt in the return line from the dry box to the equilibrator and water trapped in the tubing between the headspace pump and the dry box blocking the sample gas flow. Slow flushing of lines means that we omit data from the first 10-minutes after the standard run.
Description: Last year, 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 the Eastern Caribbean. New York is now the permanent port for the ship and sails not only to Bermuda and the Caribbean but also to Canada and New England during the summer. 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 15* 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. During the performance period all weekly data was combined into yearly data files for the particular routes (East, West, and North). The yearly data and metadata in IOCCP recommended format from 2003-2006 has been submitted to CDIAC.

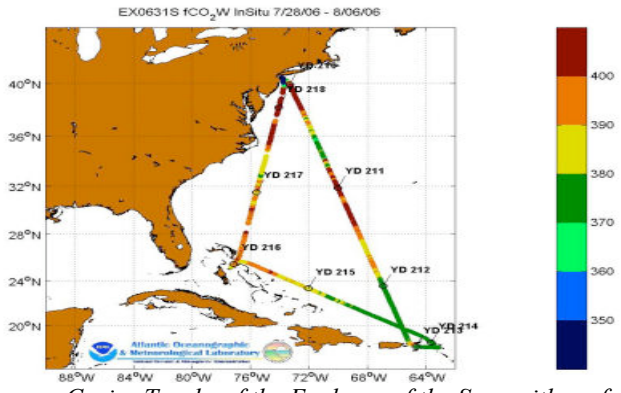


Figure 15: One of the Summer Cruise Tracks of the Explorer of the Seas with surface water pCO2 levels for late summer 2006.

Container Ship *Skogafoss*- AOML & RSMAS lead

Causes for non-return: This system has run unattended or with untrained observers except for 3 cruises when AOML were onboard. Data gaps have occurred for a variety of reasons, including failure by ship's personnel to open the seawater valves and malfunctioning gas flow sensors. On the last cruise, the CO_2 analyzer water channel drifted out of calibration, causing negative water concentrations to be registered. Although the effect on the CO_2 concentration is small, the data had to be flagged for caution.

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* ***16***. 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. The *Skogafoss* did its last transit in May of 2007 and is expected to be replaced by a permanent ship later this year. The system will be re-installed as soon as it happens so that we can continue the measurements on the same line.

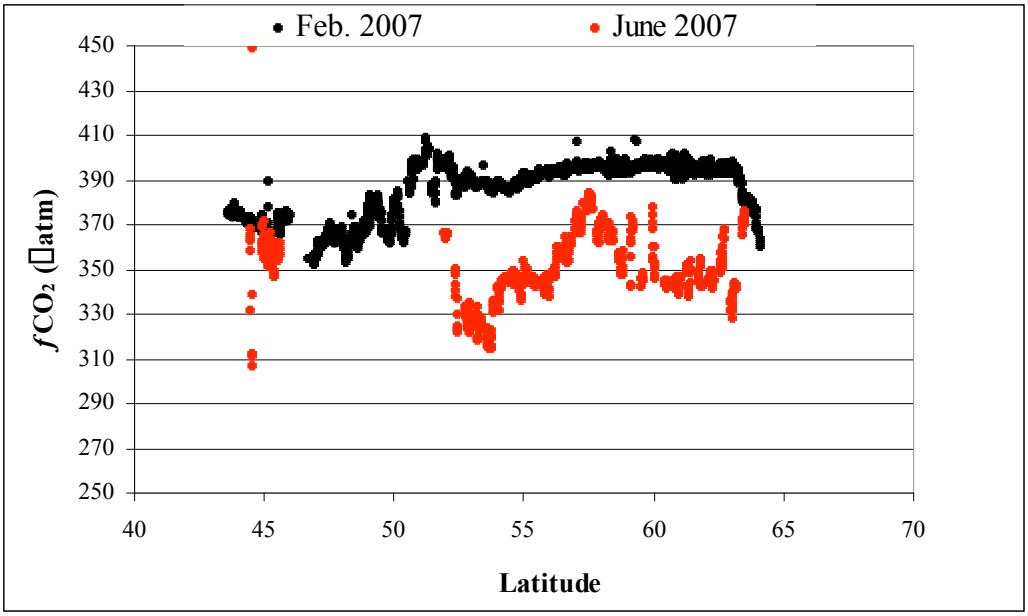


Figure 16: pCO_2 levels along the transect of the Skogafoss in February 2007 and June 2007

Container Ship *Oleander*- BIOS lead

Description: The MV *Oleander* crosses weekly between New Jersey and Hamilton, Bermuda. Given the ~100 crossings a year, this gives excellent temporal and spatial coverage of the North Atlantic subtropical gyre, Gulf Stream, middle Atlantic Bight and coastal zone. The MV *Oleander* transits the region of Subtropical Mode Water (STMW) formation during the winter southeast of the Gulf Stream, and the highly productive coastal zone of the Eastern Seaboard.

Data Return:

The pCO_2 system was installed on the MV *Oleander* in February 2006. Over the year, the total data collected was ~108,000, with a ~68% data recovery. The remaining 32% 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. Maintenance of the pCO_2 system has become relatively routine with weekly visits to the ship during the ship's turnaround in Hamilton, Bermuda. Our group has developed a good rapport with the ship officers, engineers and crew, and their good will has contributed greatly to the success of the system installation on the ship.

The seawater and atmospheric pCO_2 data from 2006 and 2007 (up to May) have been submitted to LDEO. We are in the process of preparing the metadata information and data QC/QA for submission of data to CDIAC in yearly reports (i.e., 2006, 2007). The seawater and atmospheric pCO_2 data will also be served at the following site (http://www.bios.edu/Labs/co2lab/vos.html).

Causes for non-return:

On the MV *Oleander*, the primary causes for non-return have been associated with ship-related issues (seawater pump system turned off; delays getting on to the ship); failure of the waste reservoir and delays related to component replacement. Over the last year there have been occasions when the seawater system were not turned on during the weekly turnaround of the ship. There have also been several occasions when our group has not been

able to access the ship in port due to offload/onload pressures when the ship is undertaking very quick turnarounds due to weather delays. On a couple of occasions, the pump that drains seawater from the waste reservoir has failed and we have had delays in replacing the pump. 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 is drained by a pump back into the seawater line downstream of the tap off to the pCO_2 system. In 2007, the pump has failed twice with shutdown of the system after overflow into the ship's bilges. Recently, we have added a second, stronger pump to ensure that the waste water is pumped overboard. 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. 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 average temperature of the engine room has been ~47°C with the CPU failing in 2006 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 (80*C) with no problems since. 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..

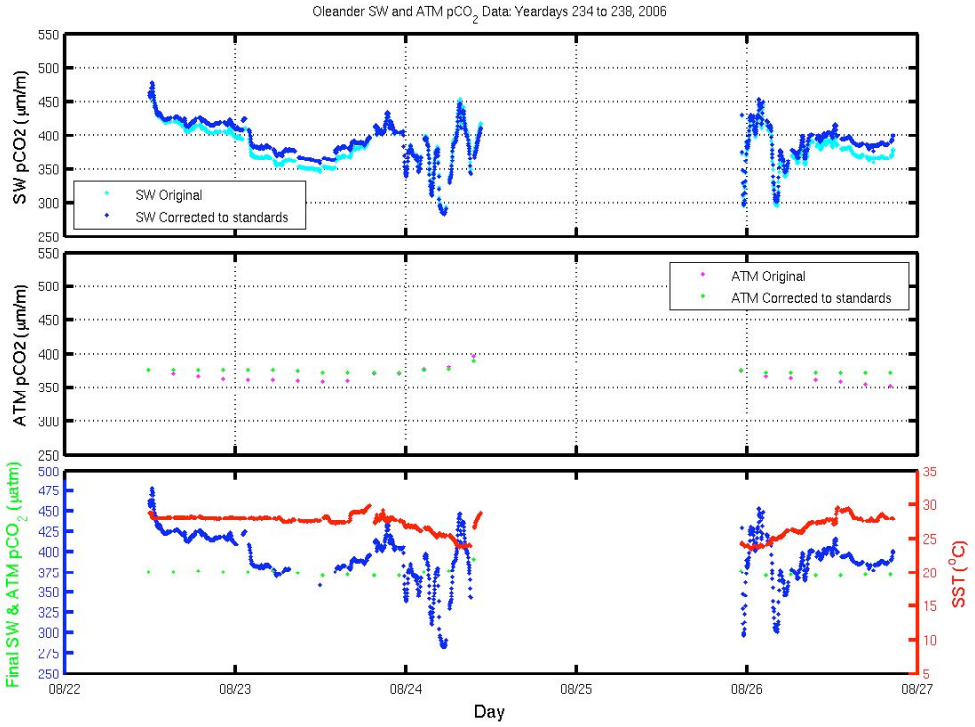


Figure 17: Example of Oleander data during a crossing from New Jersey to Bermuda, and back again in August 2006. The data gap is when the ship on 8/25 was in port

R/V *Atlantic Explorer* - BIOS lead

Description: The R/V *Atlantic Explorer* operates in the North Atlantic Ocean (zone NA6), servicing four oceanographic time-series (e.g., Bermuda Atlantic Time-series Study, Hydrostation S, Bermuda Testbed Mooring, Ocean Flux Program) and other research projects. This data stream provides groundtruthing pCO_2 datasets for the subtropical gyre of the North Atlantic Ocean. In 2007, the *Atlantic Explorer*has been scheduled for 173 days.

Data Return:

The pCO_2 system was installed on the RV *Atlantic Explorer* in April 2006. Over the last 16 months, the total data collected was ~92,000, with a ~83% data recovery. The

remaining 17%% were flagged due to problems associated with the Valco multi-position valve and distribution of standards through the system, and delays in replacing the standards.Maintenance of the pCO_2 system has become relatively routine during the ship's turnaround at the BIOS dock. The seawater and atmospheric pCO_2 data from 2006 and 2007 (up to May) have been submitted to LDEO. We are in the process of preparing the metadata information and data QC/QA for submission of data to CDIAC in yearly reports (i.e., 2006, 2007). The seawater and atmospheric pCO_2 data will also be served at the following site (http://www.bios.edu/Labs/co2lab/vos.html).

Causes for non-return:

In 2007, 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 485 converter, and faulty comport.

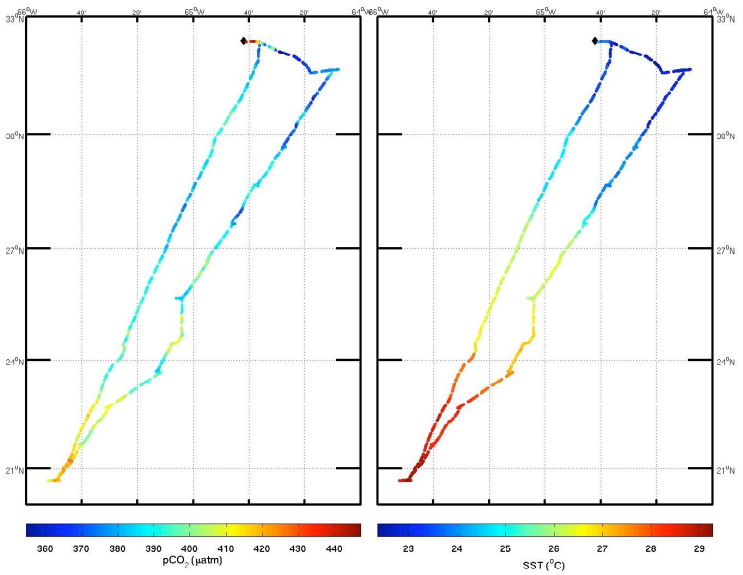


Figure 18:Example of Atlantic Explorer data during a transect across the North Atlantic subtropical gyre in May 2006.

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 close interactions including organizing training session for customers with the manufacturer General Oceanics who is building instruments to our specifications, uniform operating protocol, and uniform data reduction procedures.

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. This way, virtually infinite metadata sets could be created from the same real dataset but 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. One of the many advantages is that it allows for a robust and fast development. The reduced data is then submitted to a full automatic quality check, were the initial check is redone on the reduced data. Additionally, it allows comparisons with other measurements, such as from profiling floats, XBTs, and climatology. Every 6 hours the GTS is updated with the new reduced approved data. The capability to transmit data to the Coriolis center and NODC are under development. Details on each of the quality control steps can be found in : *www.aoml.noaa.gov/phod/tsg/data/qc_sheet.pdf.*

The PMEL group wrote new software to quickly process data files that are transmitted daily via iridium satellite from the Ka'imimoana and Albert Rickmers. This software processes the daily data and creates diagnostic plots of pCO_2, temperature, salinity, barometric pressure, water flow and gas flow. The plots are posted on a newly created internal website and are used as a diagnostic tool for data processing and quality control of the underway pCO_2 data. All current and previous VOS data files are quality controlled using the data submission protocol for ships under the NOAA Office of Climate Observations (OCO) workplan "pCO_2 measurements from ships".
The LDEO group, in close interaction with the data acquisition groups, oversees shipboard quality control so that the quality of data and consistency is monitored for the whole group. The participants of the VOS program are able to access the data which are listed in a uniform format. For this purpose, the LDEO group established an open web site at the following URL: http://www.ldeo.columbia.edu/CO2. The site provides not only the

numerical data, but also maps showing the ship's tracks for each data file. The new data will be accessible only to the VOS participants for a period of three years, and will be sent to the Carbon Dioxide Information and Analysis Center (CDIAC), Oak Ridge, TN, for the permanent archiving and distribution to the public after this period. This close coupling of the data acquisition with data processing/evaluation and interpretation will guarantee high quality field observation data.

As a part of the VOS program, the LDEO group processed and added to its database the measurements from the 2 other field operations; 1) the R/V Laurence M. Gould, which is supported by NSF as a part of the Long-Term Research in Environmental Biology (LTRE) program in the Drake Passage area, Southern Ocean; 2) Yacht Turmoil in coastal waters. The sampling locations during the R/V L. M. Gould program are shown in ***Figure 19***. A total of approximately 35,718 pCO_2 measurements that were made aboard the R/V Gould during the calendar year 2007 have been added to the database. This makes a total of 337,097 pCO_2 measurements for the Gould program from March, 2002 through September, 2007.

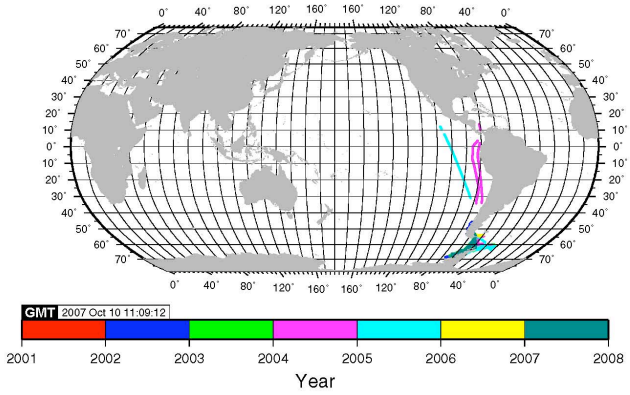


Figure 19: The locations of the surface water pCO2 measurements obtained aboard the R/V Gould during this project, March, 2002 through August, 2007. The years of the measurements are color coded.

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 3.3 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.* (2007) 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. Data obtained as part of the CO_2 on ships effort has been extensively used in the recently submitted paper by Takahashi et al. (2007) "Climatological Mean and Decadal Change in Surface Ocean pCO_2, and Net Sea-air CO_2 Flux over the Global Oceans". Takahashi and colleagues were the first to produce a monthly air-sea CO_2 flux climatology based on surface water CO_2 data. An updated climatological mean distribution for the surface water pCO_2 over the global oceans in non-El Niño conditions has been constructed with spatial resolution of 4° (latitude) x 5° (longitude) for a reference year 2000 based upon about 3 million measurements of surface water pCO_2 obtained from 1970 to 2006. The database used for this study is about 3 times larger than the 0.94 million used for our earlier paper (Takahashi et al., 2002). A global ocean database for a single reference year 2000 is assembled using this mean rate for correcting observations made in different years to the reference year. The annual mean for the contemporary net CO_2 uptake flux over the global oceans is estimated to be -1.4 ± 0.7 Pg-C yr^{-1}. Taking the pre-industrial steady state ocean source of 0.4 ± 0.2 Pg-C yr^{-1} into account, the total ocean uptake flux including the anthropogenic CO_2 is estimated to be -1.8 ± 0.7 Pg-C yr^{-1} in 2000.

3. As part of our continuing effort to understand decadal changes in the carbon fluxes of the equatorial Pacific, we developed seasonal and interannual pCO2-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 September 2007. 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 four La Niña periods (1988–1989, 1995–1996, 1998–2000 and 2007). 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 fCO2-SST relationships. A linear fit through the data sets yields an inverse correlation between SST and fCO2, with both interannual and seasonal differences in slope. In particular, the results indicate a strong interannual El Niño – Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and weaker seasonal variability. There is also a slight increase (~27%) in the out-gassing flux of CO2 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. In the summer of 2007, equatorial pCO2 values were extremely high, likely resulting from the development of La Niña conditions in the late summer of 2007.

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)

5. The VOS CO_2 data is providing valuable information on CO_2 variability in surface seawater over a wide range of time- and spatial scales that have not been fully examined. In 2006, both BIOS' ships collected high frequency data in the region of the subtropical gyre of the North Atlantic Ocean, Gulf Stream, Middle Atlantic Bight and coastal ocean of the eastern seaboard.

   Comparisons of underway seawater pCO_2 data collected from BIOS's ship, R/V Atlantic Explorer with the BTM pCO_2 sensor have been initiated (*Figure **20***). Over 15,000 seawater pCO_2 datapoints were collected from the Atlantic Explorer within 80 km of the BTM in 2006. Seawater pCO_2 data collected from the R/V Atlantic Explorer underway system within 10 km of the BTM (also within 3 minutes of each BTM datapoint) had an average difference of less than 0.5 µatm.

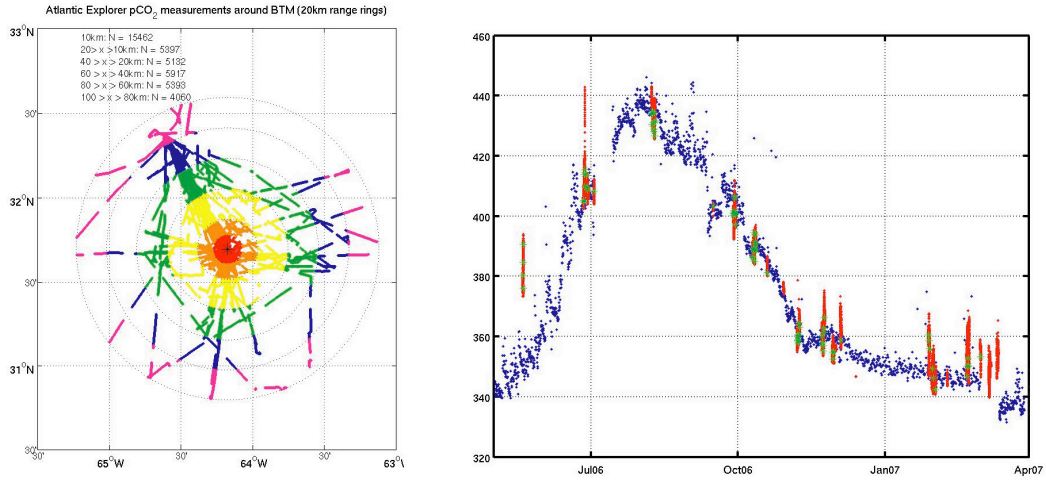


Figure 20. Left Panel. Seawater pCO2 data collected from the RV Atlantic Explorer within 80 km of the BTM site (64.2°W, 31.7°N). Red zone indicates data collected within 10 km of the BTM. Right Panel. Comparison of R/V Atlantic Explorer seawater pCO2 data (red data) with BTM pCO2 sensor data (blue data). The AE data was collected within 10 km of the BTM. The green datapoints indicate AE data collected within 3 minutes of each BTM datapoint.

Publications 2006 & 2007 resulting wholly or in part from this work:

Chavez, F. and Takahashi, T. (2007). Coastal oceans, Chapter 15, in "The First State of the Carbon Cycle Report (SOCCR): North American Carbon Budget and Implications for the Global Carbon Cycle". A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [King, A.W. L. Dilling. G.P. Zimmerman, D.M. Fairman, R.A. Houghton, G.H. Marland, A.Z. Rose, and T.J. Wilbanks (eds.)] National Ocean and Atmospheric Administration, Climate Program Office, Silver Spring, MD, USA, pp. 83-92.

Chierici, M., A. Olsen, J. Triñanes, and R. Wanninkhof (2007), Algorithms to estimate the carbon dioxide uptake in the northern North Atlantic using ship-observations, satellite and model data., Deep -Sea Res., submitted.

Corbière, A., Metzl, N., Reverdin, G., Brunet, C. and Takahashi, T. (2007). Interannual and decadal variability of the carbon dioxide and air-sea CO_2 fluxes in the North Atlantic subpolar gyre.Tellus B, 59, 168-179, doi:10.111/j.1600-0889.2006.00232.

Cosca, C.E., Feely, R., Tilbrook, B., Quay, P., Wisegarver, D., Wolfe, C., Juranek, J. First Underway fCO_2 Observations from the VOS Container Ship *Columbus Waikato* in the Tropical and Subtropical Pacific. EOS Trans AGU. (2006).

Doney, S., I. D. Lima, R. A. Feely, D. M. Glover, K. Lindsay, N. Mahowald, J. K. Moore, and R. Wanninkhof (2007), Mechanisms Governing Interannual Variability in the Upper Ocean Inorganic Carbon System and Air-Sea CO2 Fluxes , Deep -Sea Res., submitted.

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

Jiang, L.-Q., W.-J. Cai, Y. Wang, R. Wanninkhof, and H. Lüger (2007), Air-sea CO2 fluxes on the South Atlantic Bight: CO2 dynamics on a marsh-dominated shallow continental shelf., accepted JGR.

Li, Z., D. Adamec, T. Takahashi, and S. C. Sutherland (2005), Global aurocorrelation scales of the partial pressure of oceanic CO_2, J Geophys. Res., 110, doi:08010.01029/02004JC002723

Lüger, H., R. Wanninkhof, D. W. R. Wallace, and A. Kortzinger (2006), CO_2 fluxes in the subtropical and subarctic North Atlantic based on measurements from a volunteer observing ship , J Geophys. Res., 111, C06024, doi:06010.01029/02005JC003101.

Lüger, H., R. Wanninkhof, A. Olsen, J. Trinanes, T. Johannessen, D. Wallace, and A. Koertzinger (2006), The CO_2 air-sea flux in the North Atlantic estimated from satellite data, Tellus, submitted.

McGillis, W., and R. Wanninkhof (2006), Aqueous CO_2 gradients for air-sea flux estimates, Marine Chemistry, 98, 100-108.

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.

McNeil, C., D. Katz, R. Wanninkhof, and B. Johnson (2005), Continuous shipboard sampling of gas tension, oxygen and nitrogen, Deep-Sea Research, Instruments and

Methods, 52, 1767-1785
Olsen, A., R. Wanninkhof, J. A. Trinanes, and T. Johannessen (2005), The effect of wind speed products and wind speed-gas exchange relationships on interannual variability of the air-sea CO_2 gas transfer velocity, Tellus, 57B, 95–106.
Park, G.-H., K. Lee, R. Wanninkhof, and R. A. Feely (2006), Ocean data-based estimates of recent year-to-year variability of oceanic uptake of CO_2, J. Geophys. Res., 111, doi:10.1029/2005JC003090.
Pierrot, D., Neill, C., Sullivan, K., Castle, R., Wanninkhof, R., Lüger, H., Johannessen, T., Olsen, A., Feely, R.A., Cosca, C.E. (submitted) Recommendations for Autonomous Underway pCO_2 Measuring Systems and Data Reduction Routines. Deep Sea Res. II.
Sabine, C.L., R.A. Feely, and R. Wanninkhof (2006): Global Oceans: Ocean carbon. In State of the Climate in 2005, K.A. Shein (ed.), Bull. Am. Meteorol. Soc., 87(6), S29–S30.
Schuster, U., Watson, A.J., Bates, N., Corbière, A., Gonzalez-Davila, M., Metzl, N., Pierrot, D., Santana-Casiano, M. (submitted) Trends in North Atlantic sea surface pCO_2 from 1990 to 2006. Deep Sea Res. II.
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.
Takahashi, T., Sutherland, S. C. and Kozyr, A. (2007). Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed during 1968-2006 (Version 1.0). Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN 37831. RNL/CDIAC-152, NDP-088, pp.9.
Takahashi, Taro[1*], Stewart C. Sutherland[1], Rik Wanninkhof[2], Colm Sweeney[3], Richard A. Feely[4], David W. Chipman[5], Burke Hales[6], Gernot Friederich[7], Francisco Chavez[7], Andrew Watson[8], Dorothee C. E. Bakker[8], Ute Schuster[8], Nicolas Metzl[9], Hisayuki Yoshikawa-Inoue[10], Masao Ishii[11], Takashi Midorikawa[11], Christopher Sabine[4], Mario Hopemma[12], Jon Olafsson[13], Thorarinn S. Arnarson[13], Bronte Tilbrook[14], Truls Johannessen[15], Are Olsen[15], Richard Bellerby[15], Hein J. W. de Baar[16], Yukihiro Nojiri[17], C. S. Wong[18], Bruno Delille[19] and N. R. Bates[20] (in review). Climatological mean and decadal changes in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. Deep-Sea Res. II.
Thomas, H., F. Prowe, I. D. Lima, S. Doney, R. Wanninkhof, and R. J. Greatbach (2007), Changes in the North Atlantic Oscillation govern uptake in the North Atlantic, in preparation.
Wanninkhof, R., Olsen, A., Trinanes, J., 2007. Air-sea CO_2 fluxes in the Caribbean Sea from 2002-2004. Journal of Marine Systems 66 (1-4), 272-284.

Conference Proceedings & Technical Reports

Lüger H., R. Wanninkhof, R. Castle, K. Sullivan, T.-H. Peng, R. Feely, C. Cosca, C. Neill, A. Olsen, T. Johannessen, D. Pierrot, F.J. Millero, T. Steinhoff, A. Koertzinger, D. Wallace, Common Data Reduction Practices for Underway fCO_2 Measurements by Ships of Opportunity, 2006 Ocean Sciences Meeting, Honolulu, Hawaii, 20-24 February 2006, Abstract.

Russell, J.L., C. Sweeney, A. Gnanadesikan, R.A. Feely, and R. Wanninkhof (2006): Optimal network design to detect spatial patterns and variability of ocean carbon sources and sinks from underway surface pCO_2 measurements. 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, 229–231.

Wanninkhof, R., R.A. Feely, N.R. Bates, F.J. Millero, T. Takahashi, and S. Cook (2006): Document ocean carbon sources and sinks—surface water pCO_2 measurements from ships. 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, 207–216.

APPENDIX

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

Taro Takahashi
Lamont-Doherty Earth Observatory of Columbia University
Palisades, NY

1. INTRODUCTION:

This proposal is a request for the fourth year continuation of the active NOAA grant which is ending August 31, 2008: **NA030AR4320179P27** entitled "Underway CO_2 Measurements aboard the RVIB Palmer and Data Management of the Global VOS Program". In this proposal, the funds supporting the activities of the Lamont-Doherty Observatory (LDEO) and the Bermuda Institute for Ocean Sciences (BIOS, formerly BBSR) (as a subcontract) are requested jointly. Although these groups share a common goal for the elucidation of sea-air CO_2 flux over the oceans, the progresses made by each group are documented separately.

2. SCIENTIFIC OBJECTIVES:

The sea-air net flux of CO_2 is governed by the difference between pCO_2 in surface ocean water and the overlying atmosphere as well as by the gas transfer rate across the sea-air interface. The seawater pCO_2 depends primarily on the processes occurring within the sea (such as seawater temperature, biological productivity and upwelling of deep waters), and the gas transfer rate is regulated mainly by atmospheric processes including turbulence of the interface induced by winds. The primary objective of this proposed investigation is to determine the space-time distribution of the ocean surface pCO_2 and the sea-air pCO_2 difference. Combining the sea-air pCO_2 difference with the CO_2 gas transfer coefficient which is being investigated by other scientific groups, a reliable net sea-air flux of CO_2 over regional to global scales can be estimated using improved sea-air pCO_2 difference data. The work by the LDEO group is primarily focused in the southern high latitude areas surrounding the Antarctic continent, whereas the BIOS group is in the western North Atlantic Ocean. Thus, the results will give us an improved geographical coverage for the sea-air CO_2 transfer flux over the global ocean.

The LDEO group operates a semi-automated surface water pCO_2 system aboard the RVIB Nathaniel Palmer with significant operational assistance from the Raytheon Polar Support group (funded by NSF). RVIB Palmer is an ice-breaking research vessel, one of the few research ships operated in high latitude areas of the Southern Ocean even during winter months. Hence, the LDEO program yields observations critical to our understanding of the role of the high latitude Southern Ocean around Antarctica including the Weddell and Ross Seas in the global carbon cycle (see Fig. 1). The BIOS program is directed to the mid-latitude areas of the western North Atlantic Ocean aboard a container ship Oleander and R/V Weatherbird II and Atlantic Explorer.

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;; Frank Millero and his group at the University of Miami investigates coastal waters and Caribbean Sea. Pooling of the data among the participants will allow us to cover a large part of the global oceans. Under this grant, the Lamont-Doherty Observatory group is responsible for quality-control and management of the data produced by the NOAA-supported groups as well as those from international collaborators from Japan, Iceland, Germany and France. The data are processed into a single uniform format and are made accessible to the participants via the LDEO web site (www.ldeo.columbia.edu/CO2).

3. PROGRESS TO DATE, LDEO Program:

The progress made during a period January, 2001 through April, 2008, is described in this section.

3-A) LDEO Field Program aboard the RVIB Palmer:

The Lamont group is primarily responsible for the acquisition of the surface water pCO_2 data aboard the RVIB Palmer. Our pCO_2 system has been upgraded a year ago with the support from NOAA, and some new modifications are being added in order to make the system more stable and reliable. As the data are obtained, they are processed and added to our global database, which consists presently of about 3.4 million pCO_2 measurements in surface waters plus supplemental information including the SST, salinity, wind speeds, barometric pressure and atmospheric CO_2 concentration.

The locations of our data obtained since the beginning of this project in 2001 are shown in Figure. 1, and the dates, location and number of measurements are listed in Table 1. The total number of surface water pCO_2 data obtained to date is 637,382, of which about 93,481 measurements were added to the database during this project year 2007-08.

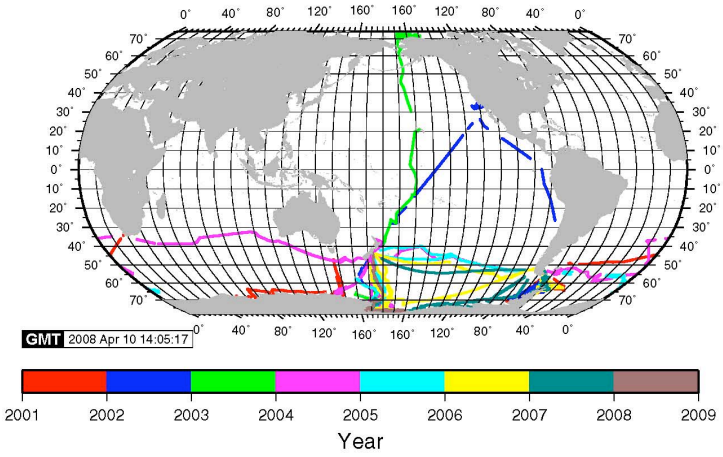


Fig. 1- The locations of surface water pCO_2 measurements made aboard the RVIB Palmer since 2001. The yellow lines indicate the observations made during the current project year 2007-08, about 93,481 pCO_2 measurements were obtained.

Table 1 – List of the RVIB N. B. Palmer expeditions and the number of surface water pCO_2 measurements obtained from January, 2001 through April, 2008.

Cruise No.	Project Name	Dates	No. Obs.	Annual No.
01/1	East Antarctic Margin	30 Jan - 20 Mar 2001	12,300	
01/2	SouthWest Pacific	01-19 Apr 2001	6,541	
01/3	SO-GLOBEC	23 Apr - 06 Jun 2001	20,446	
01/4	SO-GLOBEC	21 Jul - 01 Sep 2001	14,960	
01/5	Antarctic Peninsula	07 Sep - 26 Oct 2001	27,312	
01/6	SO-GLOBEC	09 Nov- 01 Dec 2001	10,317	
01/7	Antarctic Peninsula	05 Dec 01 - 12 Jan 02	22,627	**114,503**
02/1	Antarctic Penninsula	18 Jan - 04 Mar 02	24,542	
02/2	GLOBEC III	09 Apr - 21 May 2002	25,327	
02/4	GLOBEC IV	31 Jul - 09 Sep 2002	29,640	
02/5	Transit along W. South America	23 Sep - 19 Oct 2002	8,317	
02/6	USCG Inspection	30 Oct - 08 Nov 2002	6,732	
02/7	Reconst. of Paleo S. Pac.	10 Nov - 06 Dec 2002	5,702	
02/9	ANSLOPE, Transit fm Lyttleton to McMurdo	11 Dec 2002 - 03 Jan 2003	6,925	**107,185**
03/1	Ross Ice Shelf Survey	5 - 30 Jan 2003	8,062	
03/1A	Ross Sea Research	2-20 Feb 2003	7,227	
03/2	Ross Sea Research	25 Feb - 09 Apr 2003	13,897	
03/4	Transit N.Z to Alaska	23 May - 02 Jul 2003	9,864	
03/4A	Alaska North Slope	06 Jul - 18 Aug 2003	17,136	
03/5	Southern Ocean near 175E	26 Oct - 13 Dec 2003	7,427	
03/5A	Ross Sea Research	18 Dec 2003 - 02 Jan 2004	4,501	**68,114**
04/1	Western Ross Sea	20 Jan - 19 Feb 2004	12,299	
04/2	ANSLOPE III	26 Feb - 11 Apr 2004	17,708	
04/3	Transit New Zealand to Chile	16 Apr - 12 May 2004	9,463	

04/4	Ice Fish	18 May - 19 Jul 2004	22,755	
04/6	Transit, South Africa to New Zealand	27 Jul - 04 Sep 2004	14,277	
04/8	ANSLOPE IV	12 Oct - 06 Dec 2004	21,958	
04/9	Biochemical Research	18 Dec 2004 - 25 Jan 2005	14,443	**112,903**
05/1	ANSLOPE/IVARS	28 Jan - 15 Feb 2005	5,736	
05/1B	N.Z. to Chile Transit	03 - 22 Mar 2005	7,494	
05/2	Antarctic Penninsula	02 - 24 Apr 2005	8,235	
05/5	Coastal Chile	23 Jun - 14 Jul 2005	3,983	
05/6	Maud Rise	20 Jul - 18 Sep 2005	19,066	
05/7	Chile to N.Z. Transit	23 Sep - 21 Oct 2005	9,554	
05/8	Ross Sea Biology	26 Oct - 12 Dec 2005	18,387	**72,455**
06/1	Interaction of Iron, Light, & CO2	17 Dec 05 - 30 Jan 06	16,174	
06/2	Late Cretaceous & Cenozoic Recreations	03 Feb - 23 Mar 2006	7,740	
06/3	Paleo History of Larsen Ice Shelf	12 Apr - 05 May 2006	10,005	
06/6	Plankton Community Struct & Iron Concent.	03 Jul - 18 Aug 2006	17,565	
06/8	Ross Sea Plankton Dynamics	01 Nov - 15 Dec 2006	17,257	**68,741**
07/1	Geological Research	22 Dec 2006 - 29 Jan 2007	14,963	
07/2	Amundsen Sea Research	03 Feb - 25 Mar 2007	20,780	
07/3	Collaborative Research	31 Mar - 05 May 207	12,781	
07/4	Open Period	10 May - 20 Jun 2007	no data	
07/5	Transit to Maintenance Period	21 - 25 Jun 2007	pending	
07/6	Drydock	25 Jun - 28 Jul 2007	no data	
07/7	Transit to Punta Arenas, Chile	28 Jul - 02 Aug 2007	pending	
07/8	Open Period	02 - 27 Aug 2007	no data	
07/9	Sea Ice Balance in the Antarctic	01 Sep - 31 Oct 2007	14,616	
07/10	Palmer Station Resupply	14 Nov - 07 Dec 2007	8,548	
07/11	Transit, Chile - New Zealand	14 - 30 Dec 2007	6,355	**78,043**
08/1	Ross Sea Research	08 - 27 Jan 2008	6,876	
08/2	Ross Sea Research	29 Jan - 20 Feb 2008	8,562	
08/3	Ross Sea Research	Feb - Mar 2008	pending	
08/4	Ross Sea Research	Mar - Apr 2008	pending	**15,438**
GRAND TOTAL SINCE THE BEGINNING OF THE PROJECT				**637,382**

3-B) pCO_2 Data Processing and Management at LDEO for the VOS Program:

The Lamont group is responsible for processing and managing the surface water pCO_2 data acquired by the members of the Volunteer Ocean Survey (VOS) consortium, so that the participants of the program are able to access of the data in an uniform electronic format. For this purpose, we have established an open web site at the following URL: http://www.ldeo.columbia.edu/CO2. The site provides not only the numerical data, but also maps showing the ship's tracks for each data file. The new data will be accessible only to the VOS participants for a period of three years, and will be released to the public after this period.

As a part of the VOS program, we added quality-controlled data to our database from the following field operations; 1) the R/V Laurence M. Gould, which is supported by

NSF as a part of the Long-Term Research in Environmental Biology (LTRE) program in the Drake Passage area, Southern Ocean; 2) the NOAA's Ronald Brown program, mostly in the Atlantic Ocean (R. Wanninkhof); 3) the "Explorer of the Seas" program in and around the Caribbean Sea (R. Wanninkhof); 4) the Kaimimoana program in the equatorial Pacific (R. A. Feely). The sampling locations during the R/V L. M. Gould program are shown in Figure 2. The dates and the number of pCO_2 measurements made during each of these programs are summarized in Table 2. A total of approximately 67,307 pCO_2 measurements that were made aboard the R/V Gould during this funding period have been added to our database. This makes a total of 326,393 pCO_2 measurements for the Gould program from March, 2002 through April, 2008.

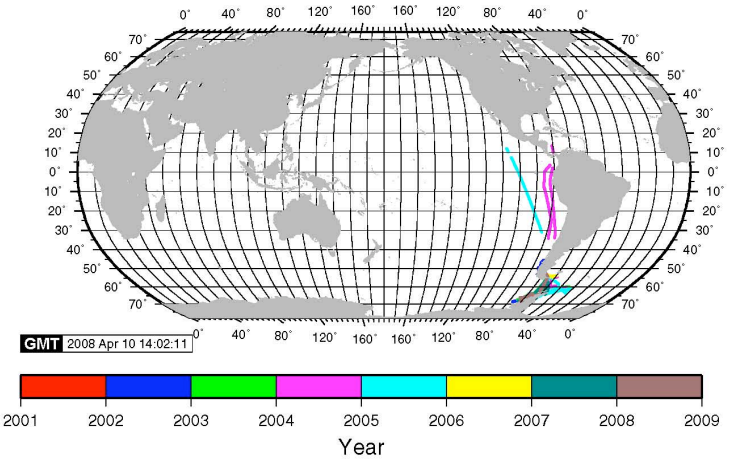


Figure 2 – The locations of the surface water pCO_2 measurements obtained aboard the R/V Gould during this project, March, 2002 through April, 2008. A total of 326,393 pCO_2 measurements were made since the beginning of the project in 2002. During the current funding period 2007-2008, 67,307 pCO_2 measurements were made. The years of the measurements are color coded. These data have been processed and quality-controlled by the VOS project.

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.	Year Total
02/1	Antarctic Penninsula	07 - 18 Mar 02	2,731	
02/2	Palmer Shuttle	22 Mar - 02 Apr 02	1,879	
02/3	GLOBEC III	07 Apr - 20 May 2002	8,659	
02/4	Palmer Shuttle	21 Jun - 22 Jul 2002	4,815	
02/5	GLOBEC IV	29 Jul - 19 Sep 2002	6,787	
02/6	Palmer Shuttle	23 Sep - 07 Oct 2002	2,332	
02/8	Open Cape Shirreff	03 Nov - 17 Nov 2002	3,137	
02/9	Scotia Arc GPS Project	23 Nov - 23 Dec 2002	8,209	**38,549**
03/1	LTER	31 Dec 2002 - 08 Feb 2003	13,831	
03/2	GLOBEC	13 Feb - 07 Mar 2003	4,167	
03/2	Palmer Shuttle	12 Mar - 29 Mar 2003	5,721	
03/4	Biological Research	05 Apr - 07 May 2003	9,334	
03/4A	Biological Research	10 May - 05 Jun 2003	4,629	
03/5	Palmer Shuttle	15 Jun - 29 Jun 2003	2,618	

03/5A	Palmer Shuttle	15 Aug - 04 Sep 2003	5,774	
03/6	Palmer Shuttle	23 Sep - 06 Oct 2003	2,495	
03/7	Palmer Shuttle	10 - 22 Oct 2003	3,450	
03/8	Palmer Shuttle	07 - 18 Nov 2003	3,758	
03/9	Antarctic Penn Research	23 Nov - 29 Dec 2003	12,288	**68,065**
04/1	Antarctic Penn Research	01 Jan - 07 Feb 2004	12,556	
04/2	Antarctic Penn Research	12 Feb - 24 Mar 2004	14,222	
04/3	Antarctic Penn Research	28 Mar - 12 Apr 2004	2,100	
04/4	Antarctic Penn Research	16 Apr - 10 May 2004	5,510	
04/5	Antarctic Penn Research	14 - 24 May 2004	3,797	
04/6	Palmer Shuttle	30 May - 09 Jun 2004	2,609	
04/7	Palmer Shuttle	13 - 27 Jun 2004	2,835	
04/8	Transit Chile to Louisiana	06-16 Jul 2004	3,849	
04/11	Palmer Shuttle	25 Sep - 12 Oct 2004	3,165	
04/12	Palmer Shuttle	17 - 30 Oct 2004	2,091	
04/13	Palmer Shuttle	08 - 18 Nov 2004	4,014	
04/14	Palmer Shuttle	24 Nov - 31 Dec 2004	10,916	**67,664**
05/1	LTER Palmer Penn.	31 Dec 2004 - 05 Feb 2005	14,091	
05/2	Palmer Shuttle	11 Feb - 11 Mar 2005	11,411	
05/3	Palmer Shuttle	15 Mar - 29 Mar 2005	2,398	
05/4	Palmer Shuttle	04 - 07 Apr 2005	1,377	
05/5	Palmer Shuttle	21 Apr - 11 May 2005	3,675	
05/6	Palmer Shuttle	19 May - 09 Jun 2005	3,126	
05/7	Palmer Shuttle	14 - 28 Jun 2005	2,837	
05/8	Hazmat Transit	03 - 31 Jul 2005	4,440	
05/9	Hazmat Transit	23 Aug - 03 Sep 2005	3,876	
05/11	Palmer Shuttle	17 - 29 Sep 2005	2,436	
05/12	Palmer Shuttle	23 Oct - 03 Nov 2005	3,032	
05/14	Palmer Shuttle	08 - 21 Nov 2005	3,900	
05/15	Palmer Shuttle	27 Nov - 26 Dec 2005	6,462	
06/1	LTER Antarctic	01 Jan - 08 Feb 2006	10,538	
06/2	Deploy Engler Buoys	14 Feb - 18 Mar 2006	8,137	
06/3	Palmer Shuttle	21 Mar - 04 Apr 2006	3,072	**84,808**
07/1	LTER Antarctica	01 Jan - 11 Feb 2007	12,376	
07/2	Peterman Is. Pickup, Close Stations	16 Feb - 01 Mar 2007	3,766	
07/3	Palmer Station Shuttle	08 - 19 Mar 2007	2,439	
07/4	Palmer Turnover	23 Mar - 06 Apr 2007	2,637	
07/5	Biological Research	11 Apr - 09 May 2007	6,997	
07/6	Logistic Cruise	12 May - 03 Jun 2007	5,290	
07/7	Hazardous Waste Shuttle	07 - 22 Jun 2007	2,414	
07/8 -11	Dry dock maintenance	23 June - Sept 12, 2007	0	
07/12	Palmer Station Opening	13 - 29 Sep 2007	3,200	
07/13	COPA Opening	08 - 20 Oct 2007	2,750	
07/14	Open Period, maintenance	21 Oct - 3 Nov, 2007	0	
07/15	Palmer Shuttle	04 - 16 Nov 2007	3,395	
07/16	Not Used			
07/17	Antarctic Penn. Research	22 Nov - 22 Dec 2007	9,960	**55,224**

08/1	LTER Antarctica	30 Dec 2007 - 09 Feb 2008	12,083	
08/2	COPA Opening	14 Feb - 17 Mar 2008	Pending	
08/3	Palmer Turnover	22 Mar - 04 Apr 2008	Pending	
08/4	Palmer Shuttle	08 - 23 Apr 2008	Pending	**12,083**
GRAND TOTAL SINCE THE BEGINNIN OF PROJECT				**326,393**

The data obtained by the AOML/NOAA and PMEL/NOAA groups are summarized in Table 3. For this funding period of 2007-08, about 171,787 measurements were obtained aboard the Ronald Brown, the "Explorer of Sea", the Kaimimoana and the Columbus Waikato. The total number of surface water pCO_2 measurements made by these NOAA groups since 2001 through April 2008 is about 777,226.

Table 3 - Surface water pCO_2 data received from the AOML/NOAA and PMEL/NOAA groups for quality control and archiving. These data have been quality-controlled and added to the VOS database.

Year	Number of Legs (files)		pCO_2 Obs	Ship Total
Ship:	**Ronald Brown**			
2001	12		41,358	
2002	13		26,341	
2003	10		26,291	
2004	10		23,499	
2005	10		26,714	
2006	11		32,537	
2007	0	0		
				176,740
Ship:	**Explorer of the Seas**			
2002	30		39,262	
2003	39		76,322	
2004	50		82,043	
2005	44		67,231	
2006	39		57,576	
2007	35	53,268		
				375,702
Ship:	**Kaimimoana**			
2001	2		5,641	
2002	5		15,017	
2003	5		18,597	
2004	4		13,742	
2005	0		0	
2006	0	0		
2007	2			

		34,009		
				87,006
Ship:	**Columbus Waikato**			
2004	6		42,907	
2005	16		84,134	
2006	1		8,737	
2007	0	0		
				137,778
	Grand Total			**777,226**

3-C) LDEO Data Analysis and Synthesis:

The pCO_2 data obtained and archived by the present grant have been used extensively in the following research papers and government reports, that have been prepared during this grant period, 2007-08.

Corbiere, A., Metzl, N., Reverdin, G., Brunet, C. and Takahashi, T. (2007). Interannual variability of the carbon dioxide and air-sea CO2 fluxes in the North Atlantic subpolar gyre:1993-2003 (SURATLATIC Program). Tellus, 59B, 168-178.

Chavez, F. and Takahashi, T. (2007). Coastal oceans, Chapter 15, in "The First State of the Carbon Cycle Report (SOCCR): North American Carbon Budget and Implications for the Global Carbon Cycle". A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [King, A.W. L. Dilling. G.P. Zimmerman, D.M. Fairman, R.A. Houghton, G.H. Marland, A.Z. Rose, and T.J. Wilbanks (eds.)] National Ocean and Atmospheric Administration, Climate Program Office, Silver Spring, MD, USA, pp. 83-92.

Takahashi, T., Sutherland, S. C. and Kozyr, A. (2008). Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed during 1968-2006 (Version 1.0). ORNL/CDIAC-152, NDP-088. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U. S. Department of Energy, Oak Ridge, TN 37831, pp.20.

Takahashi, T. S.C. Sutherland, R. Wanninkhof, C. Sweeney, R. A. Feely, D. W. Chipman, B. Hales, G. Friederich, F. Chavez, A. Watson, D. C. E. Bakker, U. Schuster, N. Metzl, H. Yoshikawa-Inoue, M. Ishii, T. Midorikawa, Y. Nojiri, C. Sabine, J. Olafsson, Th. S. Arnarson, B. Tilbrook, T. Johannessen, A. Olsen, Richard Bellerby, A. Körtzinger, T. Steinhoff, M. Hoppema, H. J. W. de Baar, C. S. Wong, Bruno Delille and N. R. Bates (in press). Climatological mean and decadal changes in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. Deep-Sea Res. II.

Scott C. Doney, Ivan Lima, J. Keith Moore, Keith Lindsay, M. Behrenfeld, Natalie Mahowald, Matthew Maltrud, David M. Glover, Dennis McGillicuddy, and Taro Takahashi (in press). Skill metrics for confronting global upper ocean ecosystem-biogeochemistry models against field and remote sensing data. Jour. Marine Systems, Special Issue "*Skill Assessment for Coupled Biological/Physical Models of Marine Systems*"

Sabine, C. L., Feely, R. A., Wanninkhof, R. and Takahashi, T. (in review). The global ocean carbon cycle. Bulletin of the American Meteorological Society

4. PROGRESS TO DATE FOR THE BIOS PROGRAM:

4-A) Container Ship Oleander- BIOS lead

4-A-1) 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.

4-A-2) Data Return:

The pCO_2 system was installed on the MV *Oleander* in February 2006. Over the year, the total data collected was ~108,000, with a ~68% data recovery. The remaining 32% 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. Maintenance of the pCO_2 system has become relatively routine with weekly visits to the ship during the ship's turnaround in Hamilton, Bermuda. Our group has developed a good rapport with the ship officers, engineers and crew, and their good will has contributed greatly to the success of the system installation on the ship.

The seawater and atmospheric pCO_2 data from 2006 and 2007 (up to May) have been submitted to LDEO. We are in the process of preparing the metadata information and data QC/QA for submission of data to CDIAC in yearly reports (i.e., 2006, 2007). The seawater and atmospheric pCO_2 data will also be served at the following site (http://www.bios.edu/Labs/co2lab/vos.html).

4-A-3) Causes for non-return:

On the MV *Oleander*, the primary causes for non-return have been associated with ship-related issues (seawater pump system turned off; delays getting on to the ship); failure of the waste reservoir and delays related to component replacement. Over the last year there have been occasions when the seawater system were not turned on during the weekly turnaround of the ship. There have also been several occasions when our group has not been able to access the ship in port due to offload/onload pressures when the ship is undertaking very quick turnarounds due to weather delays. On a couple of occasions, the pump that drains seawater from the waste reservoir has failed and we have had delays in replacing the pump. 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 is drained by a pump back into the seawater line downstream of the tap off to the pCO_2 system. In 2007, the pump has failed twice with shutdown of the system after overflow into the ship's bilges. Recently, we have added a second, stronger pump to ensure that the waste water is pumped overboard.

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. 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 average temperature of the engine room has been ~47°C with the CPU failing in 2006 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 (80*C) with no problems since. 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.

4-B) R/V Atlantic Explorer - BIOS lead

4-B-1) Description:

The R/V *Atlantic Explorer* operates in the North Atlantic Ocean (primarily 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. In 2008, the *Atlantic Explorer* is scheduled for approximately 179 days.

4-B-2) Data Return:

The pCO_2 system was installed on the RV *Atlantic Explorer* in April 2006. Over the last 16 months, the total data collected was ~92,000, with a ~83% data recovery. The remaining 17%% were flagged due to problems associated with the Valco multi-position valve and distribution of standards through the system, and delays in replacing the standards. Maintenance of the pCO_2 system has become relatively routine during the ship's turnaround at the BIOS dock. The seawater and atmospheric pCO_2 data from 2006 and 2007 (up to May) have been submitted to LDEO. We are in the process of preparing the metadata information and data QC/QA for submission of data to CDIAC in yearly reports (i.e., 2006, 2007). The seawater and atmospheric pCO_2 data will also be served at the following site (http://www.bios.edu/Labs/co2lab/vos.html).

4-B-3) Causes for non-return:

In 2007, 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 485 converter, and faulty comport.

4-C) Mooring pCO_2 Effort:

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.

4-C-1) Bermuda Testbed Mooring (64.2°W, 31.7°N)

A moored pCO_2 system was first deployed on the Bermuda Testbed Mooring (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%.

4-D) Data management and dissemination:

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. An important part of the VOS effort is to disseminate quality controlled data to the community at large in an expedient fashion. The seawater and atmospheric pCO_2 data will also be served at the following site (http://www.bios.edu/Labs/co2lab/vos.html). After QC and QA, data will be transferred to LDEO.

4-F) Research highlights:

The VOS CO_2 data is providing valuable information on CO_2 variability in surface seawater over a wide range of time- and spatial scales that have not been fully examined. In 2006 And 2007, both ships collected high frequency data in the region of the subtropical gyre of the North Atlantic Ocean, Gulf Stream, Middle Atlantic Bight and coastal ocean of the eastern seaboard.

Comparisons of underway seawater pCO_2 data collected from BIOS's ship, R/V *Atlantic Explorer* with the BTM pCO_2 sensor have been initiated. Over 15,000 seawater pCO_2 datapoints were collected from the Atlantic Explorer within 80 km of the BTM in 2006. Seawater pCO_2 data collected from the R/V *Atlantic Explorer* underway system within 10 km of the BTM (also within 3 minutes of each BTM datapoint) had an average difference of less than 0.5 µatm.

4-G) Community Service, Conferences attended, and Outreach:

Nicholas R. Bates: IOCCP SSG meeting (Paris, April 2007); SOLAS-IMBER Carbon meeting (Paris, April 2007); Implementation planning meeting (Miami, December 2005); *Atlantic Meridional Transect* (AMT) meeting, Royal Society, July 2006. *CarboOCEAN* meeting, UEA, Sept. 2006

Committees He has contributed to the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment, and the SOLAS-IMBER joint carbon implementation plan. Bates is a member of the IOC-SCOR International Ocean Carbon Coordination Project (IOCCP) scientific steering group, and SOLAS-IMBER Carbon working group. Bates is a member of the US Carbon Cycle Scientific Steering Group (CCSSG), an advisory for the Carbon Cycle Interagency Working Group (CCIWG).

4-H) Publications:

Bates, N.R., Purinton, B., and Jeffries, M., 2006. Air-sea carbon dioxide exchange and fate of carbon in Eighteen Degree Water (EDW) of the North Atlantic Ocean: Initial results from the 2006 CLImate MOde water Dynamics Experiment (CLIMODE). *AGU meeting*. San Francisco, December 2006.

Bates, N.R., 2007. Interannual variability of the oceanic CO_2 sink in the subtropical gyre of the North Atlantic Ocean over the last two decades. *Journal of Geophysical Research (Oceans),* doi:10.1029/2006JC003759.

Marshall, J.D., Andersson, A.J., Bates, N.R., Dewar, W., Doney, S.C., Edson , J., Ferrari, R., Fratantoni, D., Gregg , M., Joyce, T., Kelly, K., Lozier, S., Lumpkin , R., Samelson, R., Skyllingstad, E., Straneo, F., Talley, L., Toole, J., and Weller, R., 2008. CLIMODE: a mode water dynamics experiment in support of CLIVAR. *Bulletin of the American Meteorological Society* (in preparation).

Neely, K., Bates, N.R., Johnson, R.J., and McGillicuddy, D.J., 2008. The influence of mesoscale eddies on inorganic carbon cycling and air-sea CO_2 gas exchange in the North Atlantic Ocean. *ASLO/AGU Ocean Sciences meeting*, Orlando, March 2008.

Schuster, U., Watson, A.J., Bates, N.R., Corbiere, A., Gonzalez-Davila, M., Metzl, N., Pierrot, D., Santana-Casiano, M., 2008. Decadal changes in the CO_2 sink of the North Atlantic Ocean. *Deep-Sea Research II* (special volume on Paris CO_2 meeting, April 2007) (accepted with revisions)

Takahashi, T., Sutherland, S.C., Wanninkhof, R., Sweeney, C., Feely, R.A., Chipman, D.W., Hales, B., Friederich, G.E., Chavez, F.P., Watson, A.J., Bakker, D.C.E., Schuster, U., Metzl, N., Yoshikawa-Inoue, H., Olafsson, J., Arnarson, T.S., Tilbrook, B., Johannessen, T., Olsen, A., Bellerby, R.J., de Baar, H.J.W., Nojiri, Y., Wong, C.S., Delille, B., Bates, N.R., and de Baar, H.W., 2008. Climatological mean and decadal change in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. *Deep-Sea Research II* (in press)

High-Resolution Ocean and Atmosphere pCO_2 Time-Series Measurements

Christopher L. Sabine[1], Francisco Chavez[2] and Nicholas R. Bates[3]
[1] NOAA Pacific Marine Environmental Laboratory, Seattle, WA
[2] Monterey Bay Aquarium Research Institute, Moss Landing, CA
[3] Bermuda Institute of Ocean Sciences, Bermud

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 and plots of the data are posted to the web once per day. 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 FY07, PMEL/MBARI maintained seven of the sites from FY06, had to relocate one existing site from 170°W, 2°S to 170°W, 2°N and established a new Stratus site in the South Pacific off of Chile (Figure 1). There were a total 12 servicing visits to these sites in FY07. New pCO_2 systems were needed to replace older systems or systems that were lost at sea earlier in the year.

The long term goal of this program is to populate 50 OceanSITES flux reference moorings with pCO_2 systems (Figure 1). With ten moorings currently fitted with pCO_2 systems (including the Papa mooring currently funded by NSF), we are currently at 20% completion of the open ocean moored CO_2 program goal.

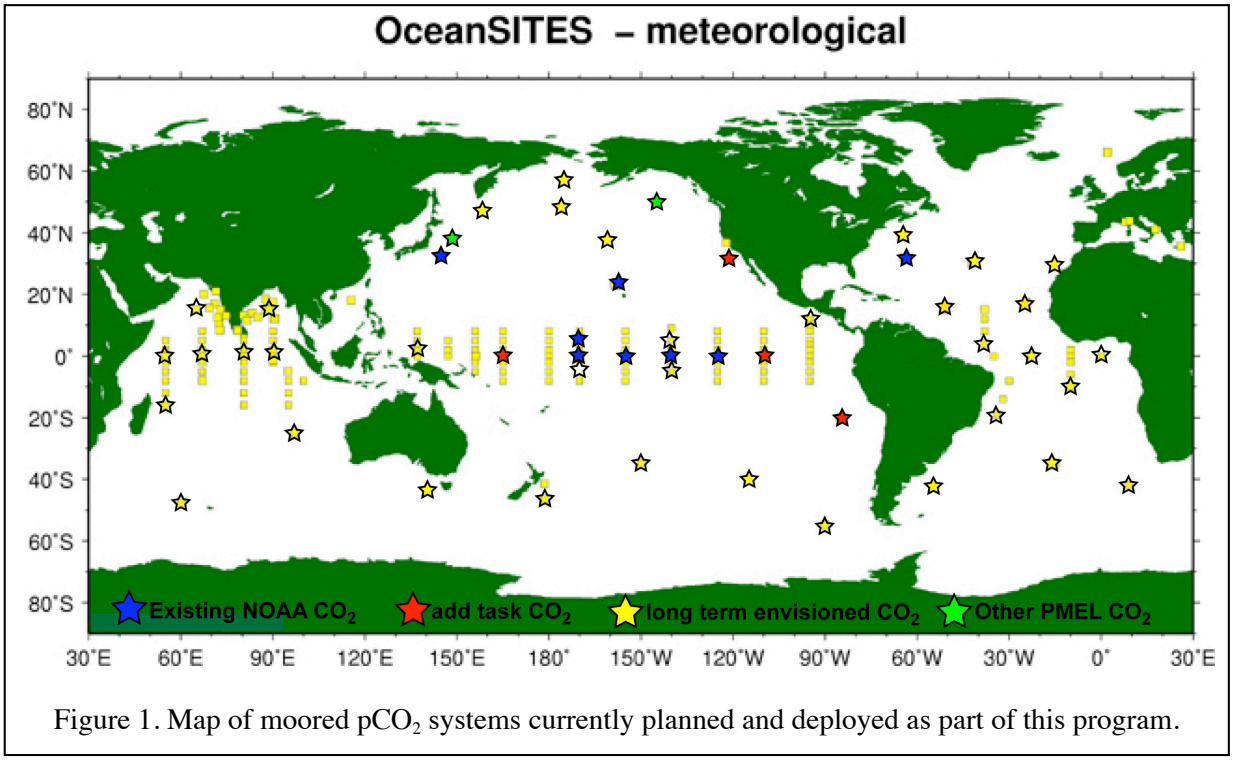


Figure 1. Map of moored pCO_2 systems currently planned and deployed as part of this program.

Instrument/Platform Acquisitions

Here we summarize the deployment schedules and instrument performance over the last year. Systems are grouped into three categories. Five systems are located in the equatorial Pacific on the TAO moorings. Three systems are on Woods Hole buoys located in the North Pacific subtropical gyre, North Atlantic subtropical gyre and in the South Pacific upwelling region off of Chile. Two of the Woods Hole buoys are co-located with shipboard time-series study sites at Hawaii and Bermuda. One system is located off of Japan in a high-latitude buoy operated by Meghan Cronin (PMEL) as part of an OCO funded OceanSITES flux mooring.

***Equatorial Pacific on TAO Moorings**:*

125°W, 0° - At the beginning of FY07, the PMEL built system at this location collected atmospheric measurements, but lacked seawater measurements due to a deployment error, the equilibrator was jammed above the sea surface and was unable to collect seawater measurements until mid-March when the equilibrator broke free. In May, the equilibrator portion of the system was replaced and the system was fully operational until the buoy was damaged and went adrift in July. The system was redeployed in October and is again fully operational. 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, FY07: 32% and Lifetime: 47%.

140°W, 0° - This PMEL-built system was redeployed in late September 2006 and was fully operational until December when the equilibrator was damaged by vandalism. The system continued to collect atmospheric measurements until the system was replaced in May. The system was then fully operational through July when the equilibrator was again damaged. During the September visit to this location, the equilibrator pipe was found bent and jammed, it was straightened by ship's personnel and replaced in the buoy. The buoy is currently fully operational. The percent data return (only counting times when both seawater and atmospheric measurements were considered good) is as follows, FY07: 56% and Lifetime: 56%.

155°W, 0° - This MBARI-built system was serviced in October 2006 but data quality was questionable. We are hopeful that some of these data can be salvaged during the post recovery processing. A new system was deployed in August 2007 and appears to be operating properly. The percent data return is as follows, FY07: 20% and Lifetime: 31%.

170°W, 2°S - This MBARI-built system was serviced in October 2006, but still exhibited intermittent problems throughout the year. In July 2007 a shortage of mooring equipment prevented the redeployment of the CO_2 sensor at this location. Instead, the CO_2 system was deployed at 2°N. The percent data return is as follows, FY07: 56% and Lifetime: 27%.

170°W, 2°N - This MBARI-built system, was deployed at this location for the first time on July 31, 2007. The instrumentation at 2°N, 170°W appears to be working well based on the telemetered data. A full assessment of the data will be possible when the system is returned to the lab. The percent data return is as follows, FY07: 100%, Lifetime: 100%

170°W, 0° - This PMEL-built system was operational until February when the equilibrator was damaged during a vandalism episode in which the buoy was dragged ten nautical miles. The system was replaced in July and continues to be fully operational. The percent data return (only counting times when both seawater and atmospheric measurements were considered good) is as follows, FY07: 50% and Lifetime: 75%.

Nutrient and Chlorophyll - Bottle samples are collected and processed by MBARI personnel from the NOAA ship *Ka'imimoana* on the two occupations of the 155°W and 170°W lines. Approximately 500 samples were collected during the cruises in FY07. Approximately 5% of the samples were discarded due to improper sampling and loss during analysis. The percent data return is as follows, FY07: 95%.

WHOI designed buoys

MOSEAN at Hawaii Ocean Time-series site (158°W, 22°N) – This system was fully operational during the entire period that the buoy was deployed in 2007. The buoy was pulled for service in mid December and was returned to the water late January. The buoy remained in the water through July when it was pulled due to lack of funding for the mooring. The percent data return is as follows, FY07: 100% and Lifetime: 88%.

WHOI Hawaii Ocean Time-series Station (WHOTS) ((157°W, 22°N) – In anticipation of the MOSEAN mooring being pulled due to lack of funding, a new system was deployed in the WHOTS mooring to continue the time series at the HOT site (the two moorings were within a few kilometers of each other). This new system was deployed in June 2007 and is fully operational. The percent data return is as follows, FY07: 100% and Lifetime: 100%.

Bermuda Testbed Mooring (BTM) (64.2°W, 31.7°N) – This system was fully operational during FY07. The mooring was pulled in early March for maintenance and was redeployed in mid-March. The mooring remained in the water through September when it was pulled due to lack of funding for the mooring. The percent data return is as follows, FY07: 100% and Lifetime: 100%.

Stratus (19.7°W, 85.5°N) – This system was deployed in October 2006 and remained fully operational the entire year. This system was recovered and a new system was deployed in October 2007. The percent data return is as follows, FY07: 100% and Lifetime: 100%.

An add task was submitted for this site in FY07, but with the October deployment, we were forced to deploy before we had confirmation that the add task would be funded. Due to budgetary constraints, the add task was not funded but we were already committed to this site. A new add task is being submitted this year to support this work. It is imperative that this add task be funded if we are to continue to maintain this site.

OceanSITES Flux Moorings

Kuroshio Extension Observatory (144.5°E, 32.3°N) – At the beginning of FY07, the system was not operational in due to a problem that occurred during the deployment in May 2006. The mooring was not redeployed until September 2007. A new high latitude mooring was deployed at the KEO site in September and the system is now fully operational.

Japanese Kuroshio Extension Observatory (146.5°E, 38°N) – Since the KEO system was not operational at the time that this new mooring was being deployed in a nearby location, we decided to add a CO_2 system in an effort to begin the data collection in the region. The new mooring was deployed in February 2007 and the pCO_2 system at this site was fully operational during the remaining part of FY07.

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 FY07, upgrades were made to the software to so that the systems can be controlled via satellite by the personnel at PMEL. During every deployment, someone from the PMEL CO_2 group is standing by to remotely turn on the system after the buoy is deployed and to ensure that is running properly before the ship leaves the site. In addition to being able to turn the system on and off, several parameters can be changed remotely to optimize data collection.

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 and to make the systems more robust. It has taken most of FY07 to implement these changes at all of sites, but the changes have made an obvious improvement. One indicator of success was the fact that our system at BATS was completely operational even though the buoy was flipped upside down during deployment.

The TAO buoys are often the target of fishing and vandalism. The pCO_2 systems on this array have suffered from these acts. In order to get fresh seawater to our equilibrator, the equilibrator pipe extends beneath the bottom deck of the buoy by several inches. On many occasions, the pipe was found bent when it was recovered. It is believed that fishing gear is getting tangled around the equilibrator pipe. We are currently researching options to prevent this from happening.

Biofouling was a bit of problem in FY06 and FY07. The copper content of the equilibrators was increased from 70% to 90% in FY07. A new copper cup was also installed at the bottom of the equilibrator to keep growth to a minimum around the equilibrator. Both of these changes have been beneficial.

Data Processing

All the PMEL summary files are processed and graphed on a website that is updated daily <http://www.pmel.noaa.gov/co2/moorings/>. The data are currently stored at PMEL and are available from Christopher Sabine at PMEL. The MBARI data are available from Francisco Chavez at MBARI. The carbon data management and synthesis teams are in the process of integrating the moored pCO_2

data together with the underway pCO_2 data from a related OCO project. Ultimately all of the surface CO_2 data will feed into the seasonal CO_2 flux map effort that is currently under development.

All systems are thoroughly tested and calibrated over a range of CO_2 concentrations using WMO traceable standard gases in the laboratory before deployment. The systems are then calibrated with a zero and WMO traceable span gas at the beginning of every three hour measurement cycle during the deployment. We have developed a system for processing the moored pCO_2 data that is collected utilizing automated quality control procedures. Based on the calibration, atmosphere, and seawater information as well as other diagnostic measurements for each identified point relative to the surrounding points, the data point may be flagged as questionable or bad. Typically less than 1% of the data are flagged as questionable or bad. To finalize a dataset, the data are compared to any underway pCO_2 data that are available as well as the Marine Boundary Layer (MBL) atmospheric CO_2 concentrations for a given buoy location as provided by NOAA's GLOBALVIEW-CO_2 network. Based on these comparisons and various diagnostics of the automated system calibration information, the entire data set (air and water values) may be adjusted to match these higher accuracy measurements. Typically these adjustments are less than a couple of parts per million. The data are then merged with sea-surface temperature and salinity data collected by other groups on the same buoy. As all data become available, final calibrated data are archived at the Carbon Dioxide Information Analysis Center (CDIAC) and the National Oceanographic Data Center (NODC) on a yearly basis. During the field season it is difficult to keep up with the data processing, but now that the season has ended we are on target to have all the data through March 2007 finalized and submitted to CDIAC for public release by February 2008. We anticipate being able to maintain the one year final data release from the date of recovery for the foreseeable future.

Analysis and Research Highlights

An underway pCO_2 system was recently added to the *R/V Atlantic Explorer*, the research vessel that conducts the time-series work off of Bermuda. Thus, the ship passes very close to the Bermuda Testbed Mooring on at least a monthly basis allowing regular comparisons of the moored and shipboard CO_2 data (Figure 2). An analysis of the moored and shipboard data showed that the two systems agreed to within 0.5±4.7 µatm (n=15,462) when the ship was within 10km of the mooring and the time was within 3 minutes. By comparing data over a range of distances one can begin to assess the correlation length scales for the region. Preliminary analysis at BTM suggests that data are coherent within about 80 km regardless of season.

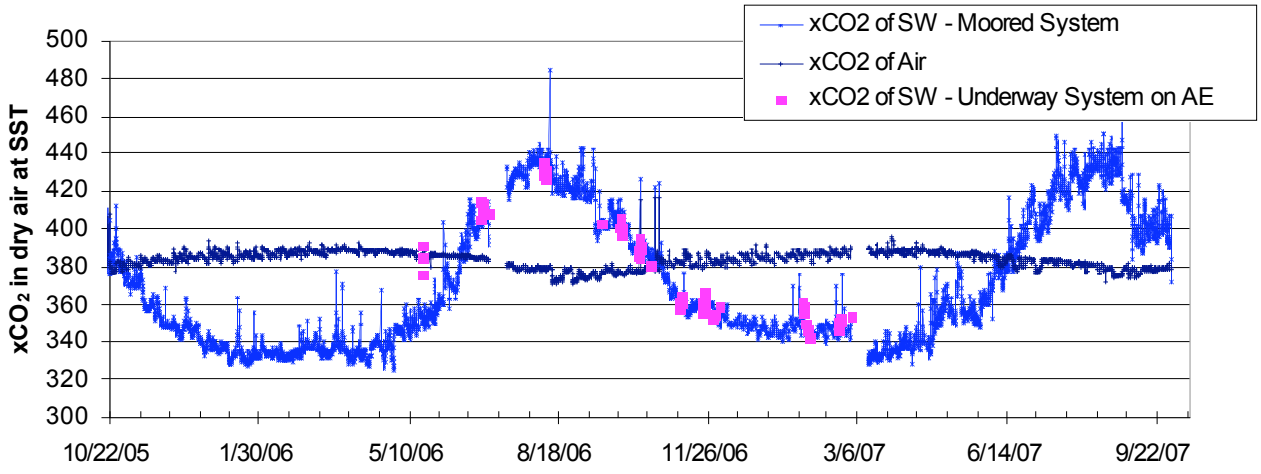


Figure 2. Comparison of time-series CO_2 measurements from the Bermuda mooring and the underway system aboard the R/V Atlantic Explorer.

The addition of new sites in the moored CO_2 network allows the characterization of previously understudied regions. In FY07 the first South Pacific mooring was deployed at the Stratus site off Chile. The first full year of data are shown in Figure 3. These data show that this site is a large source of CO_2 to the atmosphere during the austral summer then drops to about neutral during the winter months. The observed pattern is somewhat different than suggested by the latest Takahashi climatology; but this is not surprising given the lack of data in this region of the world.

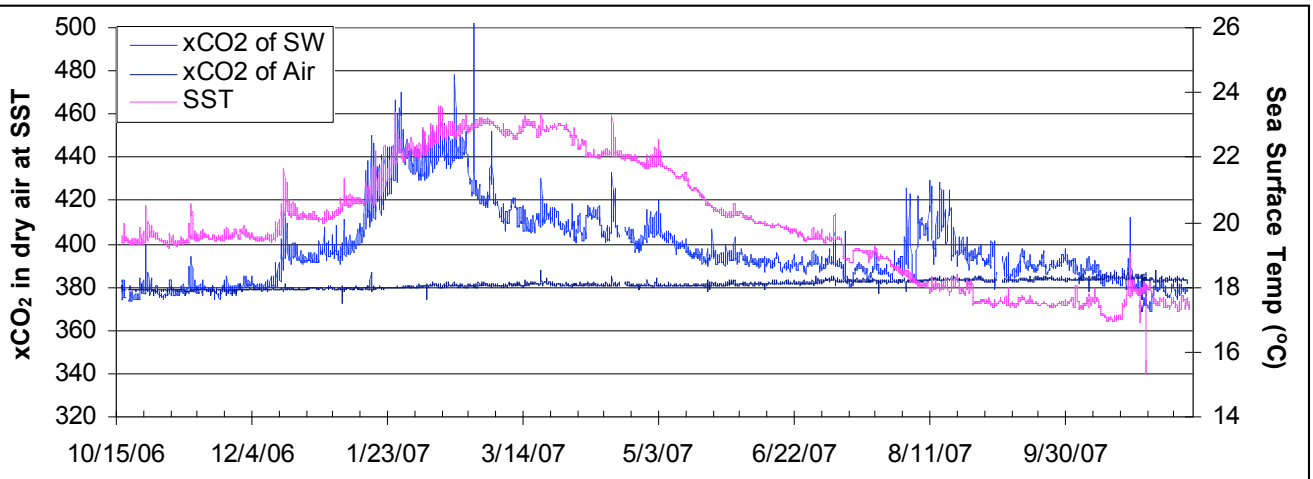


Figure 3. Time-series of CO_2 and sea surface temperature measurements from the South Pacific off of Chile (Stratus mooring).

Due to logistical problems with the moorings at 170°W, the MBARI CO_2 system that is normally deployed at 2°S had to be deployed at 2°N until the next servicing interval. While it is unfortunate that the long time series at 2°S had to be broken, it provides a nice opportunity to study the similarities and differences of the CO_2 system north of the equator relative to south of the equator. Figures 4 and 5 show the latest data from 2°S and 2°N, respectively.

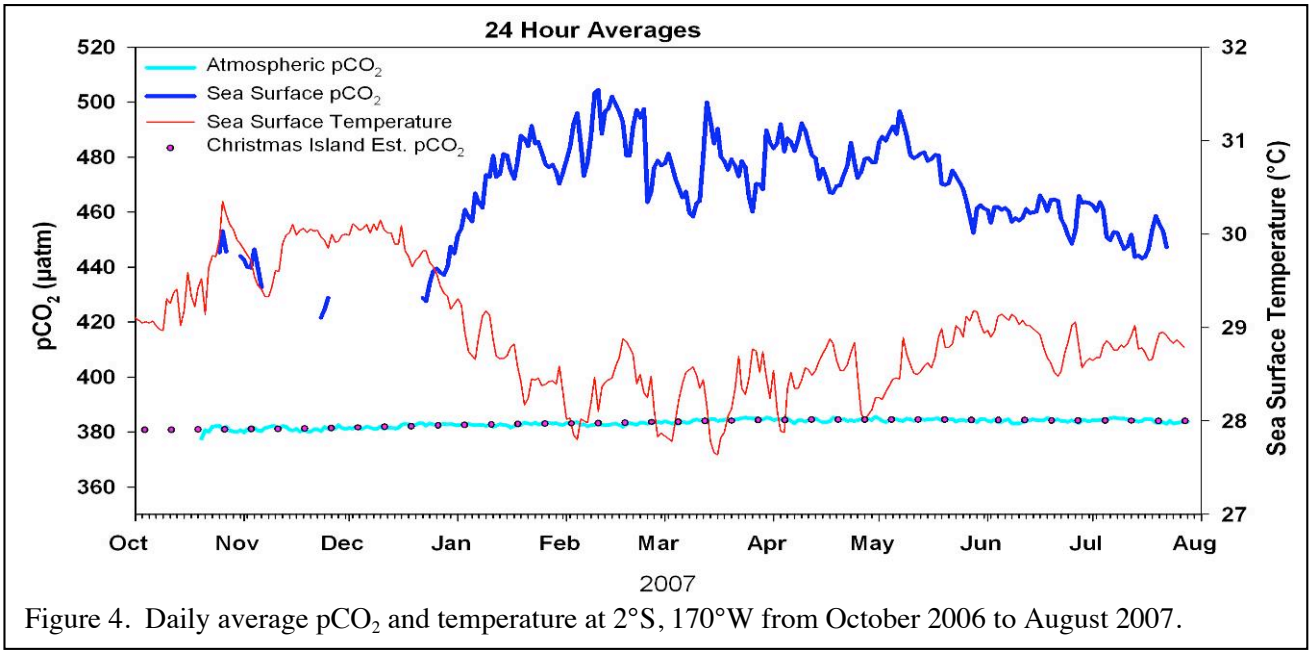


Figure 4. Daily average pCO_2 and temperature at 2°S, 170°W from October 2006 to August 2007.

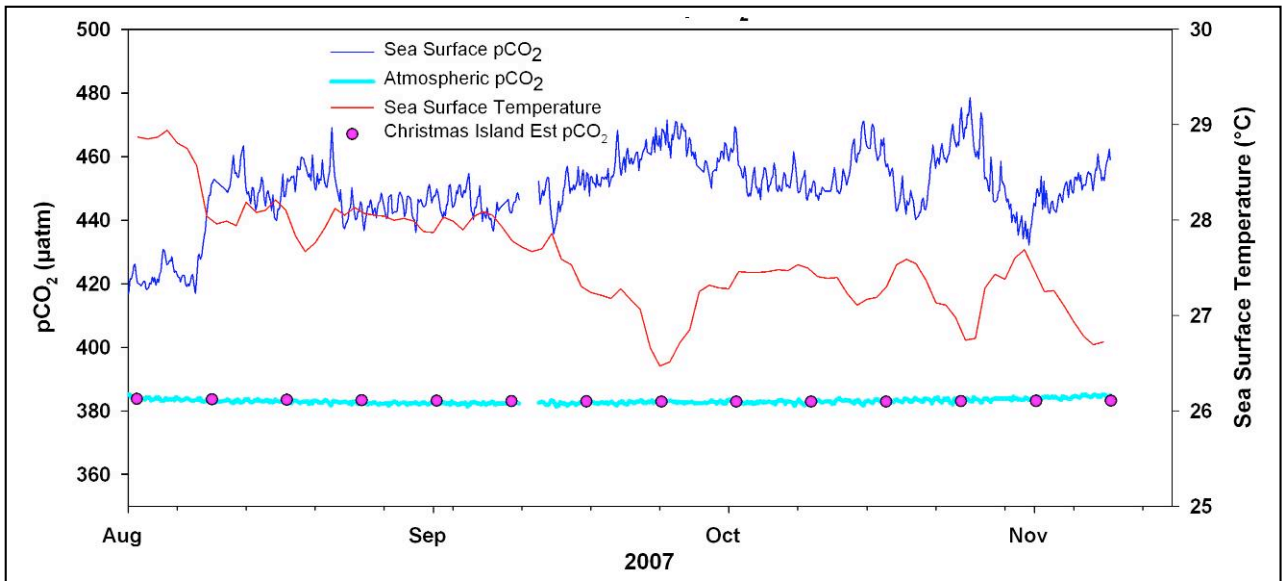


Figure 5. High resolution measurements of pCO_2 and daily average sea surface temperature at 2°N, 170°W from August 2007 to present.

This is the first time that a CO_2 mooring has been located on the northern side of the equatorial upwelling region. The 2°N time series is still too short to evaluate the seasonal differences, but the shorter time scale variability is similar in magnitude and frequency to the 2°S site. The overall magnitude of the air-sea difference is also similar at both sites. What remains to be determined is whether the seasonal trends have the same pattern and whether there is a north-south difference in how the CO_2 system responds to the passage of Kelvin Waves, Tropical Instability Waves, or ENSO events. These data will continue to be examined closely as the times-series grows. Of course the value of time series observations grows as the data sets become longer. The moored time-series program in the

equatorial Pacific is among the longest in the world. These data have been able to directly document the increase in surface water CO_2 over time (see figure 6).

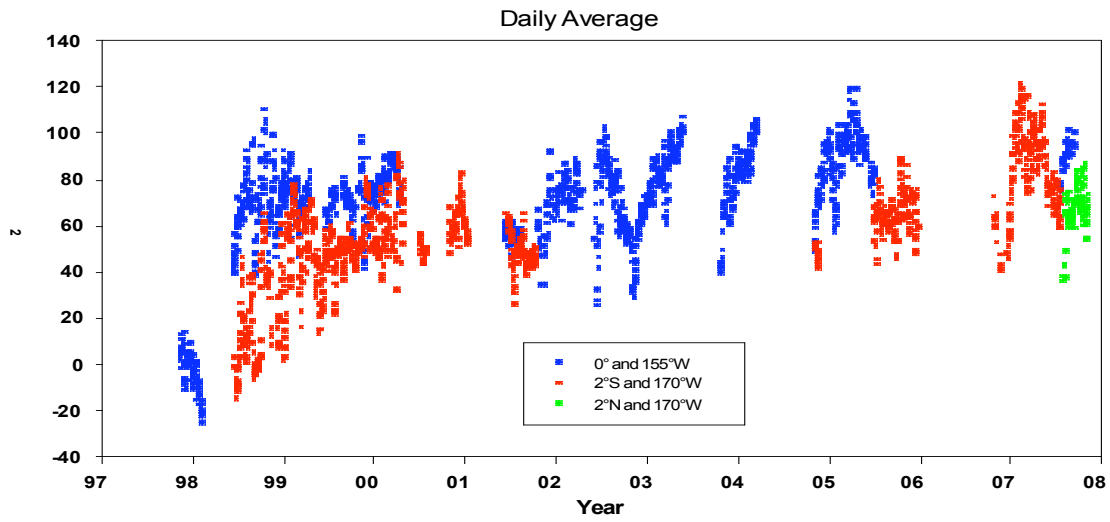


Figure 6. Daily average pCO_2 observations on the equator at 155°W, 2°S, 170°W and 2°N, 170°W from 1997 to present. Even without the '98 El Niño signal there is an apparent increase in pCO_2 over the course of the record.

PUBLICATIONS AND REPORTS

Relevant Publications in FY07

Sabine, C.L., and R.A. Feely (2007) The oceanic sink for carbon dioxide. In Greenhouse Gas Sinks, D. Reay, N. Hewitt, J. Grace, and K. Smith (eds.), CABI Publishing, Oxfordshire, UK.

Sabine, C.L., R.A. Feely, and R. Wanninkhof (2007) 3. Global Oceans; f. Global ocean carbon cycle — in *State of the Climate in 2006*, A. Arguez (ed.).. Bull. Am. Meteorol. Soc., 88 (suppl.)(6), S40–S43.

Birdsey, R.A., R. Cook, S. Denning, P. Griffith, B.E. Law, J. Masek, A.M. Michalak, S. Ogle, D. Ojima, Y. Pan, C.L. Sabine, E. Sheffner, and E.T. Sundquist (2007) Investigators share improved understanding of the North American Carbon Cycle. Eos Trans. AGU, 88(24), doi: 10.1029/2007EO240004.

Lucier, A., M. Palmer, H. Mooney, K. Nadelhoffer, D. Ojima, and F. Chavez (2006) Ecosystems and Climate Change: Research Priorities for the U.S. Climate Change Science Program. Recommendations from the Scientific Community. Special Series No. SS-92-06 of the University of Maryland Center for Environmental Science, Chesapeake Biological Laboratory, Solomons, MD.

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.

Montecino, V., P.T. Strub, F. Chavez, A. Thomas, J. Tarazona, and T. Baumgartner (2006) Bio-physical interactions off western South-America. Chapter 10 In The Sea, Volume 14, A. Robinson and K. Brink (eds.), Harvard University Press, Cambridge, Massachussetts, pp. 321-390.

Chai F., M.-S. Jiang, Y. Chao, R. C. Dugdale, F. Chavez, R. T. Barber (2007) Modeling responses of diatom productivity and biogenic silica export to iron enrichment in the equatorial Pacific Ocean, Global Biogeochem. Cycles, 21, GB3S90, doi:10.1029/2006GB002804.

Chavez, F.P., T. Takahashi, W.J. Cai, G. Friederich, B. Hales, R. Wanninkhof, and R.A. Feely (2007) "Coastal Oceans" In: *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle*. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Dilling, L., A. King, D. Fairman, R. Houghton, G. Marland, A. Rose, T. Wilbanks, and G. Zimmerman (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA.

Saba, V., J. Spotila, F. P. Chavez, and J. Musick (in press) Bottom-up and climatic forcing on the worldwide populations of leatherback turtles. Ecology.

Freon, P. C. Werner and F.P. Chavez (in press) Conjectures on the influence of climate change on ocean ecosystems dominated by small pelagic fish. In D. Checkley, C. Roy and J. Alheit (Eds). Predicted effects of climate change on SPACC systems. Cambridge University Press.

Invited/Contributed Presentations 2007

Sabine:

CLIVAR Global Synthesis and Observations Panel (GSOP-2) SSG meeting, La Jolla, CA, Dec. 8-9 (invited talk: Global Carbon and Synthesis needs)

JAMSTEC 5-year review of biogeochemical time-series program, Tokyo, Japan, January 17-19, 2007 (invited talk: global carbon time-series)

NACP PI meeting, Colorado Springs, CO, January 22-24, 2007 (invited talk: Carbon Exchanges between the Continental Margins and the Open Ocean; coauthor on 3 posters)

NACP SSG Meeting, Colorado Springs, CO, January 24, 2007

NOAA CO_2 Science Team Meeting, Miami, FL, February 4-7, 2007 (meeting organizer and discussion leader)

Marshall Islands Workshop, Seattle, WA, March 3, 2007 (participated in discussion of ocean acidification issues with Marshall Islanders).

IOCCP SSG meeting, Paris, France, April 10, 2007 (chair of meeting)

Ocean Surface pCO_2 and Vulnerabilities Workshop, Paris, France, April 11-13, 2007 (invited talks: Moorings: New Results and New Technology Overview, Overview of Proxy Techniques for Data Extrapolation and Interpolation)

Anthropogenic Stresses on Ocean Ecosystems Workshop, Seattle, WA, April 23-24, 2007 (breakout discussion leader; invited talk: Existing Technology and Challenges for Monitoring the CO_2 System in Seawater)

Seminar to King County Department of Natural Resources and Parks, Seattle, WA, April 25, 2007 (Ocean CO_2 and its Impact on Marine Ecosystems)

OCB scientific steering committee meeting, Washington DC, May 3-4, 2007.

OCB annual summer workshop, Woods Hole, MA, July 23-26, 2007 (discussion leader for day 2 theme on ocean acidification, organizer of day 3 talks and working group on coastal ocean theme).

OCB scientific steering committee meeting, Woods Hole, MA, July 27, 2007.

NOAA GCC program PI meeting, Silver Spring MD, September 10-11, 2007 (invited talk on moored CO_2 observations).

Chavez:

Invited to workshop to develop Decadal Plans for Research and Calibration/Validation for NASA's Ocean Biology and Biogeochemistry research program, Montreal, Canada, October 7-8, 2006.

Taught 3 day course for Oceans and Climate – SEA Semester Class S-208 - Oceans in the Global Carbon Cycle at Woods Hole, October 21-23, 2006.

Keynote Speaker, Invited by International Oceanographic Commission (UNESCO), at International Seminar on Global Climate Change: Perspectives for Peru, Lima, Peru, October 25-25, 2006.

Organized and Participated in International Conference on the Humboldt Current Ecosystem, Lima, Peru, November 27-December 1, 2006.

Invited Speaker at Round Table Discussion at the Week of the Anchoveta to encourage human consumption rather than fish meal production, Lima, Peru, December 2, 2006.

Invited Participant in Second joint ECO-UP EUR-OCEANS workshop on upwelling systems, Lima, Peru, December 4-6, 2006

Invited Speaker in Hopkins Laboratory of Stanford University Lecture Series on February 9, 2007. Talk entitled "Biological Consequences of Climate Change."

Invited Speaker at AAAS meeting in San Francisco at session on "Informing Management of the Earth's Environment with New Ocean-Observing Systems" on February 17, 2007. Talk was entitled "Designing observing systems to link climate and fisheries."

Participated in an Advisory Group meeting for the National Data Buoy Center (NDBC) in Stennis Space Center, Mississippi on May 24-25, 2007. The primary recommendation of the Advisory Group was the establishment of Science and Technology Teams akin to those put together by NASA for satellite missions.

Invited Speaker at the UC Davis Bodega Marine Laboratory on May 29, 2007 as part of the Synergistic Ocean/Atmosphere/Climate Seminar series.

Delivered a talk entitled "Ocean Ecosystem in a Warmer World" at the International Union of Geodesy and Geophysics meeting in Perugia, Italy on July 5, 2007.

Invited Participant Symposium on "Exploring Ocean Iron Fertilization: the scientific, economic, legal and political basis" Woods Hole Oceanographic, September 26-27, 2007.

Honors and Awards

Chavez appointed to the Graduate Faculty of the University of Maine.

Sabine awarded Department of Commerce Gold Medal Award for pioneering research leading to the discovery of increased acidification in the world's oceans due to the absorption of carbon dioxide.

Public Service

Sabine:

2007-present	member of International Repeat Hydrography Advisory Group
2006-present	member of Ocean Carbon and Biogeochemistry Time-Series Advisory Committee
2005-present	member of PICES section on Carbon and Climate
2005-present	Scientific Steering Committee member for U.S. Ocean Carbon and Biogeochemistry Program
2005-present	Scientific Steering Committee member for U.S. Ocean Carbon and Climate Change Program

2004-present Scientific Steering Committee member for U.S. North American Carbon Program
2004-present Chair of IOC/SCOR International Ocean Carbon Coordination Project (IOCCP)
2003-present Member of the US CLIVAR/CO_2 Repeat Hydrography Oversight Committee

Chavez:
Advisory Committee for Instituto del Mar del Peru (2004-)
Board of Directors, Center for Integrated Marine Technologies (2002-)
Board of Governors, Pacific Coastal Ocean Observing System (2004-)
Science Team for OceanSites (2002-)
Governing Council (Vice-President) Central and Northern California Ocean Observing System (2005-)

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]
[1] University of Arizona, Tucson, AZ
[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, 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).

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.

DELIVERABLES

By the culmination of this study (July 31, 2008), we will have provided the following deliverables:

1) A peer reviewed assessment of spatial and temporal variability of surface ocean pCO_2 and the associated air-sea CO_2 fluxes now and into the future.

Status: Currently undergoing internal review prior to submission

2) A recommendation of the optimal sampling network design needed to capture the variability of air-sea CO_2 fluxes in a way that will reduce the errors in regional scale estimates of the seasonal and annual air-sea CO_2 fluxes to +/-0.2 Pg-C/yr. The network design will make recommendation in the following categories:

- Sampling frequency
- Spatial distribution
- Distribution and type of surface ocean pCO_2 measurement platforms

Status: Near completion – undergoing incorporation of Takahashi dataset.

ACCOMPLISHMENTS

1) We have added several new datasets to our global pCO2 database raising the total number of measurement to **1.8 million** (Figures 1). Very recently (this month), the entire Takahashi pCO_2 dataset with over **3 million** measurements became available through CDIAC and we are incorporating these data (some of which were already included) into our database. We anticipate having approximately 4.5 million measurements in our database when the Takahashi data is fully integrated and duplicate measurements are weeded out. Our analysis with this newest data is still underway.

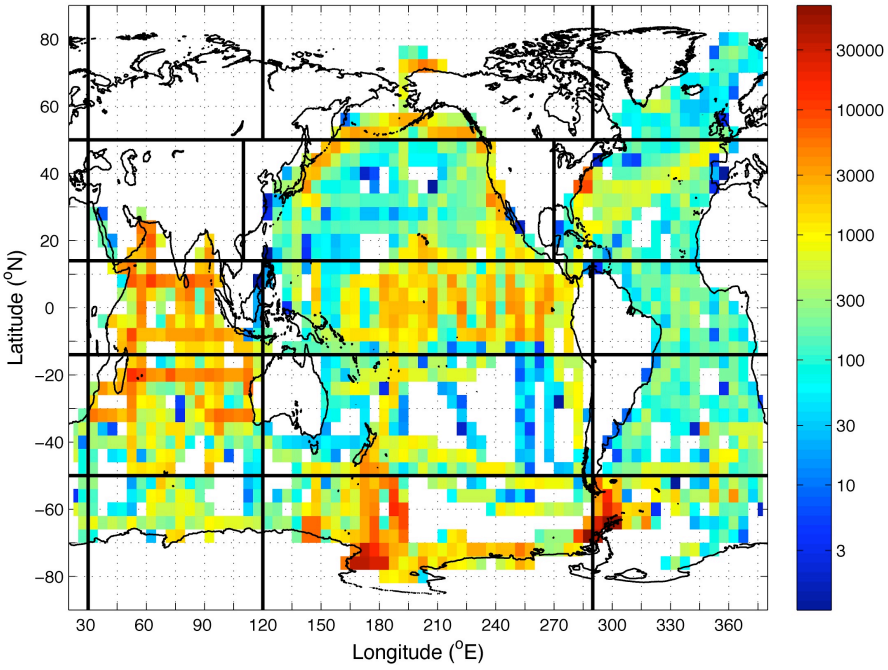


Fig. 1. The number of pCO_2 measurements in the assembled database (pre-Takahashi release) binned into 4° by 5° boxes, independent of time of year.

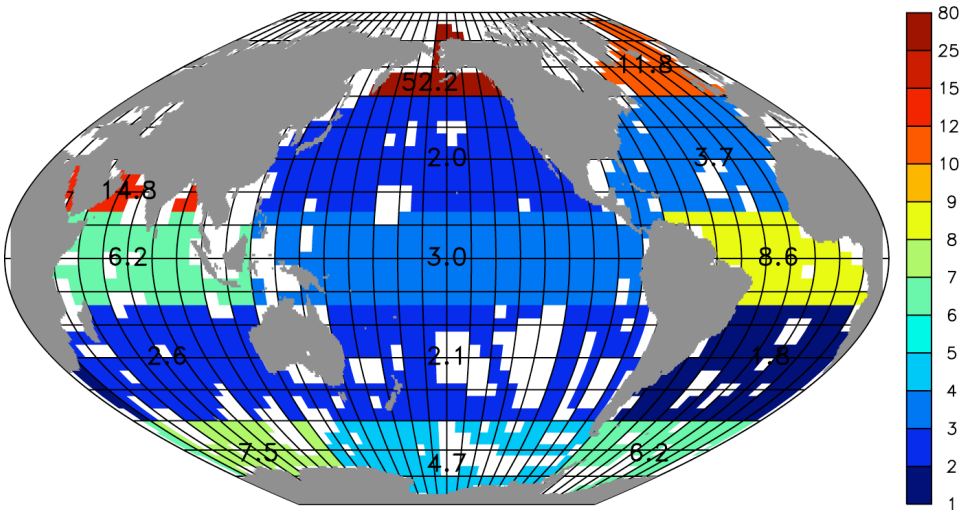


Fig. 2. Target ΔfCO_2 to estimate a regional CO_2 flux within ± 0.1Pg-C/yr for the major oceanic regions.

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 2 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.

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	-0.18	11.8
Temperate North Atlantic	23.71	-19.0	-0.25	3.7
Equatorial Atlantic	17.13	11.2	0.06	8.6
Temperate South Atlantic	24.38	-8.4	-0.22	1.8
Polar South Atlantic	9.89	-5.9	-0.05	6.2
Polar North Pacific	5.26	-15.3	0.01	52.2
Temperate North Pacific	42.01	-19.5	-0.46	2.0
Equatorial Pacific	50.67	17.6	0.28	3.0
Temperate South Pacific	36.50	-15.2	-0.34	2.1
Polar South Pacific	16.53	-12.6	-0.13	4.7
Temperate North Indian	4.15	35.3	0.12	14.8
Equatorial Indian	18.61	13.0	0.10	6.2
Temperate South Indian	26.94	-25.9	-0.48	2.6
Polar South Indian	7.27	-9.3	-0.06	7.5
Global Oceans	290.09	-6.9	-1.61	0.2

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 Sweeney et al. (2006) have been used.

2) We have reanalyzed our results using the new gas-transfer velocity from Sweeney et al. (2006) which has resulted in a 33% reduction in our target estimates (Fig. 2, Table 1).

3) We have broken the available data down into seasonal and monthly components to analyze the temporal aspects of the global air-sea carbon exchange for each region. Our length-scale analysis for each season is nearly finished, but preliminary results indicate that only a few locations (e.g. the Northern Indian Ocean which has much higher variability in the summer) would require much different spacing than was determined with the annual data (Figure 3).

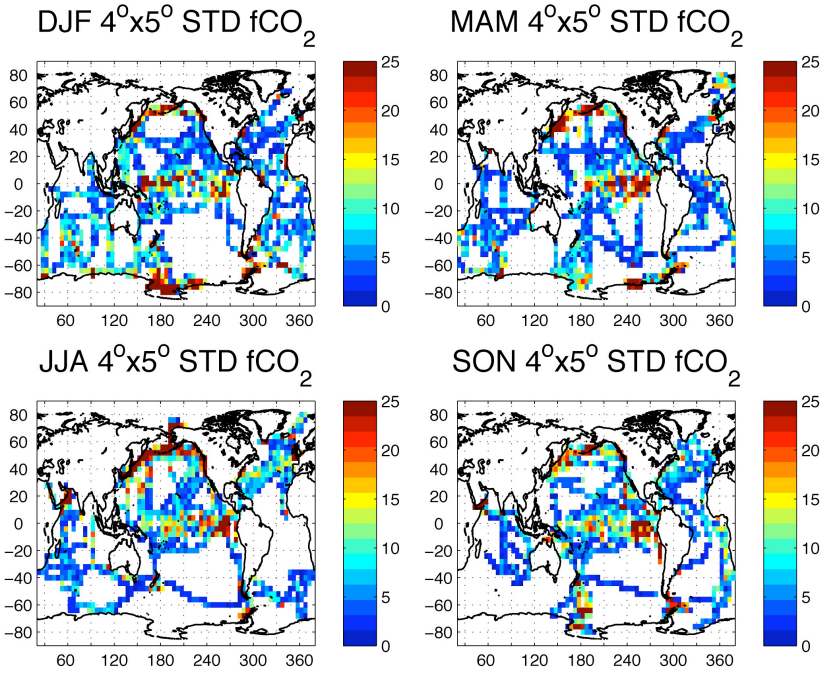


Fig. 3. Standard deviation of fCO_2 observations for each season. Most locations for which we have measurements have similar variability during each of the four seasons.

4) We have finished our spatial *decorrelation length scale* analysis of the pre-Takahashi database. This analysis uses a simple approach to resampling a series of data which assumes that a *linear interpolation* of the data set represents the true data set. We merely look at the interpolated data and resample the INDEX at regular intervals. The subsampled data (equal number of samples away from each other) is then linearly interpolated and resampled at the original sampling resolution from which a comparison is made. This routine is meant to estimate what kind of sample spacing you might need to get a standard deviation within 5% of the range in the original data.

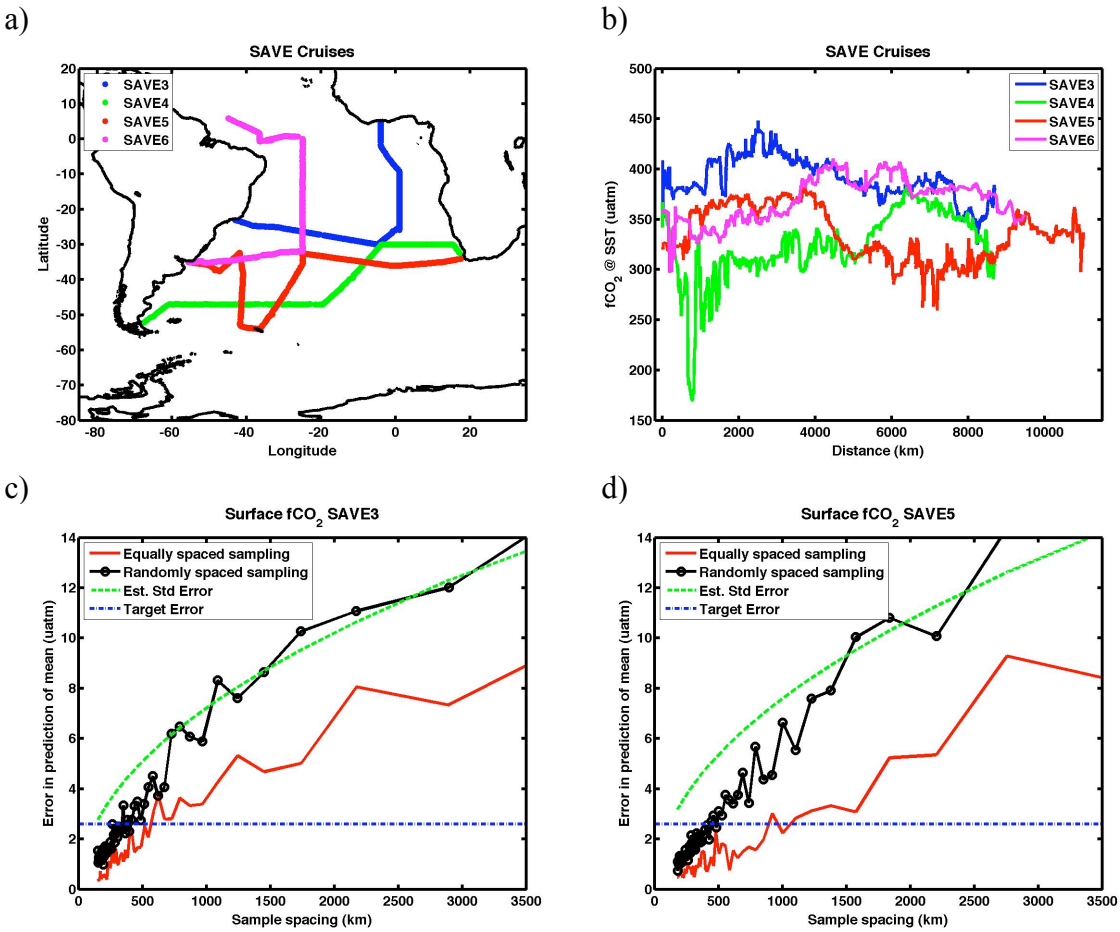


Fig. 4. The (a) cruise tracks; (b) measured fCO_2 for some of the cruises in our database (c,d) decorrelation length-scale analysis of 2 of these cruises. In (c,d) the standard error in the mean is indicated in green, sampling with equal space-intervals in red, sampling with randomly spaced intervals in black with circles, and the blue line indicates the target ΔpCO_2 needed to estimate the flux of CO_2 to the nearest ±0.1 Pg of C/yr in the temperate South Atlantic

As an example, we present the data two cruise tracks (SAVE3, SAVE5, Fig 4a,b) and the results our method provides for estimating the observed variability within the data based on regularly spaced samples (Fig.4 c,d). For the SAVE3 cruise, randomly spaced subsamples at ~350km and regularly spaced subsamples at ~600km approximate the observed variability in the data to with the 5% necessary, in order to estimate the total air-sea flux for this region to within ±0.1 Pg. For the SAVE5 cruise, regularly spaced measurements at ~1000km would achieve the desired accuracy. Our analysis of the entire assembled dataset on our targeted 4° by 5° grid is presented as Figure 5.

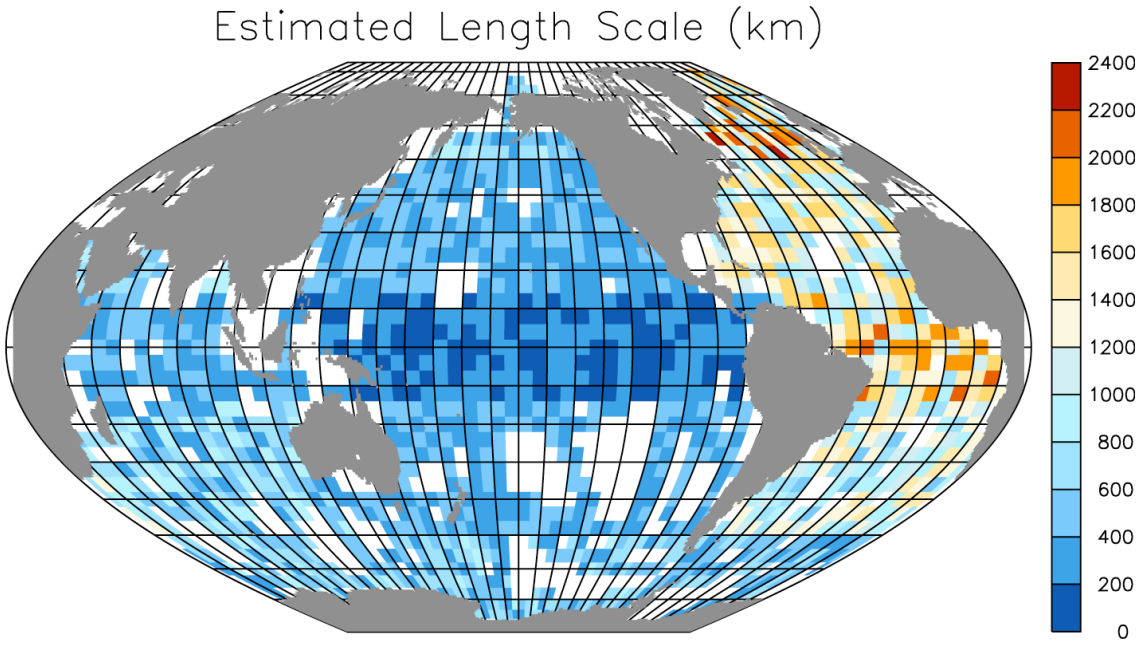


Fig. 5. Preliminary calculated length-scale for regularly spaced measurements necessary to capture the observed variability in order to estimate the total regional air-sea flux of CO_2 to within ±0.1 Pg (more data and analysis required for complete estimate).

8. Arctic Ocean Obs System

a. The Arctic Research Program, Fiscal 2007

The Arctic Research Program, Fiscal 2007

John.Calder[1], Kathleen Crane[1], J, M. Zhdanov[3], A. Ostrovskiy[3], Jackie Richter-Menge[4], James Overland[5], Igor Polyakov[6], Ignatius Rigor[7], Igor Semilitov, Taneil Uttal[8], Tom Weingartner[9], Terry Whitledge[9] and Rebecca Woodgate[7]

[1] NOAA Climate Program Office, Arctic Research Program, Silver Spring, MD
[2] Department of Ecology and Evolutionary Biology, University of Tennessee, Knoxville, TN
[3] Group Alliance, Moscow, Russian Federation
[4] U.S. Army ERDC-Cold Regions Research and Engineering Laboratory, Hanover, NH
[5] NOAA Pacific Marine Environmental Laboratory, Seattle, WA
[6] International Arctic Research Center, University of Alaska, Fairbanks, AK
[7] Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, WA
[8] NOAA Earth Systems Research Laboratory, Boulder, CO
[9] School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks, AK

Program Description

The Arctic Research Program is a component of the NOAA Climate Observations Division 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.

Developing an Arctic Observing Network: an IPY Legacy for NOAA

Both paleo-data and recent environmental observations show that climate changes in the Arctic have and still play a major role on the Earth's climate. Changes in the Earth's albedo and fluxes in fresh water from increased river flow, reduction in sea ice cover and melting ice sheets are major contributors to rapid global change by altering surface temperatures, contributing to sea level rise and affecting global thermohaline circulation. The question arises, is the Arctic approaching the climate conditions that have in the past stimulated abrupt climate change elsewhere on the planet? How close is the present state of the Arctic to a tipping point, where formerly stable climate regimes alter to new states?

What will we face if the climate of the Arctic changes as dramatically as models predict? The Arctic contains many living and non-living resources of significant economic and social importance; the US has a strong economic base in Bering Sea fisheries, esthetic concerns over Arctic marine mammals, and concerns over native subsistence hunting rights. Can we imagine a world without polar bears? What will happen to weather and climate over North America when the ice disappears?, What will be the state of storms, will the fish migrate to new habitats, what will become extinct? How will changing Arctic conditions affect drought, rainfall, tornadoes, and hurricanes in the mainland U.S.? How will changing ice conditions affect global commerce? All of these topics lie squarely in NOAA's field of responsibilities. NOAA is the agency responsible for tracking long-term environmental change and for modeling the evolution of change and its impacts.

More than 60 nations of the world are celebrating the International Polar Year in 2007 and 2008 to address global environmental change, and teleconnections from the poles to the equator. An important goal of the International Polar Year is to develop global legacies that will continue to provide information about polar induced climate changes for decades to come. Our goal in the Arctic Research Program is to facilitate the development an Arctic Observing Network as a long-lasting Legacy. Both NOAA and NSF have agreed to lead the development of the AON and continue to engage international partners in this effort. This is an outgrowth of the recommendations provided by the interagency SEARCH (Study of Environmental Arctic Change) Implementation Plan drafted in 2005. AON should accommodate observations in the Arctic Ocean (including physical, chemical and ecosystem observations), in, under and above the sea ice cover, measurements of the flux of atmospheric properties over space in time at a suite of climate observatories that will ring the Arctic, and terrestrial fluxes of greenhouse gases and fresh water.

The SEARCH implementation plan presented a series of maps annotated by proposed observing station locations. The Arctic Research Program in the Climate Program Office identified these stations as the 100% international contribution to the Arctic Observing Network. The United States contribution to this network is not yet developed, yet NOAA's initial plan is to focus efforts on the Pacific-Arctic region, (that area from the Bering Strait, to the Lomonosov Ridge bordered by the Arctic margins of Canada, USA and Russia.

CPO's Role in the Arctic Observing Network Development

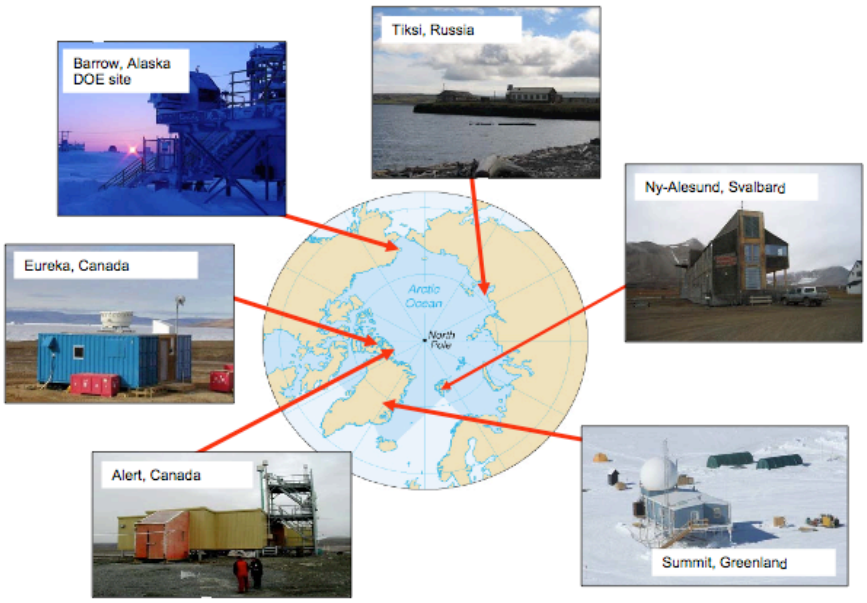
1. Arctic Climate-Atmospheric Observatory Network

Contact: Taneil Uttal, ESRL

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. It is anticipated that the Observatory sites will also be the focus of a number of interdisciplinary measurements of regional hydrology, permafrost, ecosystems and the cryosphere that will link the atmospheric measurements into the broader Arctic system. The program is heavily leveraged against Canadian and Russian programs, and has a vigorous interagency cooperation with NSF and DOE.

On March 7-9, 2007 there was a planning meeting in Boulder, Colorado to develop a work requirements document for the new facility. This meeting was open to all researchers with an interest in doing research in the Tiksi area regardless of current funding status. The four primary goals of the meeting were to:

1. Approve a final Work Requirements Document to serve as a basis for construction in the summer/fall of 2007;
2. Begin coordination of measurement activities and programs to fully utilize resources between programs, disciplines and countries;
3. Training of Tiksi personnel on the first wave of instruments intended for the Tiksi Observatory;
4. Establish a Tiksi Science Steering Committee.



NOAA hosted a delegation from Russia that included engineers from Tiksi, managers from the Moscow and Yakutsk Roshydromet offices, and Russian scientists with research interests in Tiksi. The Arctic research community was invited to attend this meeting with requests, experience, expressions of interest and ideas for development of this new research and monitoring facility.
In 2007, the following actions were undertaken to advance the development of these sites:

* Planning meeting organized with NSF and Roshydromet to develop observatory facilities in Tiksi, Russia.
* Visit to Tiksi, Russia to finalize site layout and building plans/location
* Installation of micrometeorological tower in Eureka, Canada

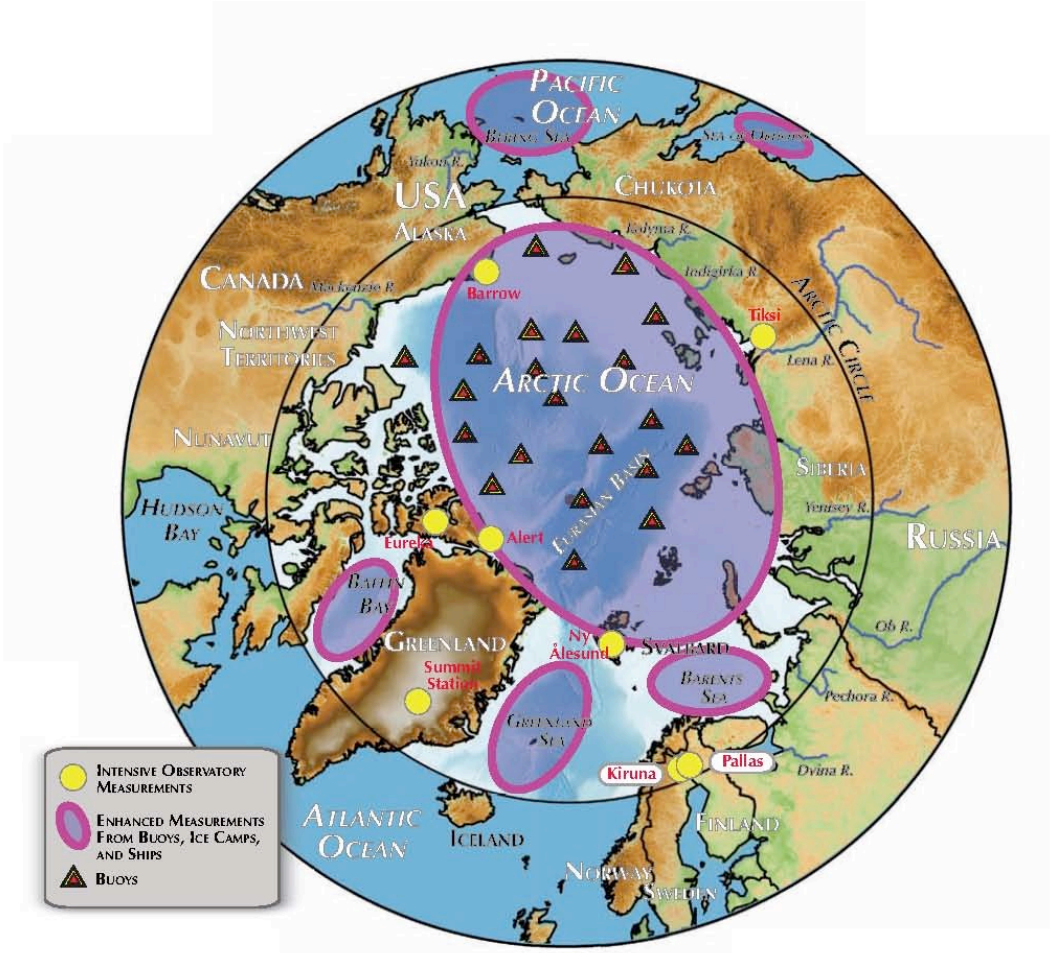


Figure 1. Priority areas for atmospheric observation activities. *A SEARCH atmospheric observing program should include coordinated intensive observatory measurements (yellow dots) in Barrow, Alaska; Alert and Eureka, Canada; Ny-Ålesund, Norway; Tiksi, Russia; the Greenland Summit Station; Pallas, Finland; 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
Contact Person: K. Crane kathy.crane@noaa.gov

The NOAA Arctic Program is also working with partners to implement the Ocean part of 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 birds. Planning 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.*

a. THE PACIFIC GATEWAY TO THE ARCTIC – QUANTIFYING AND UNDERSTANDING BERING STRAIT OCEANIC FLUXES. Russian American Long-term Census of the Arctic

Contact People: Rebecca Woodgate (UW), Tom Weingartner (UAF), Terry Whitledge (UAF)

The Bering Strait, a narrow (~ 85 km wide), shallow (~ 50 m deep) strait at the northern end of the Pacific, is the only ocean gateway between the Pacific and the Arctic. Although the flow through the strait is small in volume (~ 0.8 Sv northward in the annual mean), due to its remarkable properties (high heat and freshwater content, low density, high nutrients) it has a startling strong influence, not only on the Chukchi Sea and the Arctic Ocean, but also on the North Atlantic overturning circulation and possibly world climate. Draining the Bering Sea shelf to the south, the Bering Strait throughflow is an integrated measure of Bering Sea change. The comparatively warm, fresh throughflow contributes ~ 1/3rd of the freshwater input and possibly ~ 1/5th of the oceanic heat input to the Arctic, and provides the most nutrient-rich waters entering the Arctic Ocean.

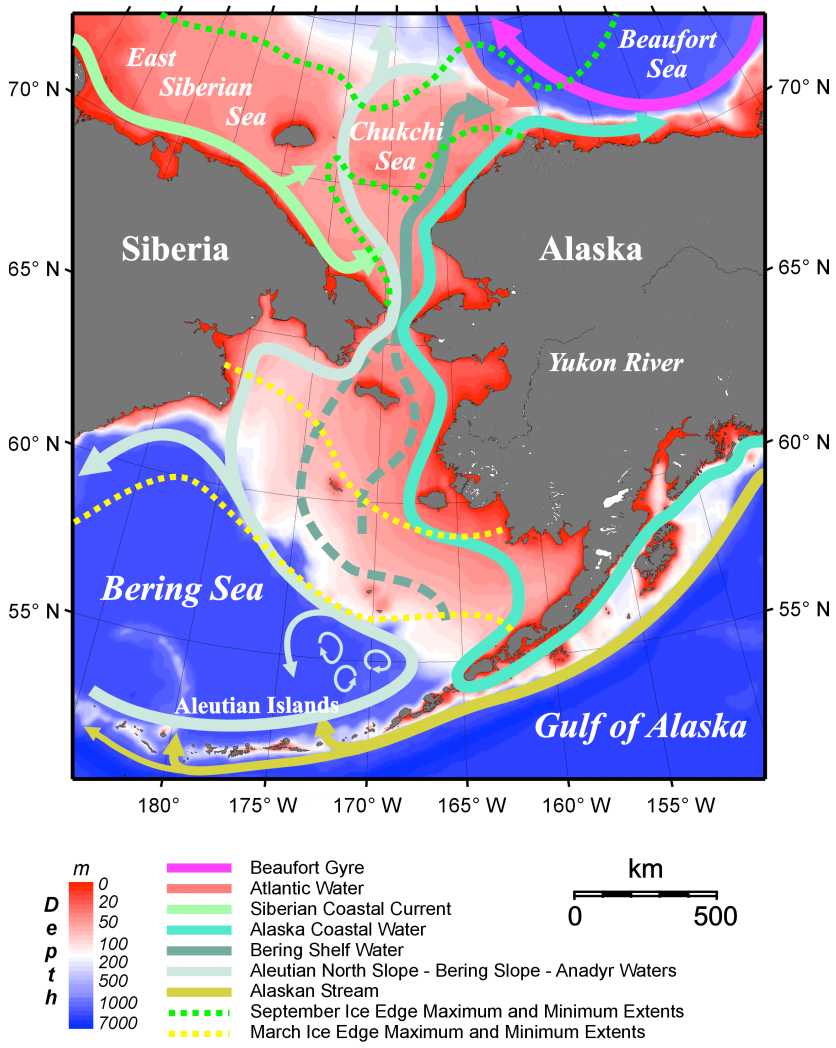
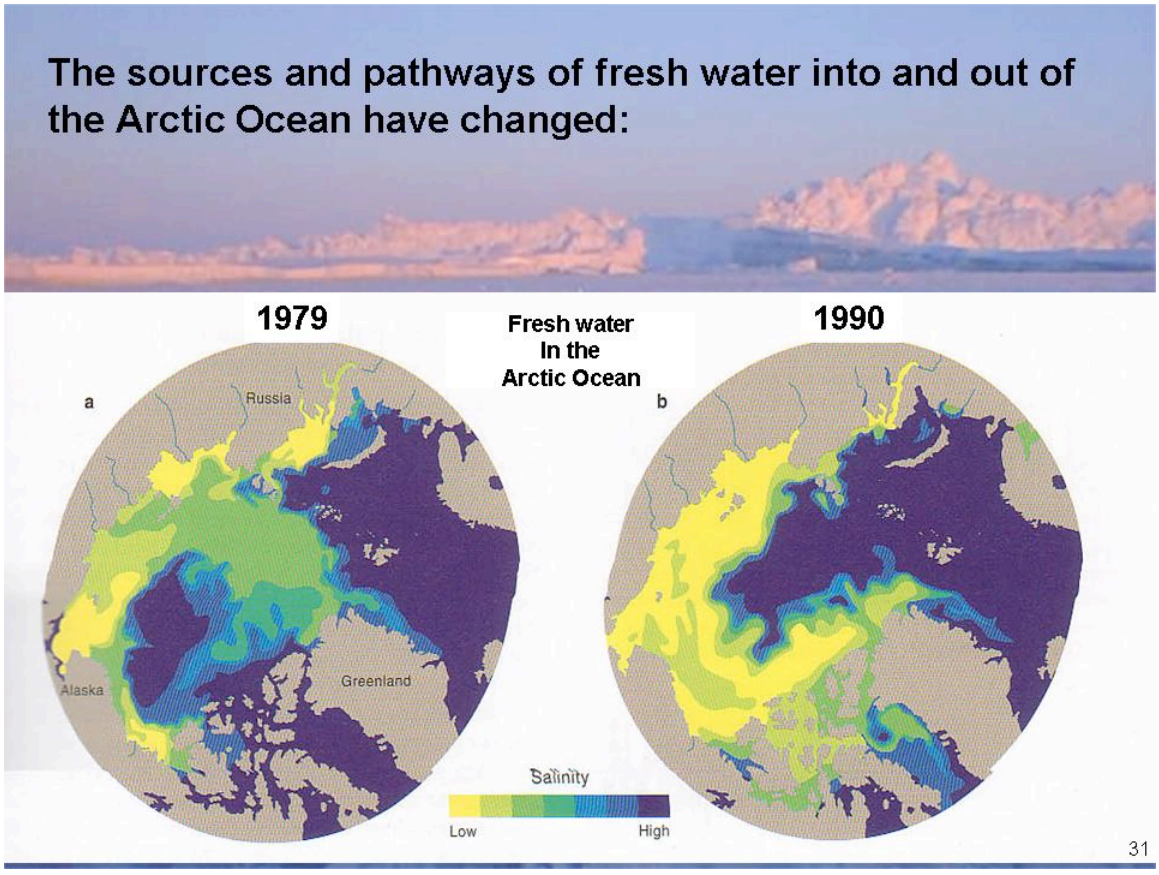


Illustration of the currents through the Bering Strait.

Furthermore, the low density of these waters keeps them high in the Arctic water column, giving them a key role in upper ocean ecosystems and physical processes including ice-ocean interactions. At the time when dramatic change, especially the retreat of sea-ice, is observed in the Bering and Chukchi seas and the Arctic, we have measured significant increases of Bering Strait fluxes of volume, freshwater and heat, the heat flux in 2004 being the maximum recorded in the last 15 years.

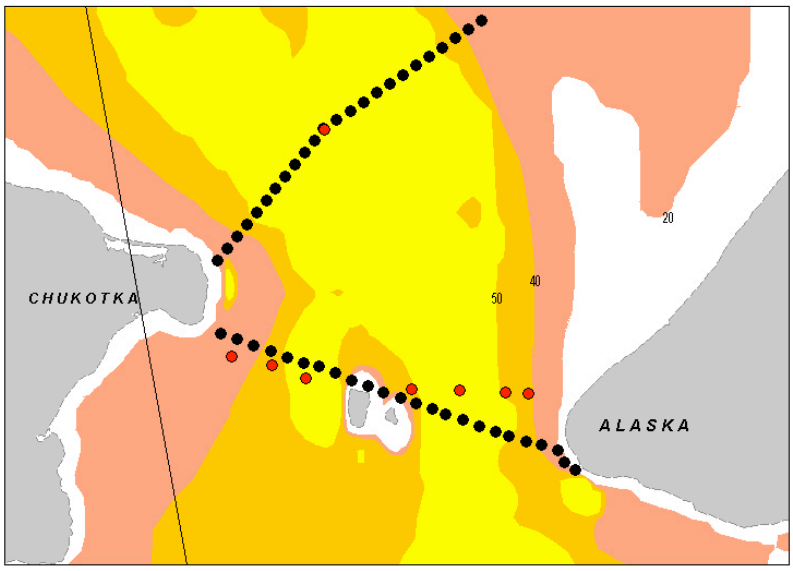
Yet, our understanding of what sets the properties and variability of the Bering Strait throughflow is still rudimentary. Indeed, our ability to measure these fluxes accurately has, in the past, been constrained by lack of data, both from the most nutrient-rich western half of the strait (which lies in Russian waters), and from the upper water column (due to potential ice-keel damage to instrumentation), where stratification and coastal boundary currents (especially the Alaskan Coastal Current in the eastern channel) contribute significantly to freshwater and heat fluxes.



More freshwater has been accumulating in the Pacific sector of the Arctic Ocean,

particularly since the 1990's. Low salinity (yellow). Transport pathways of water and ice across the Arctic have also changed significantly. The Bering Strait is on the left middle of the image.

Furthermore, although recognized as a key ocean gateway by national and international global observing initiatives, there had still been no long-term observing strategy for the Bering Strait until the development of the RUSALCA program (Russian-American Long-term Census of the Arctic). Building on US-Russian collaborations established in 2004 and NOAA- NSF collaboration to build the critical observing chain of moorings in this Pacific - Arctic Gateway, The RUSALCA program undertook the first ever deployment of instrumentation in both the Russian and U.S. waters of the Bering Strait in August-September of 2007 onboard the Russian Naval hydrographic vessel "SEVER".

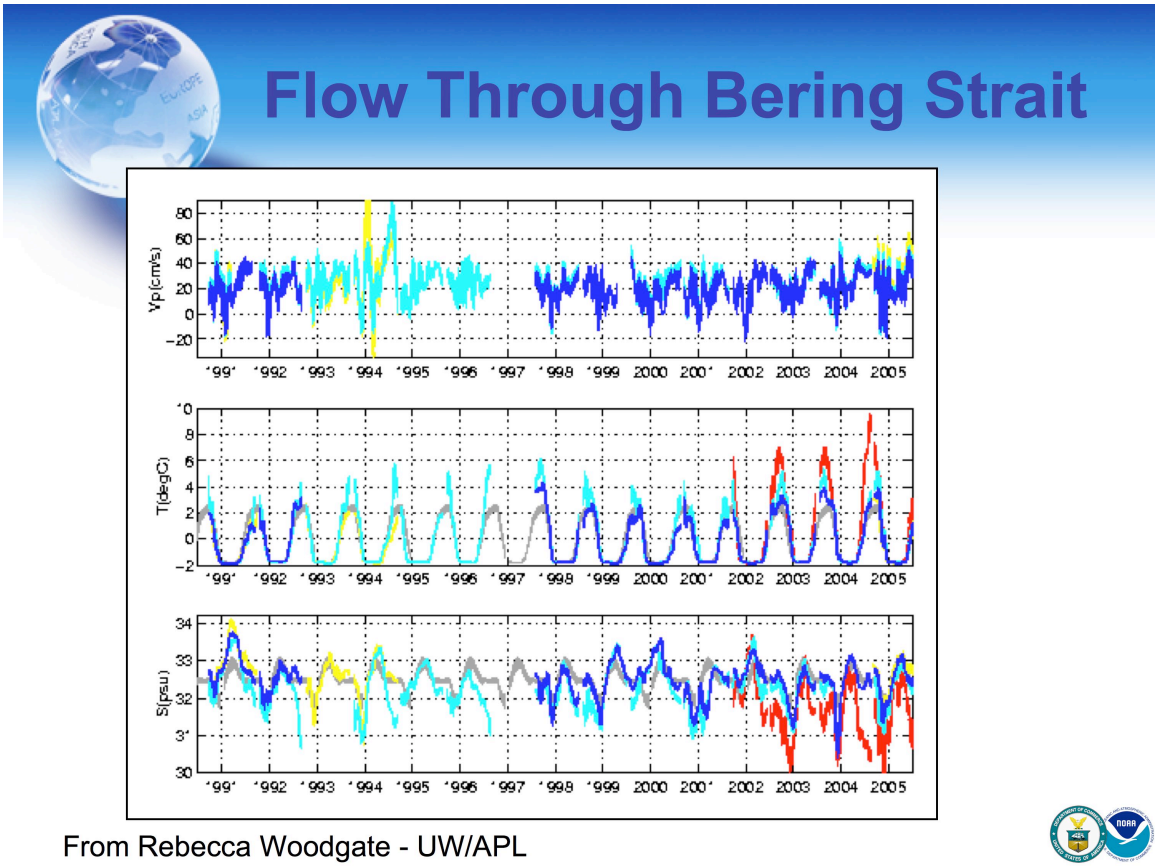


2007 mooring locations (red), CTD stations in black. Depth is in meters.

The science objectives are:

1) To measure the velocities and water properties of the Bering Strait throughflow;
2) To understand the physical processes influencing the properties of the Bering Strait throughflow, with special focus on mechanisms driving change, and impacts on the

Arctic Ocean;
3) To quantify (or at least bound) oceanic fluxes of volume, freshwater, heat, nutrients, and chlorophyll biomass through the strait; and
4) To design an optimum monitoring system for oceanic fluxes through the Bering Strait.



From Rebecca Woodgate - UW/APL

30-day running mean time-series of all available velocity, temperature, and salinity data from the Bering Strait mooring sites (Green) western channel, Russian Federation waters, (light blue) eastern channel (U.S. waters), (dark blue) north Bering Strait, (yellow) central Chukchi Sea and (red) base of the Alaskan Coastal Current. The background gray is a 15-year climatology for the central Chukchi Sea. Solid black lines are weekly averages of sea surface temperature from MODIS satellite data from the eastern channel. Prior to 2007 mooring operations in the western and eastern channels were not coordinated.

The hypotheses of the Principal Investigators in the RUSALCA program are that Bering Strait throughflow properties are set by global and regional oceanic and atmospheric processes, which are vulnerable to climate change; and that understanding the physical processes and scalings in the strait are key to quantifying current conditions, assessing future change scenarios, and designing an efficient observational scheme for this oceanic gateway.
Additionally, the RUSALCA Bering Strait moorings will provide an observational platform for other Bering Strait measurements; an annually- updated status of Bering Strait fluxes and potential Arctic impacts for the science community and the general

public; and public dissemination of results and the importance of global oceanography to US schools and the general public, including via a Polar Science Weekend at the Pacific Science Center (Seattle's major science museum).

By quantifying and understanding oceanic fluxes at this key Pacific-Arctic ocean gateway, this work contributes directly to NOAA's mission of documenting the climate system and detecting change. The work also directly fulfils RUSALCA goals and milestones, specifically by quantifying Bering Strait fluxes of freshwater, heat and nutrients, via annual mooring data; by maintaining climate CTD lines in the Bering Strait and Chukchi Sea; and by providing annual updated estimates of fluxes (including data and data products) via a public website and national data archives.

CRUISE REPORT FOR BERING STRAIT MOORING PROJECT 2007

Russian Vessel SEVER ('North') – RUSALCA2007

Nome, 27th August 2007 – Nome, 5th September 2007

Rebecca Woodgate, University of Washington (UW),woodgate@apl.washington.edu

Funding from NSF ARC-0632154 and NOAA RUSALCA program. An International Polar Year Project

Science Coordinators: *Kathy Crane, NOAA, USA, Mikhail Zhdanov, Group Alliance, Russia (RF)*
Science Liaison at Sea: *Kevin Wood, NOAA/UW, USA, and Vladimir Smolin, State Research Navigational Hydrographical Institute (SRNHI), RF*
Chief Scientist: *Terry Whitledge, University of Alaska, Fairbanks (UAF), USA*
Lead for Mooring Team: *Rebecca Woodgate, UW, USA*

As part of the joint US-Russian RUSALCA (Russian US Long-term Census of the Arctic Ocean) Program, a team of US and Russian scientists undertook an oceanographic cruise in summer 2007 on board the Russian vessel 'Sever'. The cruise started in Petropavlosk, Russian Federation, on 22nd August. It arrived in Nome, USA, on the evening of 26th August. There, it picked up the US science team and equipment on 27th August, and sailed for the Bering Strait on 28th August. A

major objective of the cruise was mooring work in the Bering Strait region (recovery of 7 moorings, deployment of 8 moorings), related high resolution CTD sections with nutrient sampling, and some benthic grab work. This cruise report concerns the mooring and physical CTD work - for details of other programs, please contact the Chief Scientist.

Cruise Participants

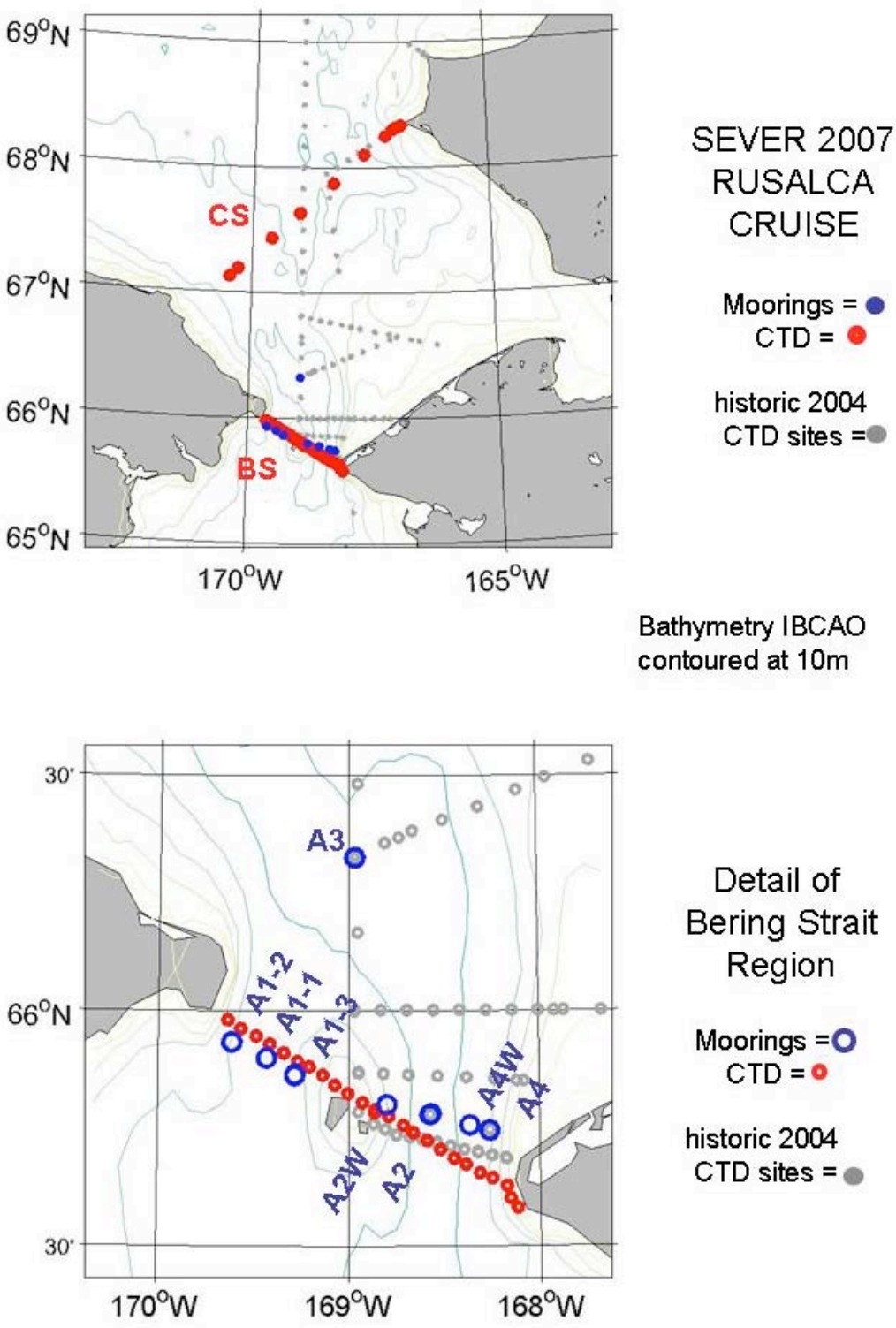
- US

1. Terry Whitedge (M), UAF, USA – *Chief Scientist, nutrients, moored nutrient sampler*
2. Kevin Wood (M), NOAA/UW – *Science Liaison*
3. Rebecca Woodgate (F), UW – *Moorings*
4. Jim Johnson (M), UW – *Moorings*

- Russian

5. Vladimir Smolin (M), SRNHI, RF – *Science Liaison and translator*
6. Igor Lukashenko (M), Pacific Hydrographic Service- *Vladimir's assistant*
7. Konstantin Bachinsky (M), Pacific Oceanography Inst, RF
8. Valerian Golavsky (M), Arctic and Antarctic Research Institute (AARI), RF – *Moorings*
9. Vladislav Djurinsky (M), Zoological Institute (ZIN) , RF – *Benthic work*
10. Vladislav Potin (M), ZIN, RF – *Benthic work*
11. Igor Karnaushevskiy (M), RF Ministry of Defense

Cruise Map of Stations relevant to UW Mooring work



SEVER 2007 RUSALCA mooring (blue dots) and CTD (red dots) locations.
The Bering Strait (BS) line was run contiguously from east to west with a 7 hour break at the Diomede Islands in the centre of the strait (one station was repeated after this break). The Cape Serdtse Kamen to Point Hope (CS) line was run contiguously from east to west. Small grey dots mark CTD stations from the Bering Strait Alpha Helix cruise in 2004 [Woodgate, 2004].

Contours from IBCAO every 10 m.

Cruise Time-schedule

Friday 24th Aug 2007 *mooring team arrive Nome.*

Saturday 25th Aug 2007 *prep mooring gear on shore in Nome.*

Sunday 26th Aug 2007 *prep mooring gear on shore in Nome, Sever docks in Nome in evening.*

Monday 27th Aug 2007 *loading, and mooring gear prep.*

Tuesday 28th Aug 2007 *cast off 8am, wait for freight, depart for Bering Strait pm, arrive at mooring site A1-3 ~ 10pm local time, recover A1-3-06.*

Wednesday 29th Aug 2007 *recover A1-1-06, fog at A1-2-06, deploy A1-1-07, wait out fog at A1-2-06, recover A1-2-06, deploy A1-3-07.*

Thursday 30th Aug 2007 *deploy A1-2-07, recover A2-06, recover A4-06, steam to A3-06.*

Friday 31st Aug 2007 *recover A3-06, deploy A3-07, deploy A2-07, deploy A2W-07, shelter over night on west side of strait.*

Saturday 1st Sep 2007 *deploy A4W-07, deploy A4-07, prep CTD gear, run half of BS line from east to the Diomede Islands (station BS12).*

Sunday 2nd Sep 2007 *continue BS line after 7hr break, redoing BS12, download data.*

Monday 3rd Sep 2007 *run CS line with mud sampling from east to west, not quite finishing line by midnight. Leave for Nome around midnight.*

Tuesday 4th Sep 2007 *data transfer and backup, packing, dock Nome ~8pm.*

Wednesday 5th Sep 2007 *offload, Sever leaves for Petropavlosk ~ 3pm, mooring team leaves Nome.*

Total: 8 days at sea,

Background to mooring and CTD program

Moorings: The moorings serviced on this cruise are part of a multi-year time-series (started in 1990) of measurements of the flow through the Bering Strait. This flow acts as a drain for the Bering Sea shelf, dominates the Chukchi Sea, influences the Arctic Ocean, and can be traced across the Arctic Ocean to the Fram Strait and beyond. The long-term monitoring of the inflow into the Arctic Ocean via the Bering Strait is important for understanding climatic change both locally and in the Arctic. Data from 2001 to 2004 suggest that heat and freshwater fluxes are increasing through the strait [*Woodgate et al.*, 2006]. The work completed this summer should tell us if this is a continuing trend.

An overview of the Bering Strait mooring work (including access to mooring and CTD data) is available at http://psc.apl.washington.edu/BeringStrait.html.

Six moorings were recovered on this cruise.

-- Three moorings (A2-06, A3-06, A4-06 in US waters) were deployed under an Alaskan Ocean Observing System (AOOS, http://www.aoos.org) grant to *Woodgate and Weingartner*.

-- The other three moorings (A1-1-06, A1-2-06, A1-3-06) were a joint US-Russian (*Weingartner and Lavrenov*) project, part of the NOAA-led RUSALCA (Russian-American Long-term Census of the Arctic, http://www.arctic.noaa.gov/aro/russian-american/) program.

A total of 8 moorings (in Russian waters – A1-1-07, A1-2-07, A1-3-07, in US waters – A2W-07, A2-07, A4W-07, A4-07, A3-07) were deployed in another joint US-Russian venture supported by RUSALCA and by NSF-OPP (*Woodgate, Weingartner, Whitledge, Lindsay, NSF-OPP-ARC-0632154*).

This is the highest resolution array ever deployed in the Bering Strait, (see map above). Three

moorings were deployed across the western (Russian) channel of the strait (from west to east - A1-2-07, A1-1-07, A1-3-07). Four moorings were deployed across the eastern (US) channel of the strait (from west to east - A2W-07, A2-07, A4W-07, A4-07). A final 8th mooring (A3-07) was deployed ca. 35 nm north of the strait at a site proposed as a "climate" site, hypothesized to measure a useful average of the flow through both channels [*Woodgate et al.*, 2007]. Testing this hypothesis is a main aim of this work. All moorings measure water velocity, temperature and salinity near bottom (as per historic measurements). Additionally, 6 of the 8 moorings (i.e., all eastern channel moorings, the climate site mooring A3, and the mooring central in the western channel) also carried upward-looking ADCPs (measuring water velocity in 1-2 m bins up to the surface, ice motion, and medium quality ice-thickness) and ISCATS (upper level temperature-salinity-pressure sensors in a trawl resistant housing designed to survive impact by ice keels). Bottom pressure gauges were also deployed on the moorings at the edges of the eastern channel (A2W-07 and A4-07). (The preferred locations – A1-2-07 and A4-07 – were unavailable.) Two moorings (A2-07, central eastern channel; and A1-2, western part of western channel) also carried ISUS nitrate sensors and optical sensors for fluorescence and turbidity. Recovered moorings in the central eastern channel and at the climate site (A2-06 and A3-06) carried Upward Looking Sonars (ULSs) measuring high-quality sea-ice thickness. These instruments were not redeployed. For a full instrument listing, see the table below.

This coverage should allow us to assess year-round stratification in the strait and also to study the the physics of the Alaskan Coastal Current, a warm, fresh current present seasonally in the eastern channel, and suggested to be a major part of the heat and freshwater fluxes [*Woodgate and Aagaard*, 2005; *Woodgate et al.*, 2006]. The current meters and ULSs allow the quantification of the movement of ice and water through the strait. The nutrient sampler, the transmissometer and fluorometer time-series measurements should advance our understanding of the biological systems in the region.

CTD: The moorings are supported by annual CTD sections, with water samples for nutrients. The best coverage achieved to date was in 2004 from the Alpha Helix, although that cruise was limited to US waters. For reference, the 2004 Helix stations are indicated as small grey dots on the map above. The most important section is the high resolution CTD section run across the Bering Strait (named BS). This was completed in 2007 and included both US and Russian waters. There are two other lines which we attempt to maintain during this cruise. One (named CS) is a coast-to-coast section with high resolution near the coasts running from Cape Serdtse Kamen (RF) to Point Hope (US) – part of that line was completed during this 2007 cruise. The other is a high resolution line through mooring site A3 – this line was not taken during this 2007 cruise.

International links: Maintaining the time-series measurements in Bering is important to several national and international programs, e.g. NSF's Freshwater Initiative (FWI) and Arctic Model Intercomparison Project (AOMIP), and the international Arctic SubArctic Ocean Fluxes (ASOF) program. The mooring work also supports regional studies in the area, by providing key boundary conditions for the Chukchi Shelf/Beaufort Sea region; a measure of integrated change in the Bering Sea, and an indicator of the role of Pacific Waters in the Arctic Ocean. Furthermore, the Bering Strait inflow may play a role in Arctic Ocean ice retreat and variability (especially in the freshwater flux) is considered important for the Atlantic overturning circulation and possibly world climate [*Woodgate et al.*, 2005].

Mooring Operations during 2007 Sever cruise

Despite fog and certain challenges (see below), the mooring work was successfully completed. The acoustic hydrophone was deployed via the window in the aft lab. Once the mooring was released, the ship brought the floating mooring along the port side, where it was grappled by hook and brought aboard onto the foredeck using the Sever's substantial forward crane. The following

issues are noteworthy:

1) On two moorings (A3-06 and A4-06), barnacles jammed the mechanism on the releases. In both cases, this problem was limited to one release of the double releases used, and thus the mooring was successfully released with the second release. In both cases, the drop link remained attached to the jammed release and was only freed on deck, in the A3 case by tugging the release and in the A4 case by chipping at the barnacle. These moorings had been in the water since July 2006, i.e., through two growing seasons). To prevent this, ***antifouling should be used on critical parts of the release mechanism.***

2) Several of the releases were found to require a special deckset, since a manufacturer's error made the acoustic circuits temperature dependent. With this deckset, codes normally starting with 4 can be retuned by changing the initial digit of the code. All recoveries except A1-3 (which had an older release) required this special deckset. For successful communication, by trial and error, the following pattern for the initial digit was found (relating somewhat to temperature) – A1-1-06 required 8, A1-2-06 required 8, A2-06 required 8, A4-06 required 9, A3-06 required 8 or 9 depending on the release. It was necessary to redeploy some of these releases – thus, ***for 2008, moorings A1-2-07 and A1-3-07 will require the special deckset.***

3) Release sn 32426 (recovered from A1-2-06 and redeployed on A1-2-07) was reported with the wrong enable code. The correct code is 474043 (with the first digit altered to 8 for the temperature dependence problem discussed above).

4) Although the weather was in general calm, fog delayed mooring recoveries in the western parts of the western channel, especially A1-2-06. It would be interesting to relate this to water properties.

5) The moorings in the eastern channel and at the northern site were deployed last summer (as compared to the autumn deployment of the western channel moorings) and showed significantly more biofouling than instrumentation in the western channel. This likely reflects the longer deployment period, and possibly warmer waters. Barnacles up to 3 cm were common on these moorings – barnacle growth has becoming the dominant form of biofouling in the strait in recent years. Unusually small barnacles were also found on the lower parts of the release mechanisms. Other than impeding the release mechanism, it does not yet seem that the data is degraded by the biofouling. In all cases, salinity cells remained clear. A future recommendation is to use anti-fouling measures on the releases.

Very preliminary analysis of the mooring data show very good data return, apart from one flooded microcat (temperature, salinity instrument) on the eastmost mooring (A4). Some instruments – ULSs (Upward Looking Sonars, measuring ice thickness), and the AARI current meter and CTD – could not be downloaded at sea, but are expected to be read on return to their institutes.

The data show the usual large annual cycle in temperature and salinity. Many of the usual features are present, i.e. high variability in autumn, generally with freshening and cooling; salting (at the freezing point) in the winter; freshening and warming in the spring [*Woodgate et al.*, 2005]. Interestingly in the spring 2007 warming, A2 is distinctly colder than the western channel data – this unusual situation requires further investigation, as do the strong warming events at A2 in the warmest period of 2006. A more detailed analysis is necessary to seek for interannual signals. Also noteworthy is the persistence of northward flow for the last ~ 3 months of the record (i.e. summer 2007). The flow through the strait is believed to be driven by a sea-level difference between the Pacific and the Arctic, which drives a flow northwards towards the Arctic. Local winds (usually southward in the annual mean) tend to oppose this flow and may reverse it on timescales of days [*Woodgate et al.*, 2005b]. However, the recovered data suggest that reversals have been unusually uncommon this summer. (This is consistent with verbal reports from Nome about the extreme clemency of the weather.) Since the variability of northward fluxes of heat and freshwater are dominantly dependent on the variability of the volume transport [*Woodgate et al.*, 2006], this may imply further increases in this fluxes, with possible implications

for the Arctic and beyond.

Details of mooring positions and instrumentation are given below, along with schematics of the moorings, photos of the mooring fouling and preliminary plots of the data.

CTD Operations during 2007 Sever cruise

Due to clearance issues, the 2007 cruise sailed without a UAF mooring technician. Lack of personnel delayed the mooring and limited the CTD sections which could be taken. Of the proposed 3 CTD lines, one (the Bering Strait line BS) was completed from east to west with a 7hr break during the run, and one (the Cape Serdtse Kamen line CS) was roughly 3/4 completed from east to west.

Two internally sampling CTDs (an SBE25 and an SBE19) were deployed strapped together from the upper deck winch on the starboard aft deck. In addition CTD, the SBE 19 also recorded oxygen, fluorescence, and PAR. At each station up to three bottle samples were taken – nominally surface (by bucket), bottom and midwater column (by niskin). The bottom niskin was suspended ~ 2 m below the CTD on a bottom trip mechanism. The mid-water bottle was attached to the wire during the downcast and closed by messenger when the cast was estimated to be at the bottom. Bottom depths were estimated from the bridge depth sounder. On station 19, the CTD hit bottom, but mostly the cast did not appear to hit bottom. The table below gives CTD positions, LOCAL times (for GMT, add 8 hrs), estimated depth from the bridge depth sounder, and depth to which the CTD was lowered (calculated by wire out). The bottom bottle is likely from ~ 2 m deeper than the maximum CTD pressure (likely the MaxP here, but this should be checked against the CTD records). An estimate of the mid-water bottle depth is also given from wire out. This could also be extracted from the CTD data since the CTD cast was stopped to attach and remove the bottle.

Preliminary CTD sections are given below. These should be treated with caution as they are (a) blindly 1-m binned and (b) based on pre-calibrations.

Table of Bering Strait Mooring Positions (US GPS) and Instrumentation

ID	LATITUDE (N)	LONGITUDE (W)	WATER DEPTH /m (corrected)	INST.
RECOVERIES				
- Russian EEZ				
A1-1-06	65 54.000	169 25.783	50.5	ADCP, SBE37
A1-2-06	65 55.982	169 36.856	50.5	AARI, ISUS, SBE/TF, RCM9T
A1-3-06	65 51.764	169 16.956	50.5	AARI, RCM7, SBE37
- US EEZ				
A2-06	65 46.775	168 34.471	56	ULS, RCM9LW SBE/TF, ISUS
A3-06	66 19.543	168 58.009	58	ULS, RCM9LW SBE37

A4-06	65 44.73	168 15.67	49	ADCP, SBE37
DEPLOYMENTS				
- Russian EEZ				
A1-1-07	65 53.994	169 25.877	52	ISCAT, ADCP, SBE37
A1-2-07	65 56.019	169 36.763	53.3	ISUS, SBE/TF, RCM9T
A1-3-07	65 51.908	169 16.927	49	AARI, RCM9LW, SBE37
- US EEZ				
A2W-07	65 48.07	168 47.95	52	ISCAT, ADCP, SBE16, BPG
A2-07	65 46.87	168 34.07	56	ISCAT, ADCP, SBE/TF, ISUS
A4W-07	65 45.42	168 21.95	54	ISCAT, ADCP, SBE16
A4-07	65 44.77	168 15.77	50	ISCAT, ADCP, SBE16, BPG
A3-07	66 19.60	168 57.92	58	ISCAT, ADCP, SBE37

AARI = AARI Current meter and CTD
ADCP = RDI Acoustic Doppler Current Profiler
BPG=Seabird Bottom Pressure Gauge
ISCAT = near-surface Seabird TS sensor in trawl resistant housing, with near-bottom data logger
ISUS= Nutrient Analyzer
RCM7 = Aanderaa Mechanical Recording Current Meter
RCM9LW = Aanderaa Acoustic Recording Current Meter
RCM9T = Aanderaa Acoustic Recording Current Meter with Turbidity
SBE/TF = Seabird CTD recorder with transmissometer and fluorometer
SBE16 = Seabird CTD recorder
SBE37 = Seabird Microcat CTD recorder
ULS = APL Upward Looking Sonar

Table of Bering Strait CTD Positions (US GPS)

SEVER 2007 CTD POSITIONS - *recreated from written logs, start and endpositions also available*

 # Name US Date Time LOCAL Lat (N) &Long (W) at Bot WD MaxP MB
year mon day in bottom out Deg min Deg min /m /m /m

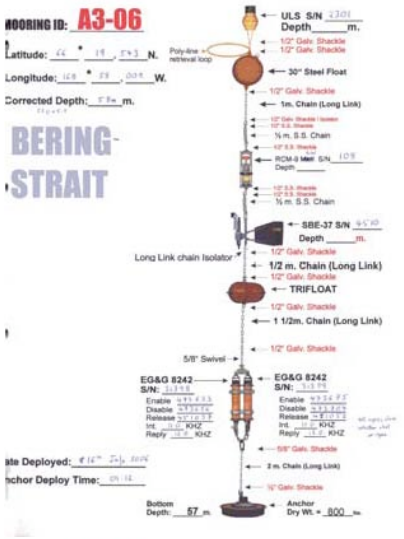
1 BS24 2007 9 1 1828 1834 1836 65 34.897 168 07.09 25 *23 13*
2 BS23 2007 9 1 1858 1902 1904 65 36.12 168 009.308 31 *26 11*
3 BS22 2007 9 1 1940 1942 1944 65 37.68 168 10.399 33 *29 14*
4 BS21 2007 9 1 *2042** 2044 2046 65 38.66 168 14.905 43 *39 19*
5 BS20 2007 9 1 2109 2113 2115 65 39.305 168 18.839 46 *42 19*
6 BS19 2007 9 1 2149 2153 2204 65 40.438 168 23.156 53 *49 24*
7 BS18 2007 9 1 2225 2229 2231 65 41.212 168 26.877 53 *49 24*
8 BS17 2007 9 1 2254 2258 2300 65 42.316 168 31.199 56 *52 27*
9 BS16 2007 9 1 2326 2330 2332 65 43.491 168 35.273 53 *49 24*
10 BS15 2007 9 1 2357 0001 0003 65 44.48 168 39.683 53 *49 24*
11 BS14 2007 9 2 0028 0032 0034 65 45.426 168 42.797 52 *48 23*
12 BS13 2007 9 2 0101 0106 0108 65 46.593 168 47.359 52 *48 23*
13 BS12 2007 9 2 0126 0130 0132 65 47.406 168 51.667 46 *42 17*
14 BS12 2007 9 2 0926 0929 0931 65 47.038 168 51.714 46 *42 17*
redone after 2am-9ambreak
15 BS11 2007 9 2 0952 0956 0958 65 48.338 168 55.559 47 *43 18*
16r BS10 2007 9 2 1029 1033 1035 65 49.474 169 00.206 41 *38.5 18*
17r BS9 2007 9 2 1057 1101 1102 65 50.549 169 04.304 46 *43.5 18*
18r BS8 2007 9 2 1124 1127 1129 65 51.832 169 08.155 46.5 *43 19*
19r BS7 2007 9 2 1241 1245 1247 65 52.903 169 12.426 49 *45 21*
hit bottom, brought up 2 sea-urchins
20r BS6 2007 9 2 1311 1315 1317 65 53.577 169 16.039 49 *45 21*
strumming, significant wire angle
21r BS5 2007 9 2 1344 1347 1349 65 54.653 169 20.429 50 *47 23*
strumming, green/brown water
22r BS4 2007 9 2 1420 1424 1426 65 55.77 169 24.86 53 *49 25*
water very brown
23r BS3 2007 9 2 1454 1458 1500 65 56.787 169 29.151 52.5 *49 25*
lots of propwash, discharge off deck, foggy
24r BS2 2007 9 2 1537 1541 1542 65 57.721 169 33.983 51 *47 23*
foggy
25r BS1 2007 9 2 1606 1610 1612 65 58.837 169 38.073 50 *46 22*
foggy, but warmer and calmer

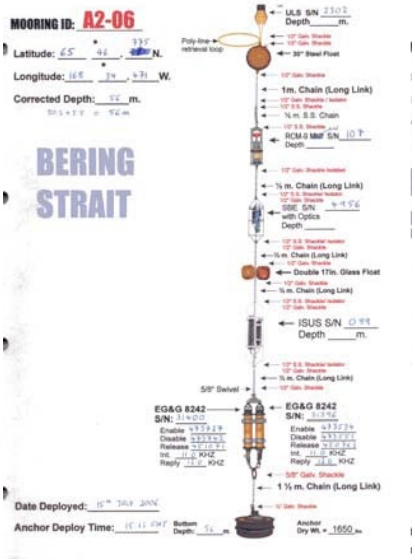
26M CS19 2007 9 3 1059 1102 -1104 68 19.975 166 52.112 27.5 *24 -*
27 CS18 2007 9 3 1129 1132 1133 68 19.047 166 57.801 34.5 *31 -*
jellyfish
28M CS17 2007 9 3 1155 1159 1200 68 18.075 167 02.69 39 *36 16*
29 CS16 2007 9 3 1251 1255 1257 68 15.029 167 11.927 44.5 *41 17*
30M CS14 2007 9 3 1421 1425 1427 68 6.126 167 39.85 53 *48 24*
31M CS12 2007 9 3 1634 1639 1641 67 52.501 168 18.799 57 *54 30*
32rM CS10 2007 9 3 1854 1858 1900 67 38.088 169 00.782 51 *47 23*
33rM CS8 2007 9 3 2054 2058 2100 67 25.976 169 35.985 50 *46 22*
34rM CS6 2007 9 3 2313 2317 2319 67 11.448 170 17.163 47.5 *44 20*
35rM CS5.5 2007 9 4 0001 0005 0007 67 7.646 170 27.585 46 *42 19*

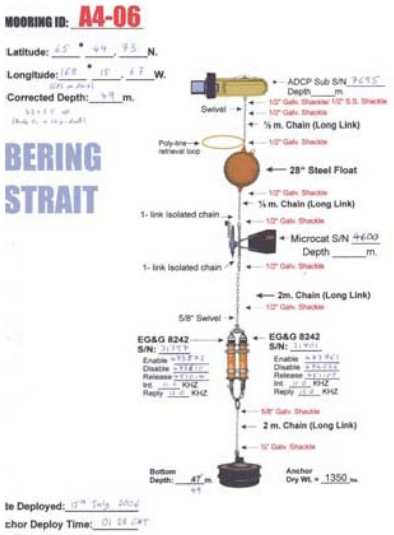
M=Mud samples were taken by Russian team. WD=water depth estimated by bridge. MaxP=distance CTD lowered from surface (bottom bottle ~ 2m deeper than this); MB=wire-out estimate of depth of middle bottle. *=estimated. r=in Russian EEZ.

SCHEMATICS OF MOORING RECOVERIES

= in US waters (AOOS moorings)



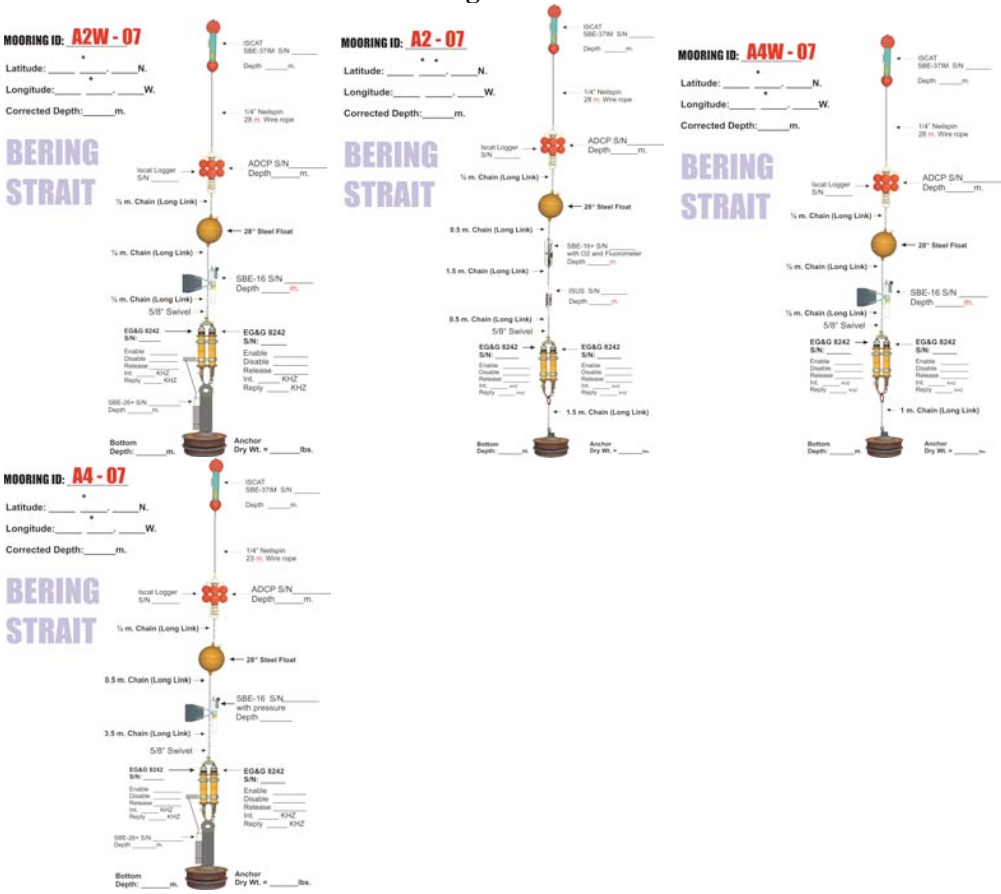




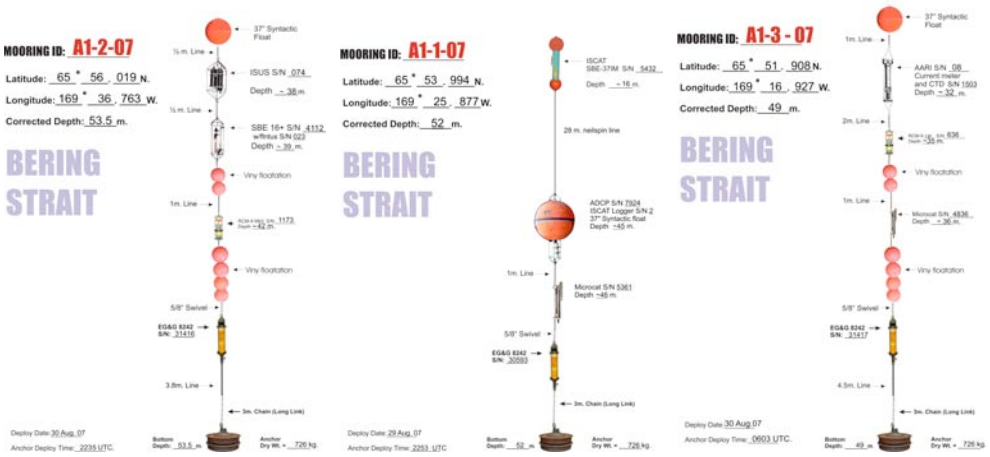
= in Russian waters (RUSALCA moorings)

SCHEMATICS OF MOORING DEPLOYMENTS

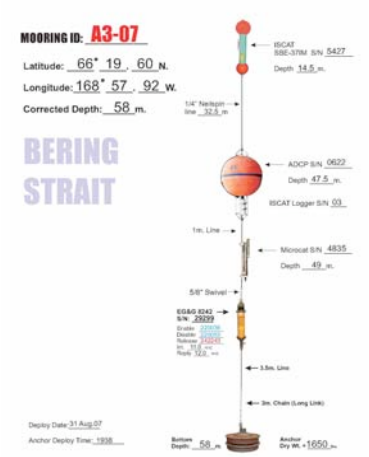
= in the eastern channel of the Bering Strait



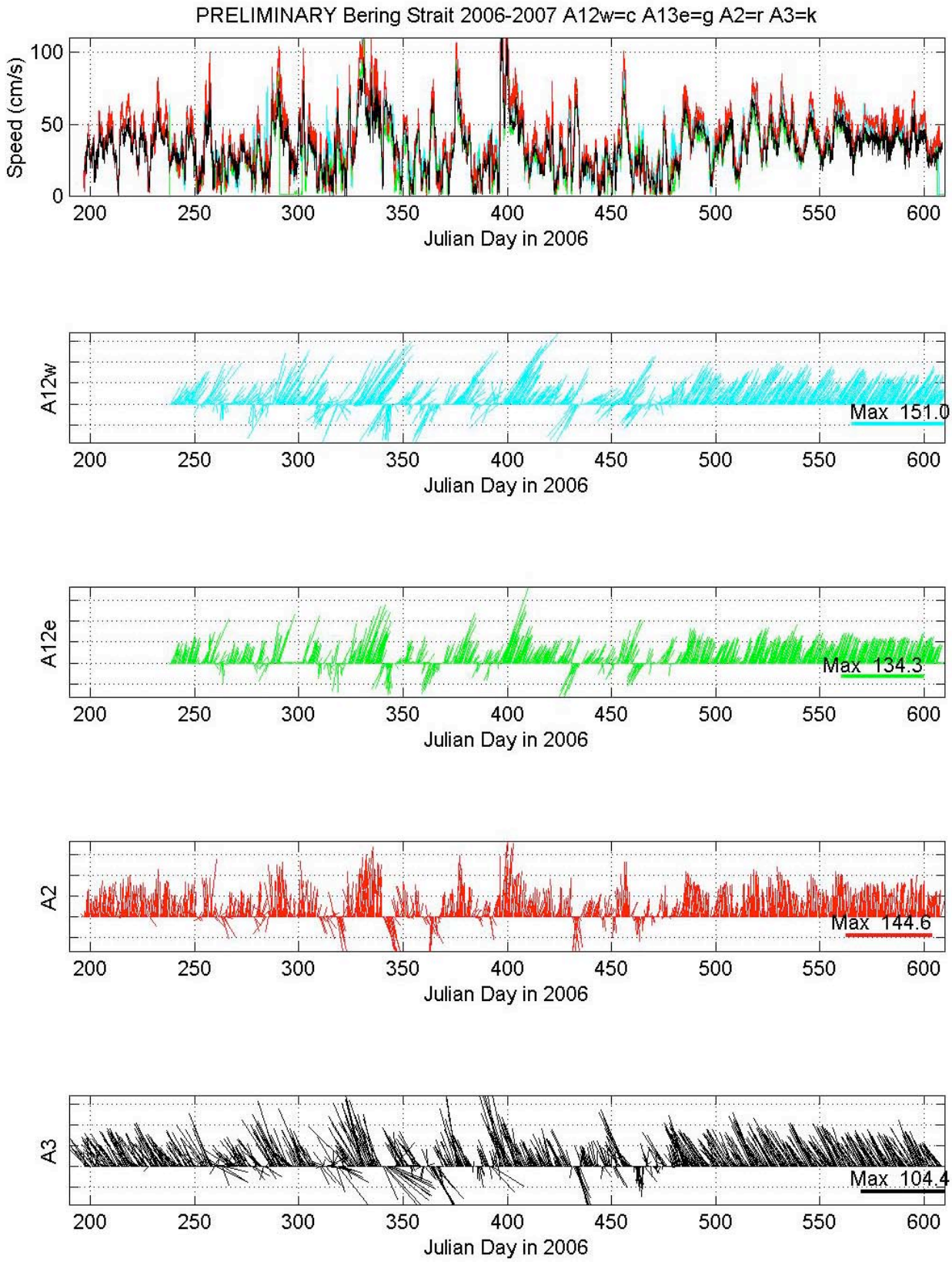
= in the western channel of the Bering Strait



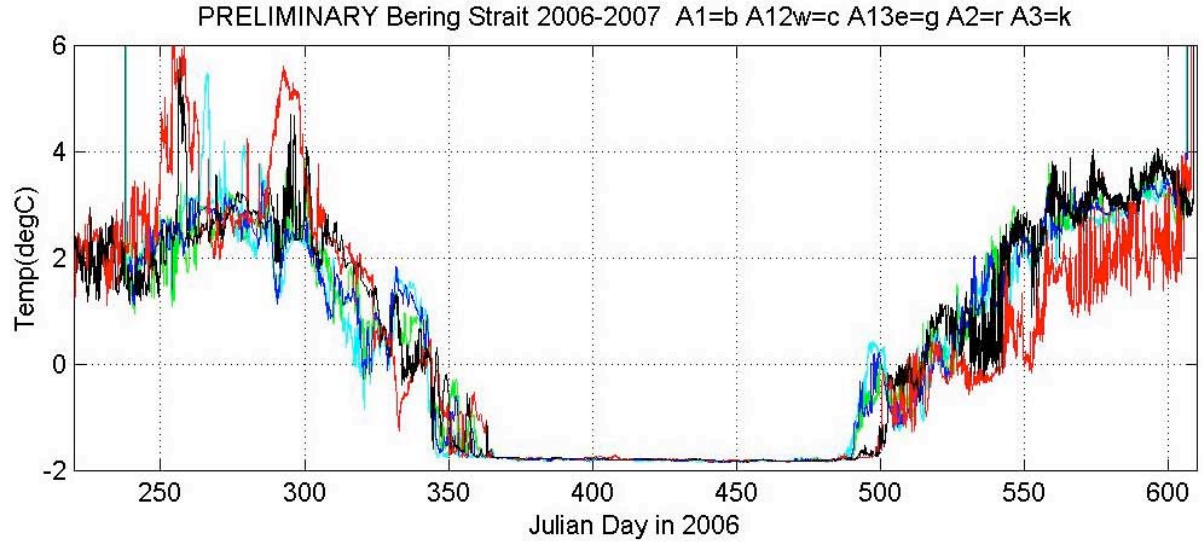
= at the climate site, ~ 60km north of the Strait

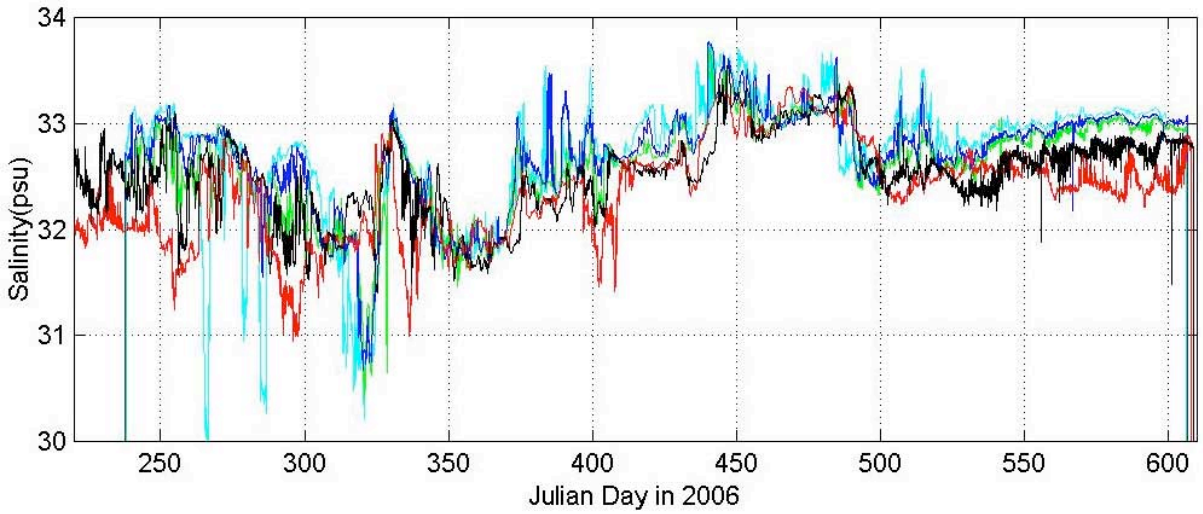


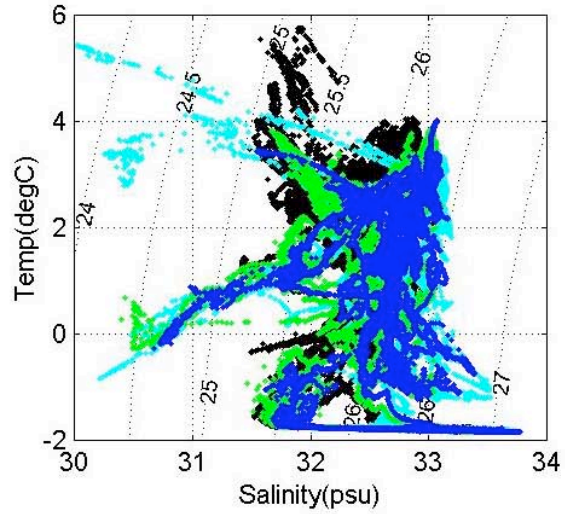
PRELIMINARY CURRENT METER RESULTS

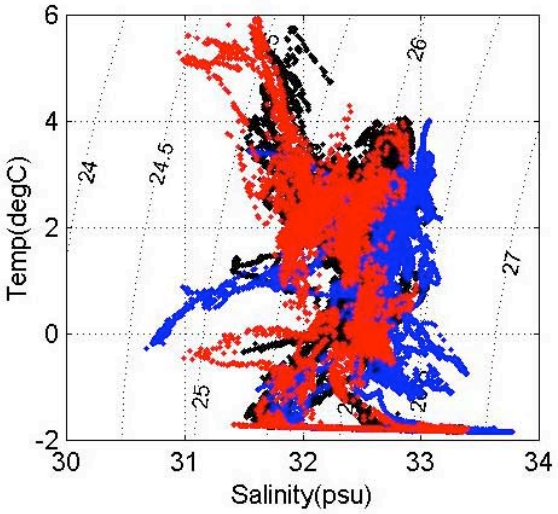


PRELIMINARY SEACAT RESULTS

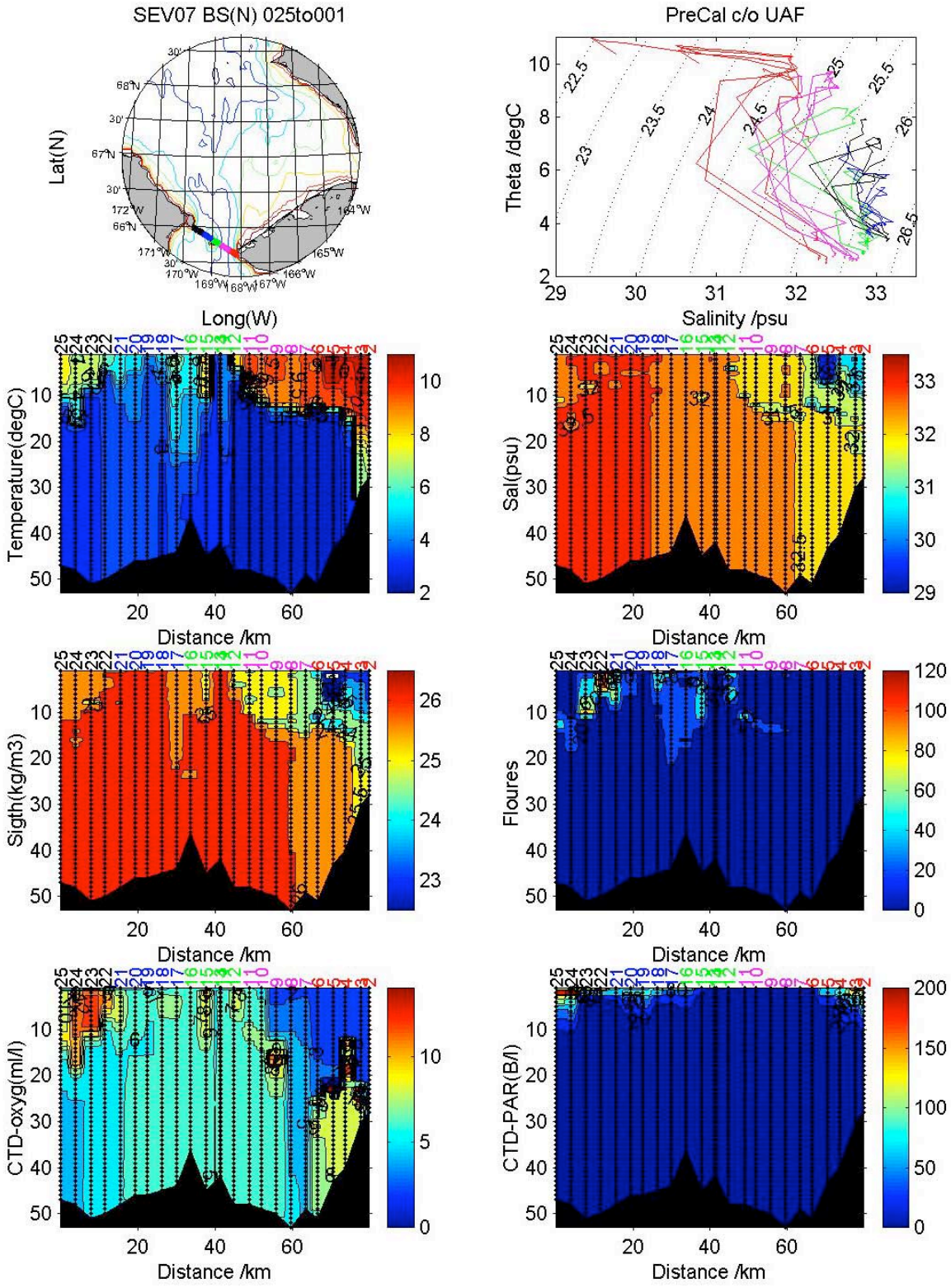

PRELIMINARY Bering Strait 2006-2007 A1=b A12w=c A13e=g A2=r A3=k
Temp(degC)
Julian Day in 2006


Salinity(psu)
Julian Day in 2006

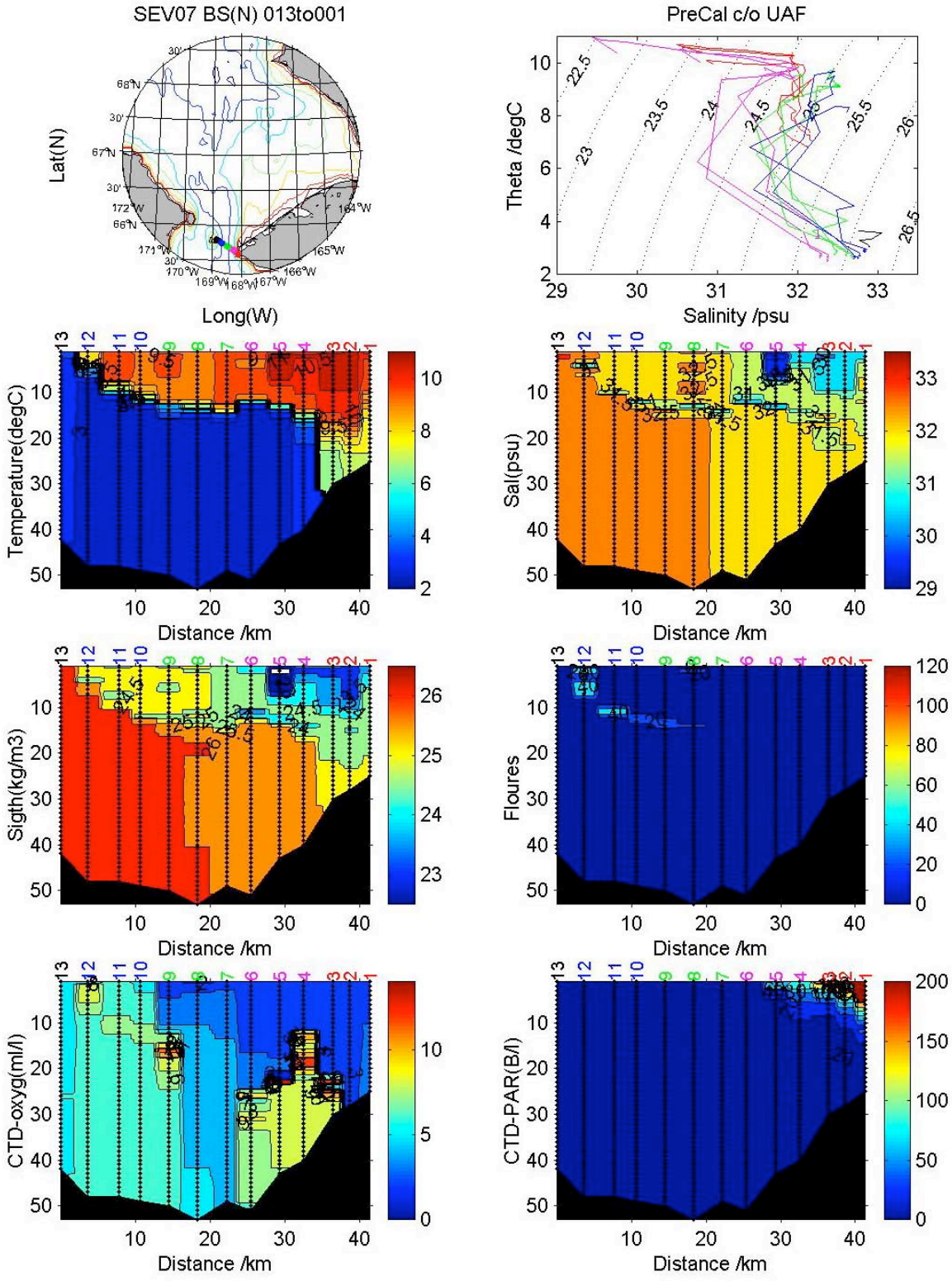

Temp(degC)
Salinity(psu)


Temp(degC)
Salinity(psu)

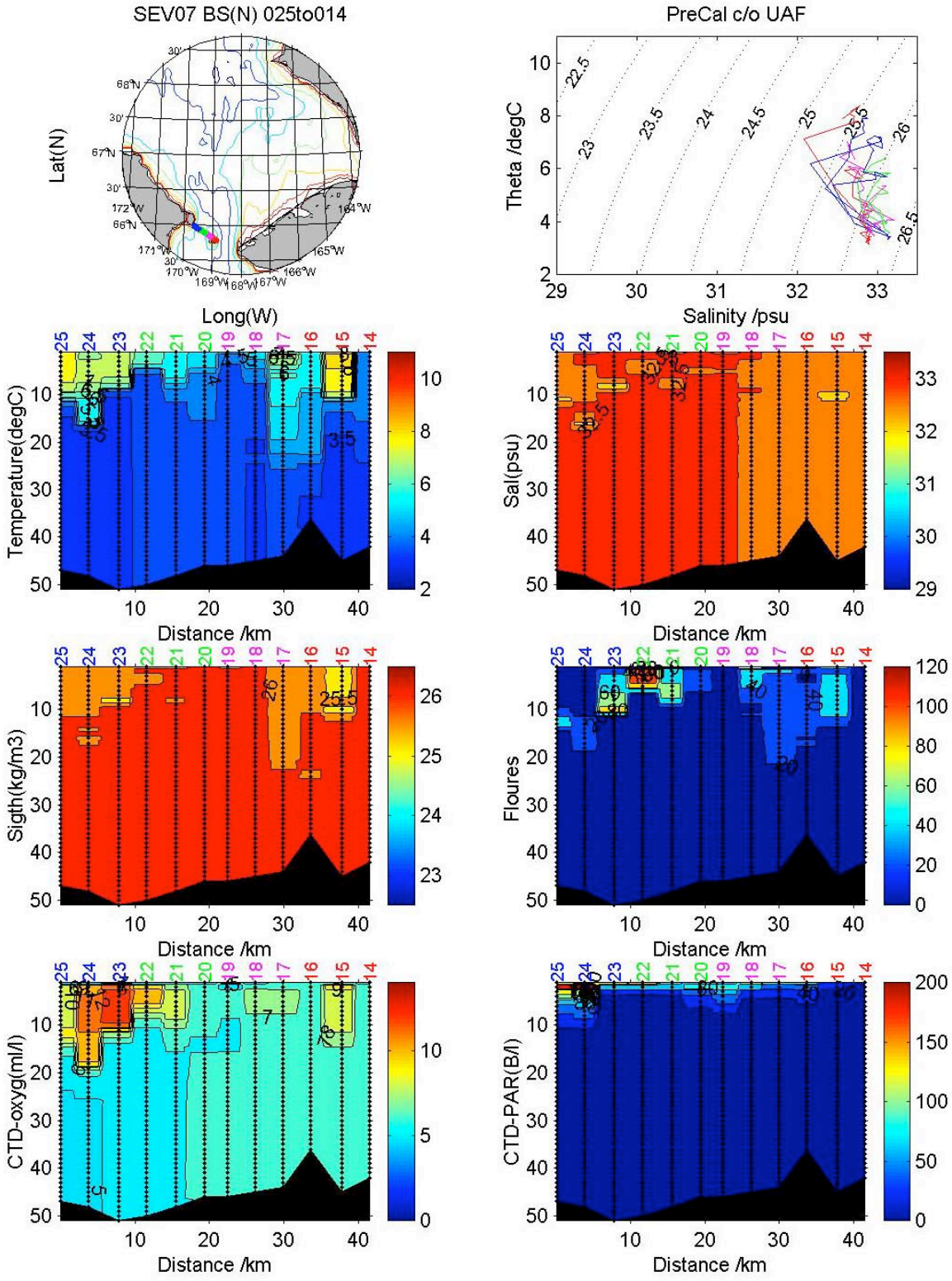
PRELIMINARY CTD SECTIONS - BERING STRAIT (whole section, except cast 1)


SEV07 BS(N) 025to001
Lat(N)
Long(W)
PreCal c/o UAF
Theta /degC
Salinity /psu
Temperature(degC)
Sal(psu)
Sigth(kg/m3)
Floures
CTD-oxyg(ml/l)
CTD-PAR(B/l)
Distance /km

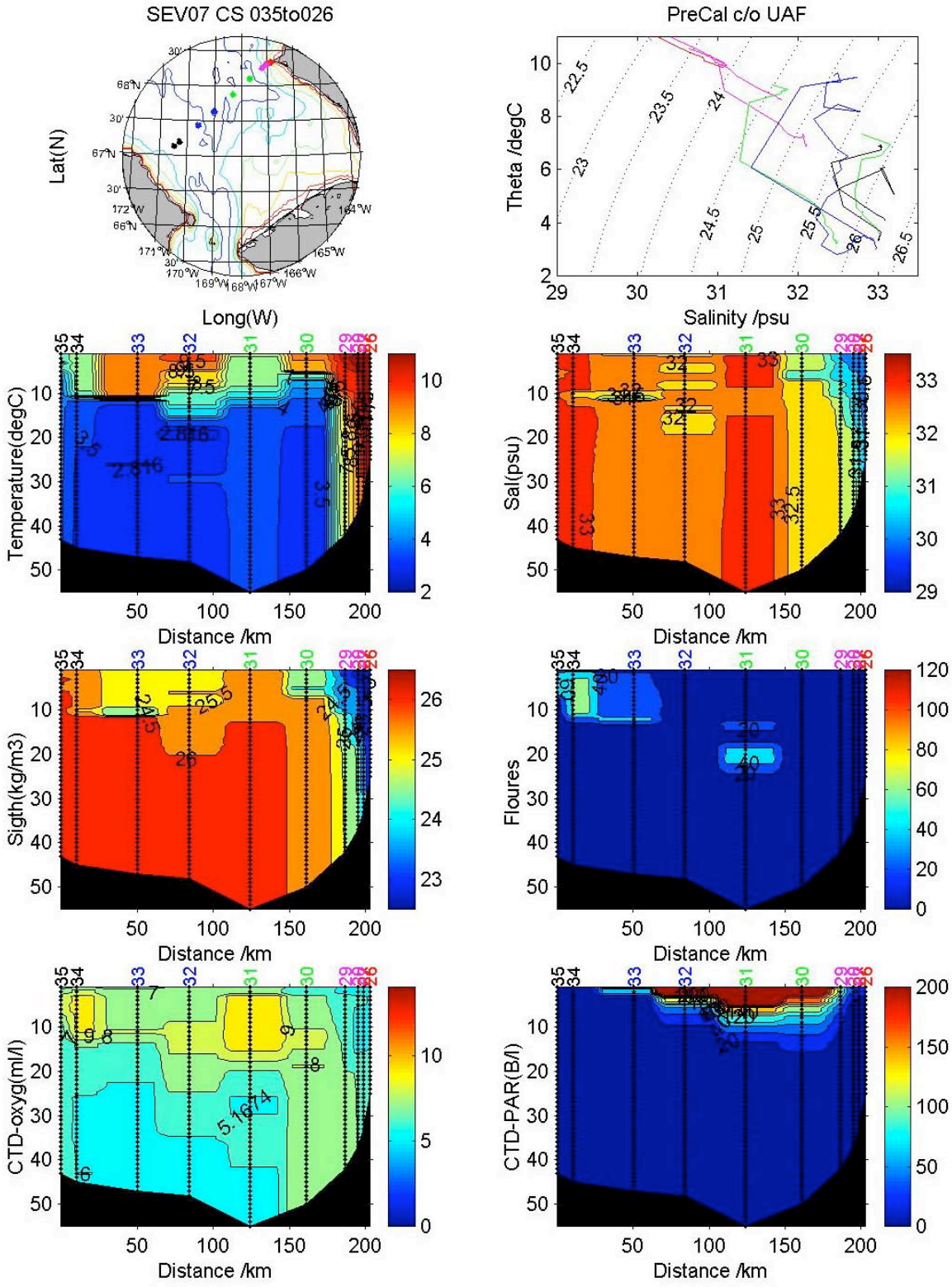
PRELIMINARY CTD SECTIONS - BERING STRAIT (eastern channel)



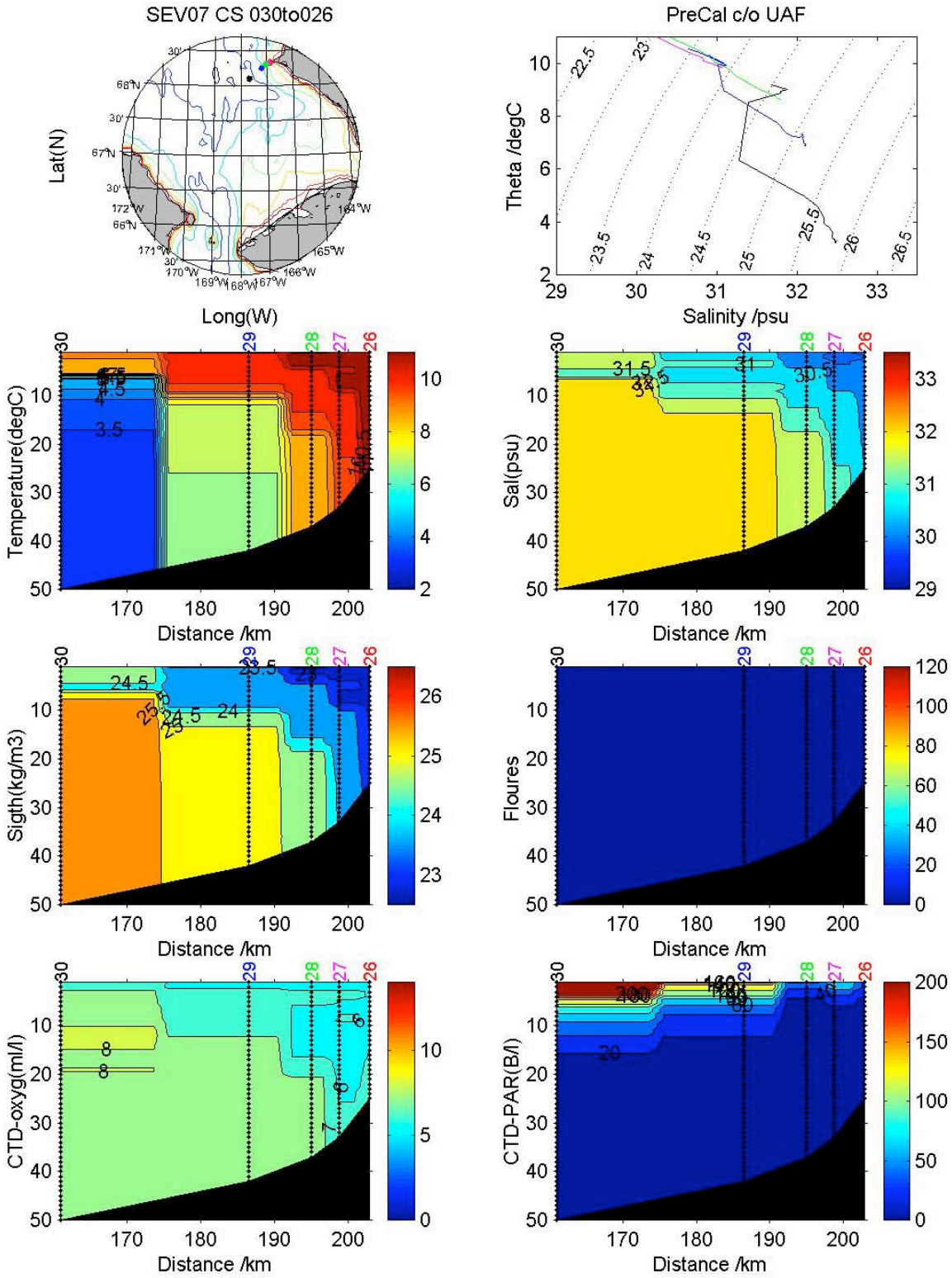
PRELIMINARY CTD SECTIONS - BERING STRAIT (western channel)



PRELIMINARY CTD SECTIONS - CAPE SERDTSE KAMEN to POINT HOPE LINE



PRELIMINARY CTD SECTIONS - CAPE SERDTSE KAMEN to POINT HOPE LINE (eastern end)


SEV07 CS 030to026
Lat(N)
Long(W)
PreCal c/o UAF
Theta /degC
Salinity /psu
Temperature(degC)
Sal(psu)
Sigth(kg/m3)
Floures
CTD-oxyg(ml/l)
CTD-PAR(B/l)
Distance /km

REFERENCES

Woodgate, R. A. (2004), Alpha Helix HX290 Cruise Report, Bering Strait Mooring Cruise August-September 2004, available at http://psc.apl.washington.edu/BeringStrait.html, University of Washington, Seattle.

Woodgate, R. A., and K. Aagaard (2005), Revising the Bering Strait freshwater flux into the Arctic Ocean, *Geophys. Res. Lett.*, *32*, L02602, doi:10.1029/2004GL021747.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner (2005), Monthly temperature, salinity, and transport variability of the Bering Strait throughflow, *Geophys. Res. Lett.*, *32*, L04601, doi:10.1029/2004GL021880.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner (2006), Interannual Changes in the Bering Strait Fluxes of Volume, Heat and Freshwater between 1991 and 2004, *Geophys. Res. Lett.*, *33*, L15609, doi:10.1029/2006GL026931.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner (2007), FIRST STEPS IN CALIBRATING THE BERING STRAIT THROUGHFLOW: Preliminary study of how measurements at a proposed climate site (A3) compare to measurements within the two channels of the strait (A1 and A2). 20 pp, University of Washington.

b. NABOS 07 Expedition in the Eurasian Basin Aboard the R/V Buynitskiy
Contact Person Igor Polyakov, IARC

The Arctic Research Program also managed an earmark to the International Arctic Research Center for the NABOS program. The 2007 field season for NABOS was difficultdue to problems with chartering the nuclear icebreaker Yamal. The NABOS scientist chartered a small ice-class research vessel Viktor Buynitsky from the Murmansk Roshydromet. The expedition proceeded into the Laptev, East Siberian and Barents Seas due to the anomalous ice-free conditions. The team successfully recovered two deep-water moorings and deployed five moorings, thus providing long-term stationary observations at key locations of the Arctic Ocean. The oceanographic cross-sections and extensive biochemistry and turbulence observations complemented mooring-based measurements. These observations showed that the exceptional warming which entered the Eurasian Basin in 1999 progressed from the Fram Strait along the Barents and Laptev slopes and was captured by conductivity/temperature/depth (CTD) cross-sections in the East Siberian Sea approaching Alaska's backyard. Observations during this cruise also documented strong warming of the very uppermost layer in the eastern Eurasian and Makarov basins. The magnitude of this warming is unprecedented in the history of regional instrumental observations. The unique strength and spatial distribution of this warm surface anomaly suggests the important role of oceanic heat in shaping the 2007 reduced Arctic Ocean ice cover. The intrusion of warm Atlantic water combined with the on-going reduction of the sea-ice cover, will have major impacts on the unique Arctic fauna and ecosystems and human inhabitants.

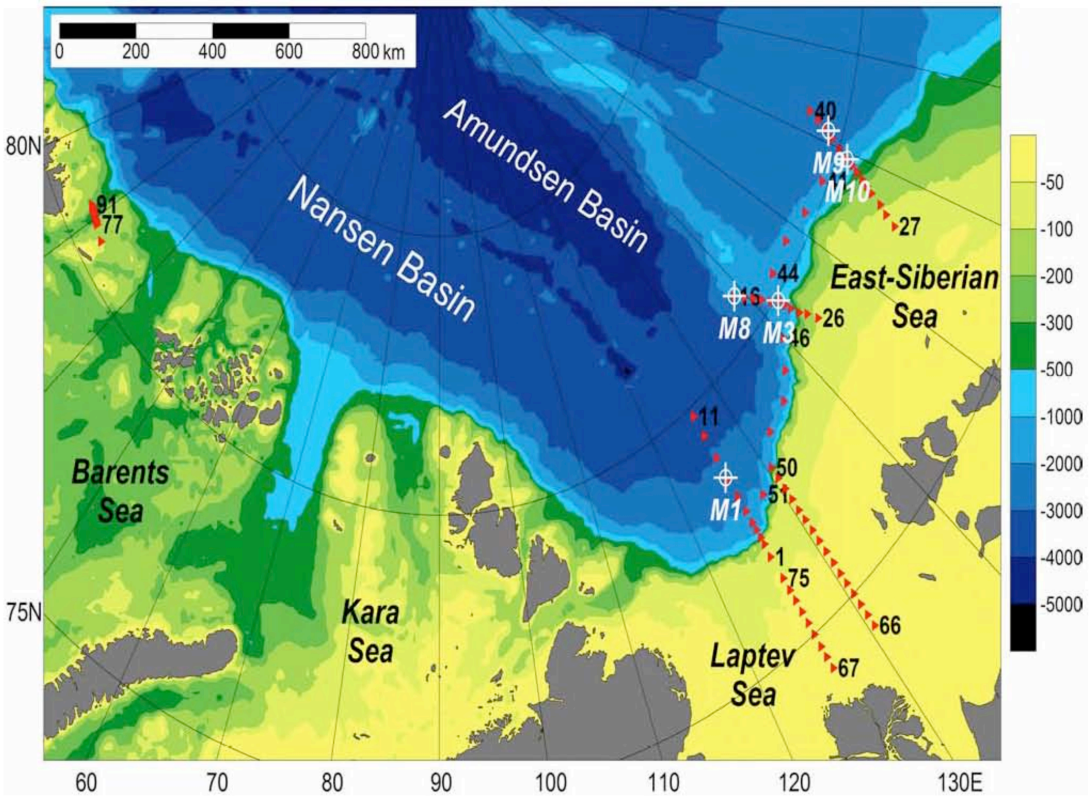


Figure I.6.1: Map of NABOS-07 operations: red triangles show CTD and XCTD stations, black numbers show station numbers, white crosses show NABOS moorings

c. Siberian Shelf Study
Contact Person: Igor Semilitov, IARC

The Siberian Shelf Study project is funded by the Arctic Research Program via an Earmark to IARC. In the summer of 2007 the US-Russian biogeochemical group joined the NABOS cruise, extending the study area to the outer shelf. The main objectives were:

1) Estimate the geographic variability of the main carbon cycle components, including partial pressure of CO_2 (pCO_2) colored dissolved organic matter (CDOM), and dissolved organic carbon/particulate organic carbon (DOC/POC), and water mass parameters including currents, water temperature and salinity, pH, total alkalinity, oxygen, turbidity, and stable oxygen isotopes.

2) Investigate the connection between seasonal anomalies of CO_2 and CH_4 in shelf water and dynamics of the water mass in connection with Lena River runoff (lateral fluxes).

3) Identify the particular sources of CH_4 and CO_2 within the shelf area, and the factors that affect sea surface-atmosphere CH_4 and CO_2 exchange (vertical fluxes).

4) Provide a benchmark of the composition and provenance and elucidate the extent of degradation of the terrOC currently being exported by coastal erosion and river runoff onto the extensive Siberian Arctic shelf.

5) Examine the transport and fate of terrestrial POC vs. marine OC.

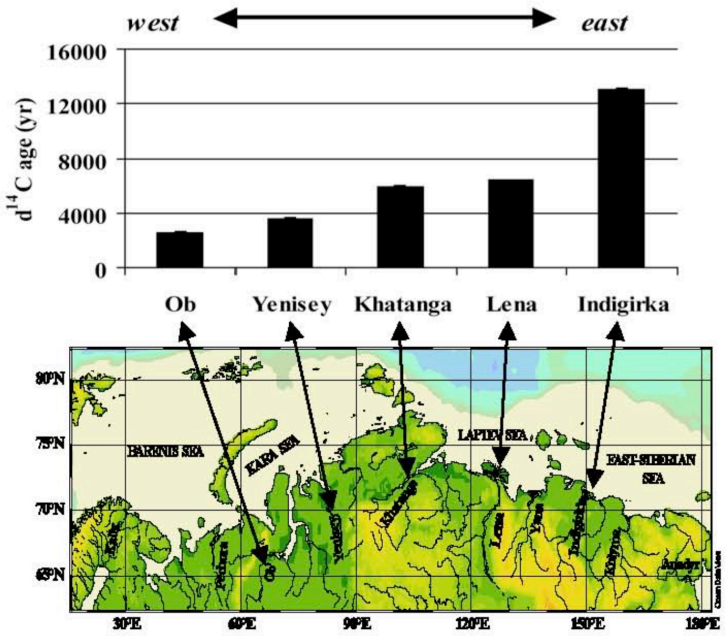


Figure I.6.7.3 The average age of bulk organic carbon in surface sediments collected from the mouths of Russian Arctic rivers along the entire continental margin [after Guo et al., 2004]

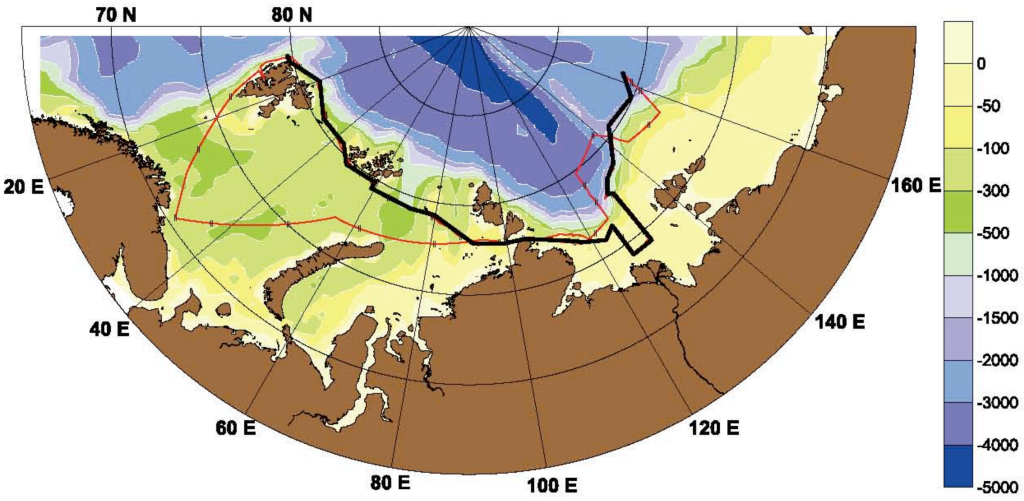


Figure I.6.7.4.6. Ship's tracks accompanied by pCO_2 measurements in the surface water.

3) Ice Buoys
Contact Persons: Ignatius Rigor and Jackie Richter-Menge

The Arctic Research Program funds efforts to expand the International Arctic Buoy program and to carry out ice mass balance measurements of the perennial Arctic sea

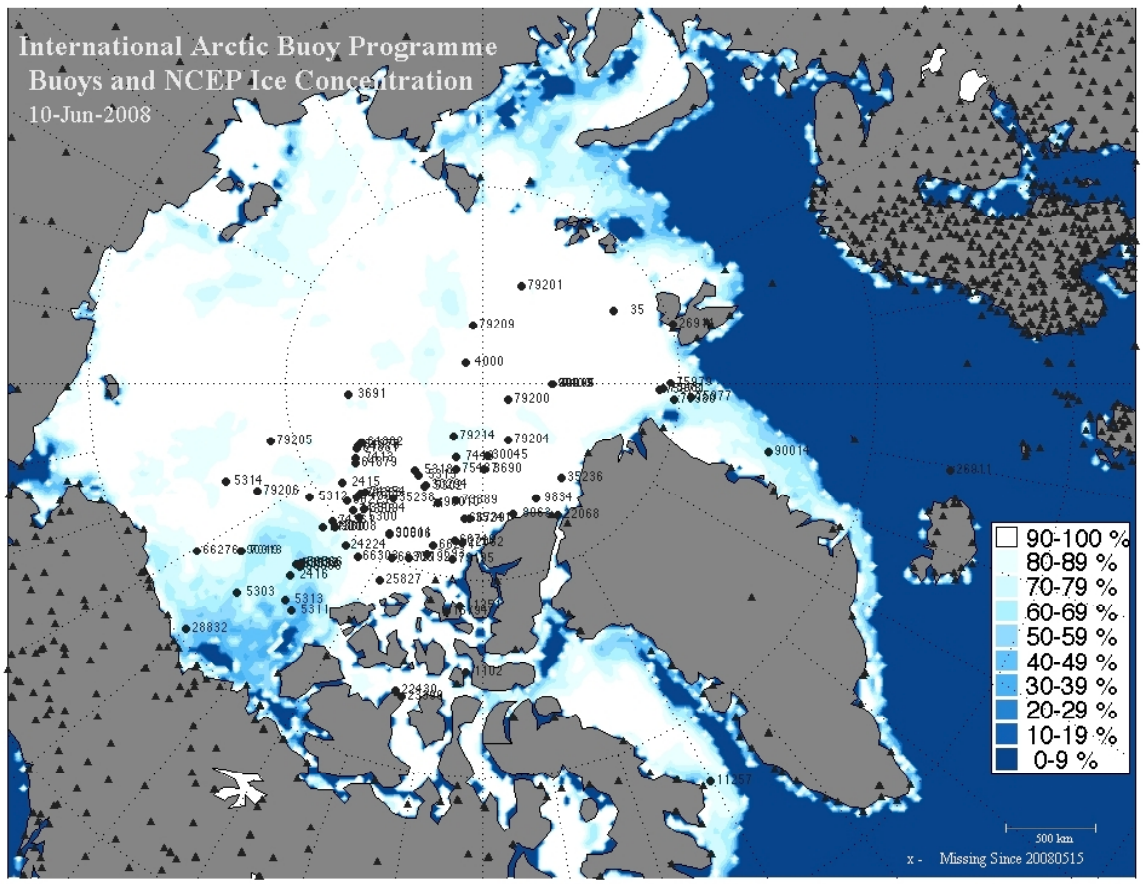
ice to measure sea ice drift, thickness and melt processes and basic meteorology; Monitoring changes in the volume or mass of the Arctic sea ice cover is crucial for developing our understanding of climate change processes and their impacts. Changes in the volume of the ice cover can result from changes 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).

The participants of the IABP work together to maintain a network of drifting buoys in the Arctic Ocean to provide meteorological and oceanographic data for real-time operational requirements and research purposes including support to the World Climate Research Programme (WCRP) and the World Weather Watch (WWW) Programme.

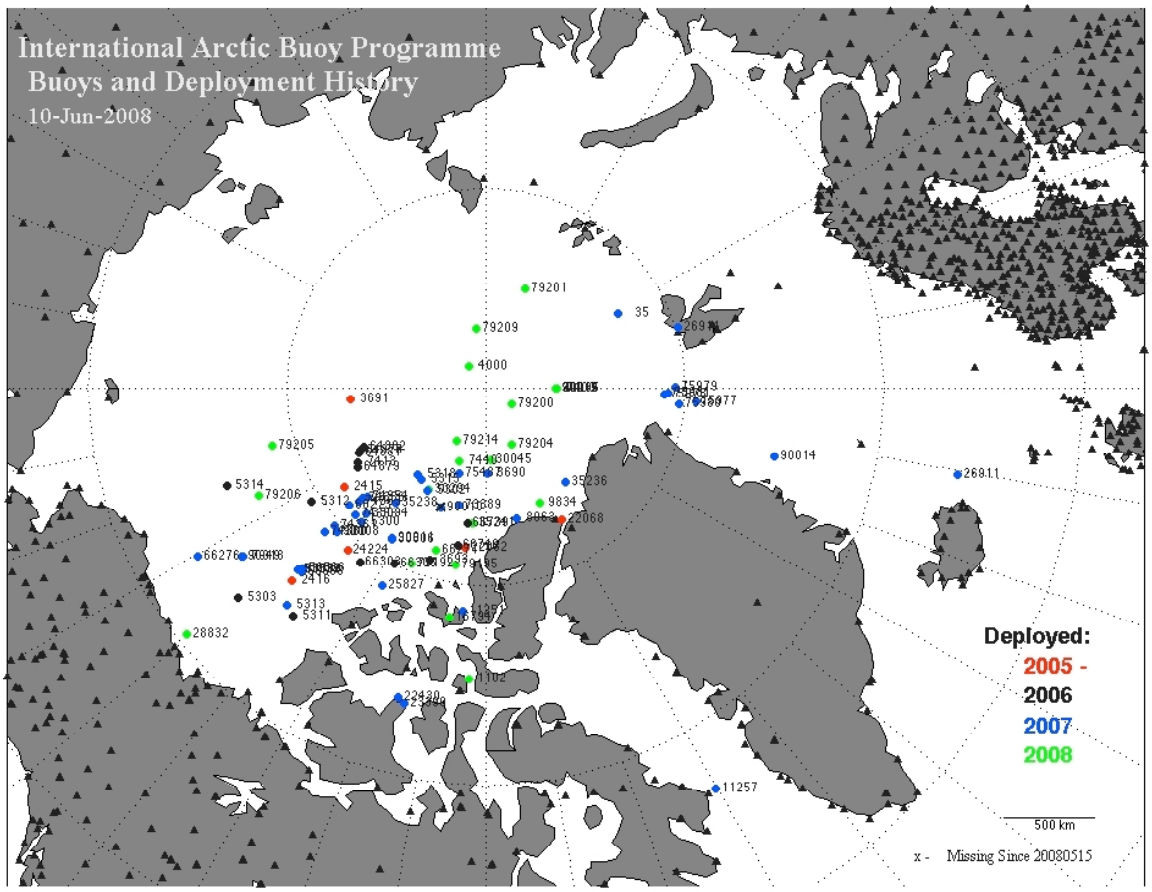
Data from the IABP have many uses. For example:
1. Research in Arctic climate and climate change,
2. Forecasting weather and ice conditions,
3. Validation of satellites,
4. Forcing, validation and assimilation into numerical climate models, and
5. Tracking the source and fate of samples taken from the ice.

Over 500 publications have benefited from observations from the IABP!

The U.S. contributions to the IABP are coordinated through the U.S. Interagency Buoy Program (USIABP), which is managed by the U.S. National/Naval Ice Center, and the Polar Science Center, and represent several U.S. agencies, including the International Arctic Research Center, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the National Science Foundation, the Naval Oceanographic Office, the Office of Naval Research, and the U.S. Coast Guard.



Location of the Arctic Ice buoys, June, 10, 2008.



Deployment Timeline of Arctic Sea Ice Buoys. Buoys deployed in 2007 are colored Blue.

Jackie Richter-Menge, ERDC-CRREL, funded by the Arctic Research Program, led an international team of research scientists as chief editor of the recently released 2007 Arctic Report Card. The peer-reviewed web site tracks multiple changes in the Arctic environment, providing a concise, scientifically credible, and accessible source of recent observations. The Report Card is organized by the National Oceanic and Atmospheric Administration (NOAA) and will be updated annually. Richter-Menge and Dr. Don Perovich (CRREL research geophysicist) also contributed to the following Sea Ice Cover section of the Report Card.

Sea Ice Cover

J. Richter-Menge[1], S. Nghiem[2], D. Perovich[1], I. Rigor[3]

1ERDC-Cold Regions Research and Engineering Laboratory, Hanover, NH
2Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
3Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, WA

Extent and Thickness

Satellite-based passive microwave images of the sea ice cover have provided a reliable tool for monitoring changes in the extent of the ice cover since 1979. During 2006 the minimum ice extent, typically observed in September, reached 5.9 million km2 (Figure I1, bottom left panel). This marked a slight recovery from the record minimum of 5.6 million km2 for the period 1979-2006, observed in 2005. Consistent with the past several years, the summer retreat of the ice cover was particularly pronounced along the Eurasian coastline. A unique feature was the sizeable isolated region of open water apparent in the Beaufort Sea.

The 2007 summer sea ice extent marked a new record minimum, with a dramatic reduction in area of coverage (4.3 million km2) relative to the previous record set just 2 years ago in 2005 (Figure I1, bottom right panel). At the end of the 2007 melt season, the sea ice cover was 23 percent smaller than it was in 2005 and 39 percent below the long-term average from 1979 to 2000.

The maximum ice extent is typically observed in March. In 2006, the maximum extent was 14.4 million km2 and set a record minimum for the ice-extent maximum for the period 1979-2006 (Figure I1, top left panel). It is notable that in March 2006 the ice extent fell within the mean contour at almost every location. In March 2007, the maximum ice extent was 14.7 million km2 (Figure I1, top right panel).

For comparison, the mean ice extent for March and September, for the period 1979-2007, is 15.6 million km2 and 6.7 million km2, respectively.

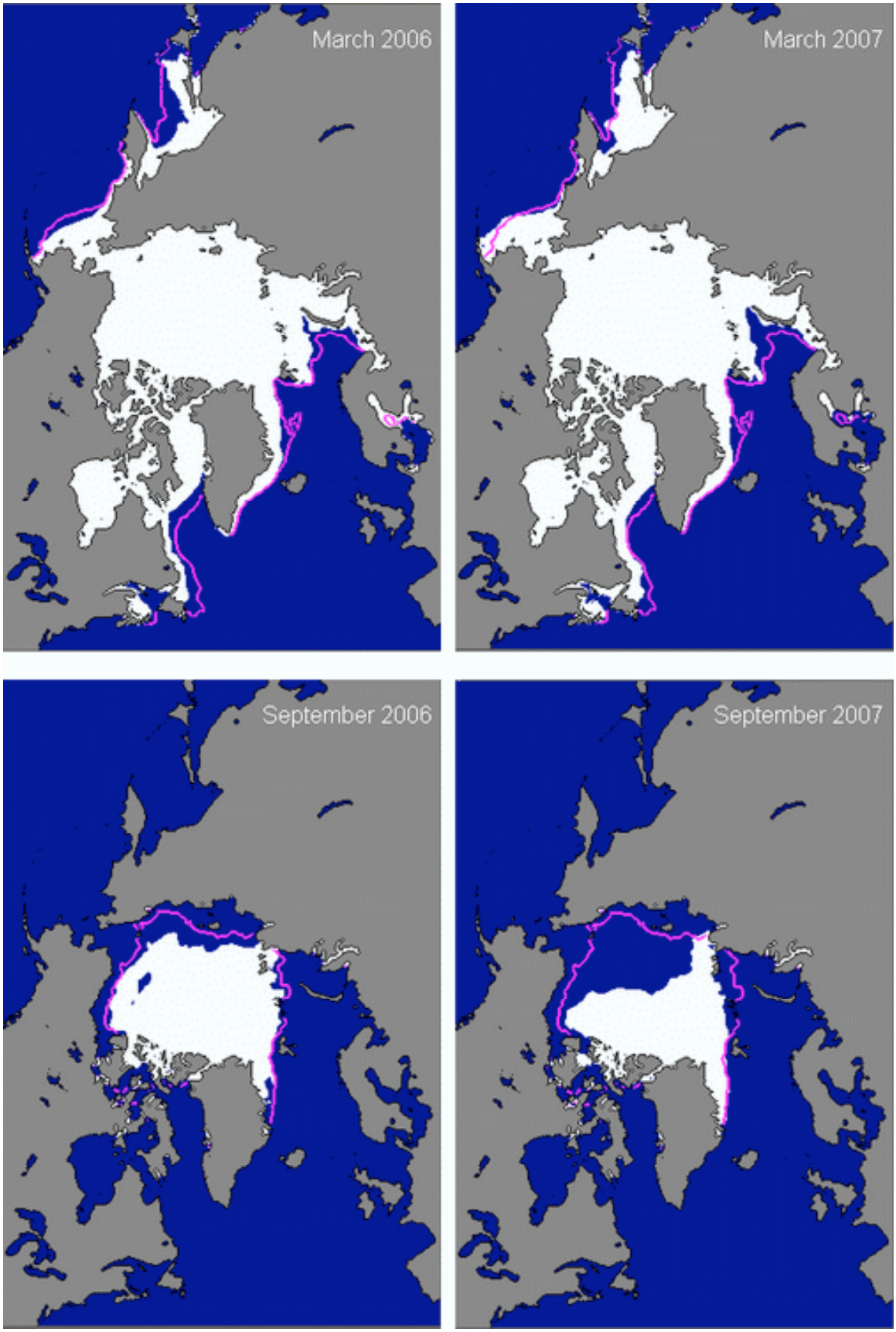

March 2006
March 2007
September 2006
September 2007

Figure I1. Sea ice extent in March and September 2006 and 2007, when the ice cover was at or near its maximum and minimum extent, respectively. The magenta line indicates the median maximum and minimum extent of the ice cover, for the period 1979-2000. The March 2006 maximum extent and the September 2007 minimum extent established new records as the lowest extents for the period 1979-2007. (Figures from the Sea Ice Index, nsidc.org/data/seaice_index)

To put the 2006 and 2007 minimum and maximum ice extent into context, the time series of the anomaly in ice extent in March and September for the period 1979-2007 is presented in Figure I2. In both cases, a negative trend is apparent with a rate of 2.8% per decade for March and 11.3% per decade for September relative to the 1979 values. The summers of 2002-2007 have marked an unprecedented series of extreme summer ice extent minima.

Ice thickness is intrinsically more difficult to monitor. With satellite-based techniques (Laxon et al., 2003; Kwok et al., 2004) only recently introduced, observations have been spatially and temporally limited. Data from submarine-based observations indicate that the ice cover at the end of the melt season thinned by an average of 1.3 m between the period 1956-1978 and the 1990s, from 3.1 m to 1.8 m (Rothrock et al., 1999). Measurements of the seasonal and coastal ice cover do not indicate any statistically significant change in thickness in recent decades (Melling et al., 2005; Haas, 2004; Polyakov et al., 2003).

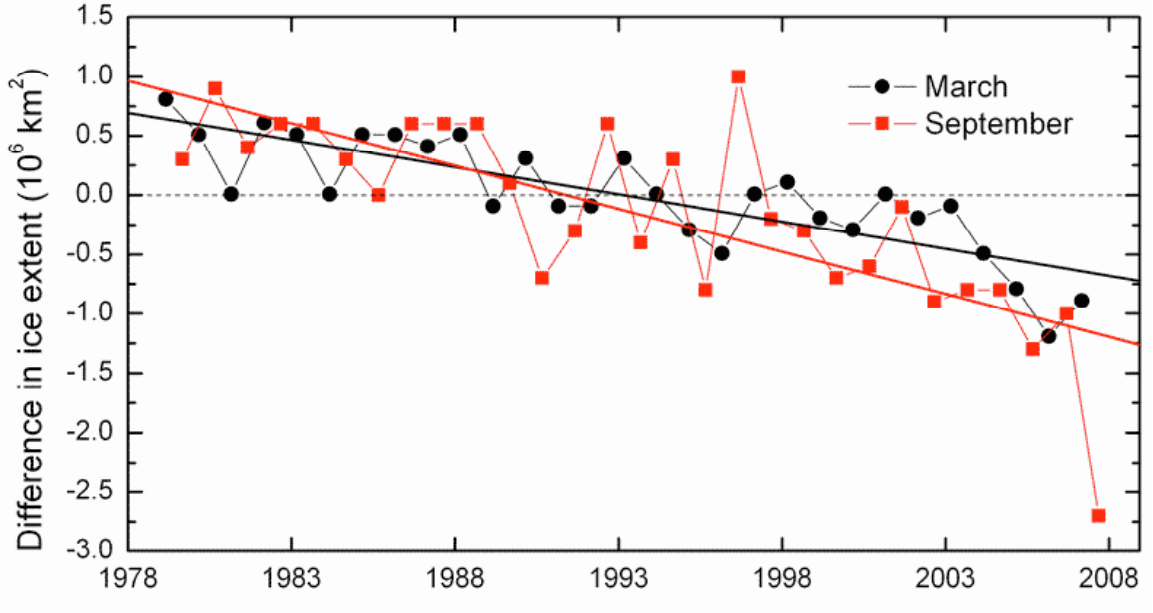


Figure I2. Time series of the difference in ice extent in March (the month of ice-extent maximum) and September (the month of ice-extent minimum) from the mean values for the time period 1979-2007. Based on a least squares linear regression, the rate of decrease for the March and September ice extents was 2.8% per decade and 11.3% per decade, respectively.

Perennial and Seasonal Ice

The Arctic sea ice cover is composed of perennial ice (the ice that survives year round, generally located towards the center of the Arctic basin) and seasonal ice (the ice around the periphery of the Arctic basin that melts during the summer). Consistent with the diminishing trends in the extent and thickness of the cover is the observation of a significant loss of the older, thicker perennial ice in the Arctic (Figure I3). Results from a simulation using drifting buoy data and satellite-derived ice concentration data to estimate the age distribution of ice in the Arctic Basin (Rigor and Wallace, 2004) indicate that the March ice cover has experienced a significant decline in the relative amount of perennial ice over the period 1958-2006, from approximately 5.5 million km2 to 3.0 million km2. While there is significant interannual variability, a generally downward trend in the amount of perennial ice begins in the early 1970s. This trend appears to coincide with a general increase in the Arctic-wide, annually averaged surface air temperature, which also begins around 1970 (Figure A2).

Results from a new technique employing data acquired by the U.S. National Aeronautics and Space Administration (NASA) SeaWinds scatterometer on board the QuikSCAT satellite (QSCAT) have recently become available (Nghiem et al. 2005; Nghiem et al.; 2006, Nghiem and Neumann, 2007). In the half decade of overlap with the buoy-derived results, which presently begins in 2002 and represents the period of data reprocessed to date by the QSCAT project, the two products provide consistent estimates of perennial ice in March and suggest a precipitous decrease in the perennial ice extent in the last few years.

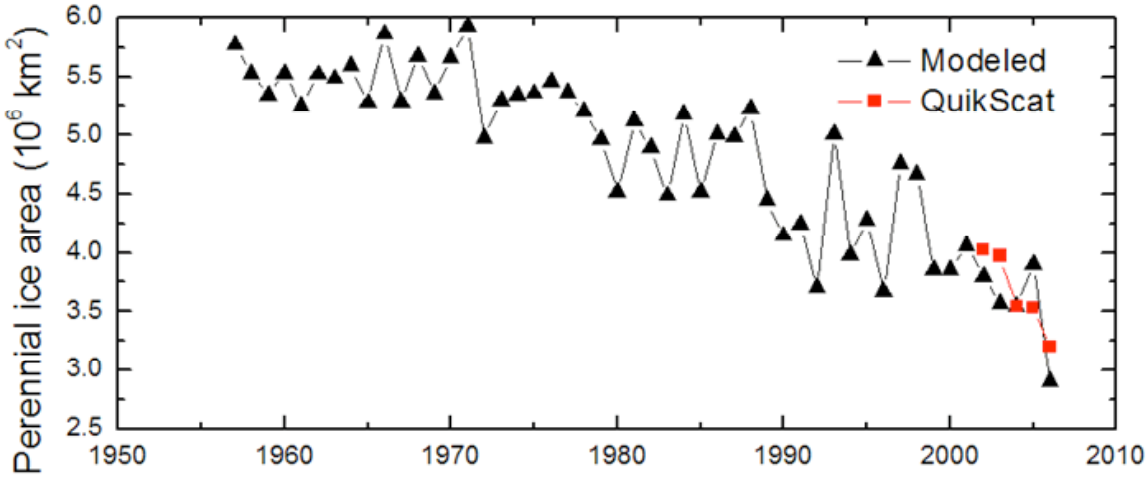


Figure I3. Time-series of the area of perennial sea ice extent in March estimated by a drift age model and satellite-derived ice concentration data and observed by the QuikSCAT scatterometer within the drift age model domain.

Figure I4 presents a comparison of the ice distribution derived from the drift age model and observed by QSCAT in March 2006. The two products provide similar results. Both indicate that the older, thicker ice is concentrated in the western Arctic basin. This result is consistent with the dominant ice circulation patterns in the Arctic (see Figure O1). Ice residence times are typically longer in the western Arctic in the region of the Beaufort Gyre. The eastern Arctic is dominated by the Trans Polar Drift, which carries sea ice out of the Arctic Basin via the Fram Strait.

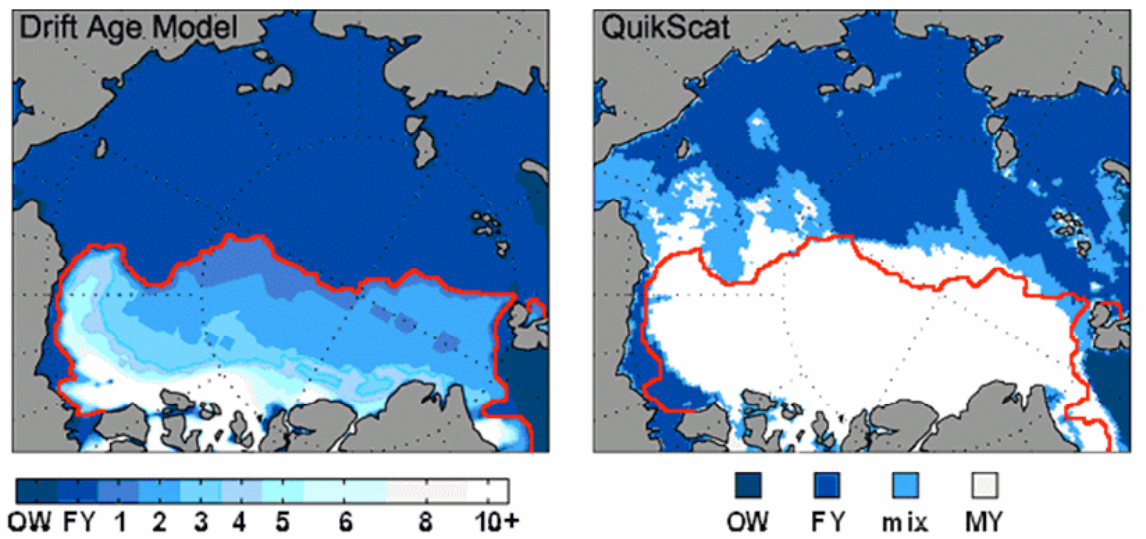


Figure I4. Comparison of sea ice distribution estimated using the drift-age model (March average, left panel) with QSCAT observations (21 March 2006, right panel). The red line in both panels indicates ice age older than 1 year (i.e. perennial ice) as estimated by the drift age model.

The development of a relatively younger, thinner ice cover coincided with a strong, persistent positive pattern in the AO from 1989 to 1995 (see Figure A1). These characteristics make the current ice cover intrinsically more susceptible to the effects of atmospheric and oceanic forcing. It is of crucial importance to observe whether the sea ice cover will continue its decline or recover under the recent more neutral AO conditions (Lindsay and Zhang, 2005).

References

Haas, C. (2004) Late-summer sea ice thickness variability in the Arctic Transpolar Drift 1991-2001 derived from ground-based electromagnetic sounding. Geophys. Res. Lett., 31, L09402, doi: 10.1029/2003GL019394.

Kwok, R., H.J. Zwally, and D. Yi (2004) ICESat observations of Arctic sea ice: A first look. Geophys. Res. Lett., 31, L16401, doi: 10.1029/2004GL020309.

Laxon, S., N. Peacock, and D. Smith (2003) High interannual variability of sea ice thickness in the Arctic Region. Nature, 425, 947-950.

Lindsay, R.W., and J. Zhang (2005) The Thinning of Arctic Sea Ice, 1988-2003: Have We Passed a Tipping Point? J. Climate, 18, 4879-4894.

Melling, H., D.A. Riedel, and Z. Gedalof (2005) Trends in the draft and extent of seasonal pack ice, Canadian Beaufort Sea. Geophys. Res. Lett., 32, L24501, doi:10.1029/2005GL024483.

Nghiem, S.V., M.L. Van Woert, and G. Neumann (2005) Rapid formation of a sea ice barrier east of Svalbard. J. Geophys. Res., 110, doi:10.1029/2004JC002654.

Nghiem, S.V., Y. Chao, G. Neumann, P. Li, D. K. Perovich, T. Street, and P. Clemente-Colon (2006) Depletion of perennial sea ice in the East Arctic Ocean. Geophys. Res. Lett., 33, L17501, doi:10.1029/2006GL027198.

Nghiem, S.V., and G. Neumann, Arctic Sea-Ice Monitoring (2007) 2007 McGraw-Hill Yearbook of Science and Technology, New York, in press.

Polyakov, I., G.V. Alekseev, R.V. Bekryaev, U. Bhatt, R. Colony, M.A. Johnson, V.P. Karklin, D. Walsh, and A.V. Yulin (2003) Long-term ice variability in arctic marginal seas. J. Climate, 16(12), 2078-2085.

Rothrock, D.A., Y. Yu, and G.A. Maykut (1999) Thinning of the Arctic sea-ice cover. GRL, 26, 3469-3472.

4. ***Arctic Change Detection***

Contact Person: - James E. Overland
james.e.overland@noaa.gov

The NOAA Arctic Research 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 Change Detection Activity had the following goals in 2007:

1) Maintain an up-to-date Arctic climate change detection activity for NOAA that includes improved understanding of Arctic climate variability, communication of Arctic change to policy and scientific forums, chairing committees, the Arctic Report card/State of the Arctic Report, and research publications.

2) Support and enhance NOAA's mission in climate variability and impacts in the Pacific sector of the Arctic. Use the North Bering and Chukchi data base to develop a paper that puts RUSALCA data in a historical context back to 1880.

NOAA has an important role in providing a scientifically credible perspective on Arctic climate research and ecosystem impacts, in addition to contributing to international planning and scientific advancement. the Arctic Change Detection projects support four of the strategies outlined to meet NOAA's Strategic Goal in Climate:

- Develop and contribute to state-of-the-science assessments of the climate system for informed decision-making
- Support educational efforts to create a more climate-literate public
- Improve the quantification and understanding of the forces bringing about climate change
- Develop the ability to predict the consequences of climate change on ecosystems

Overview:
A primary goal in 2007 was to evaluate and communicate the results of the IPCC Fourth Assessment Report (IPCC AR4) model hindcasts and projections for Arctic and sub-Arctic climate and ecosystem impacts. In addition the Arctic Change Detection Activity was engaged at the center of evaluating the causes for the record minimum sea ice extent in September 2007.

1. The Arctic Change Detection Effort carried out the following activities in 2007 aiimed at communicating Arctic Change and Impacts

- For IPCC, Overland led the AMAP and ESSAS task teams and contributed to the USARC AMSA Bering Strait Regional Case Study.
- Overland served on the NOAA Biological Response Team (BRT) for Ribbon seals' EIS (now all ice seals) and the US Marine Mammal Commission.
- The Change Detection team has given four invited keynote presentations, attended three workshops, plus prepared major AGU and Alaska Marine Science Symposium talks. These included the DAMOCLES meeting in Oslo, the Synthesis of Arctic System Science (SASS) Group at IBM, NY, and the NATO Arctic workshop in Belgium in May.
- Overland hosted the SCAR - CliC – IASC – ICPM Second Workshop on Recent High Latitude Climate Change on October 2007. An EOS article will be published in May 2008.
- Five journal papers have been written during this period.

2. Continued the *Arctic Reportcard*

The Reportcard is adopted as a product of the AMAP Climate Expert Group.

3. Research Areas

A. *IPCC model projection results for Arctic and subarctic seas*
The Arctic Change Detection Team has published a GRL paper on regional sea ice projections from IPCC models.

The team is currently working with Vladimir Kattsov and John Walsh on a grand synthesis for the Arctic to be completed during the summer of 2008.

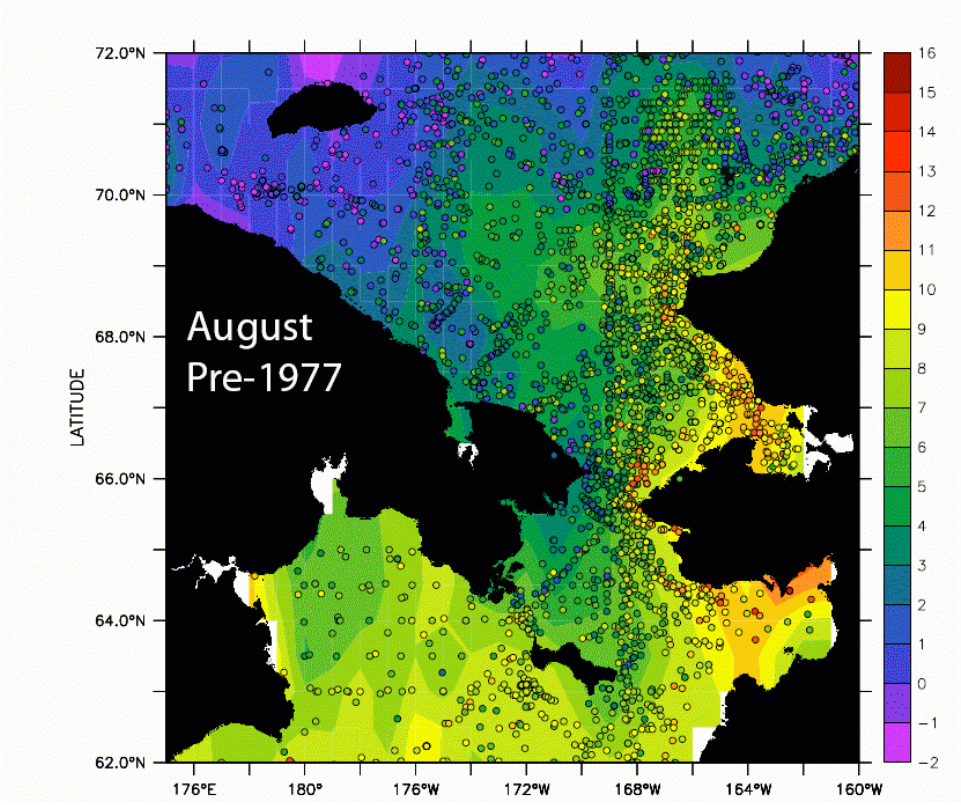
B. *Historical Arctic climate*
The Arctic Change Detection Team has a comprehensive *Journal of Climate* paper on the early 20th century warming in review, including a literature survey of what climate scientists thought about the changes that were occurring at the time and a new data synthesis. Work will continue with data from the 19th century. Overland contributed to a paper in press in *Journal of Climate* that evaluates Baltic Sea ice conditions back to 1500.

Northern Bering Sea

Overview:
The Arctic Change Detection Team has a goal is to bring together all oceanographic physical data for the northern Bering/southern Chukchi Seas and to make this data available and accessible through search software.

Historical Analysis of Bering Strait Oceanography. The team is completing a draft of a paper, which exercises the Northern Bering/Chukchi data base. It first looked at changes for all months at Nome for 1907-2006. No major shifts or decadal variability are seen before 1977. This fact was used to bin oceanographic data for two periods, before and after 1977 for three months, July, August and September. These composites provide a baseline for comparison to new RUSALCA data.

Ocean temperature data from the World Ocean Database (WOD05) were downloaded from the Ocean and Weather Data Navigator (http://dapper.pmel.noaa.gov/dchart/) for the region 175°E – 160°W, 62° – 72°N and compared with other sources. After editing the dataset consists of 18,698 oceanographic profiles. While the earliest profiles in the dataset were collected in 1855, the dataset includes only 32 profiles prior to 1925. The scattered profile data were transferred to a regular grid using objective mapping. Coherent spatial patterns lend confidence to our results. Below is the near surface ocean temperature field before 1977 for August and its spatial data distribution:



Website Development

Nancy Soreide and her web group will continue to provide updates, new material, and

web support for the NOAA Arctic Theme Page and Arctic Research Program. Timely updates are the key to information transfer, especially with recent fast moving Arctic change. The NOAA Arctic Theme Page is consistently one of the top Google results for keyword "arctic", and was visited by 91,053 unique hosts from 144 countries in March 2008. Support includes search engine optimization, website promotion, maintaining the Website in the PMEL Web Farm environment, adding and updating information and links, assuring that webmaster email is answered promptly, participating in IPY website planning activities, and posting or updating information as requested by the Arctic Research Program. We contact authors of Expert Essays (http://www.arctic.noaa.gov/essay.html) to ask for updates, install the updates that are provided, and seek new Expert Essays. In addition to these standard activities, a priority in 2008 is to update information on NOAA Arctic research activities.

Arctic Monitoring and Assessment Program and the Pacific Arctic Group

The Arctic Research Program is an active participant in several International organizations including Chairing the Arctic Monitoring and Assessment Program and the Pacific Arctic Group. AMAP is an international organization established in 1991 to implement components of the Arctic Environmental Protection Strategy (AEPS).

Now a programme group of the Arctic Council, AMAP's current objective is "providing reliable and sufficient information on the status of, and threats to, the Arctic environment, and providing scientific advice on actions to be taken in order to support Arctic governments in their efforts to take remedial and preventive actions relating to contaminants".

In 2007 AMAP released its Oil and Gas Assessment. This assessment of oil and gas activities in the Arctic was prepared in response to a request from the Ministers of the Arctic council. The Ministers called for engagement of all Arctic Council Working Groups in this process and requested that the arctic Monitoring and Assessment Programme take responsibility for coordinating the work. The objective of the 2007 "Assessment of Oil and Gas Activities in the Arctic' is to present an holistic assessment of the environmental, social and economic, and human health impacts of current oil and gas activities in the Arctic, and to evaluate the likely course of development of Arctic oil and gas activites and their potential impacts in the near future. The assessment updates information contained in the AMAP 1997/98 assessment reports, including several aspects not covered in the earlier assessments.

NOAA's contributions to the Pacific Arctic Group are also significant. Organized under the International Arctic Science Committee (IASC), the PAG has as its mission to serve as a Pacific Arctic regional partnership to plan, coordinate, and collaborate on science activities of mutual interest. PAG has ten principle science themes:

* Theme 1:Undertake seasonal and interannual ocean observations in the Pacific Arctic Sector where recent maximum sea ice retreat is occurring.
* Theme 2: Understanding oceanic and atmospheric processes in the Pacific Arctic, including the feedback loops, are critical to mid-latitude climate variability.

* Theme 3: Monitoring fresh water input via precipitation, riverine input, oceanic input, glacial and sea ice melt in the Pacific Arctic sector will improve our understanding of mid-latitude climate variability and provide additional information to support theme 1.

* Theme 4: Identify and monitor ecosystem and biological indicators (ice, water column, benthic, higher trophic organisms) of climate change in the Pacific Arctic.

* Theme 5: Investigate sea ice thermodynamics including sea ice thickness, extent, and its interactions with ocean and atmospheric forcing in the Pacific Arctic region. Investigate sea ice dynamics such as sea ice drift, interactions between different ice packs.

* Theme 6: Understanding the connectivity of warm Atlantic inflow to the Pacific sector, heat flux throughout Arctic, and associated biodiversity/invasion of Atlantic-species into the region. Physical gateways should be mapped and monitored, including outflow through the Canadian Arctic Archipelago.

* Theme 7: The Arctic Ocean is very poorly mapped from the seafloor to the ice above. Significant information gaps include the bathymetry, biodiversity, and knowledge of ocean currents and their variability over space and time. Exploration of the unknown Pacific Arctic region is essential for the construction of base maps necessary for the planning of future monitoring efforts.

* Theme 8: The Pacific water inflow through the Bering Strait region is a key conduit for heat, salt, nutrients, and biological material (including genetic material) to the Arctic basin that influences sea ice cover, halocline formation, and the carbon cycle.

* Theme 9: Nearshore coastal processes and subsea permafrost dynamics are important processes in the shallow Pacific shelf areas are subject to climate change impacts.

* Theme 10: The open and closing of the Pacific gateway has occurred over geological time periods with dramatic impact on the Arctic system. The paleorecord provides a long-term record for comparative evaluation of climatic processes relative to contemporary studies in prior themes. In 2007 PAG has initiated an effort to carry out a Pacific Arctic Group Regional Synthesis of Ocean Data and Information --A Contribution to the International Polar Year (IPY) Global Synthesis.

Partnerships

The Arctic Research Program is highly leveraged. All of the AON 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, COD, 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

Publications, Arctic Research Program, 2007-2008

Arctic Change Detection

2007

Eriksson, C., A. Omstedt, J.E. Overland, D.B. Percival, and H.O. Mofjeld (2007): Characterizing the European sub-Arctic winter climate since 1500 using ice, temperature, and atmospheric circulation time series. J. Climate, 20(21), 5316–5334.

Liu, Y., J.R. Key, J.A. Francis and X. Wang. 2007. Possible causes of the decreasing cloud cover in the Arctic winter: 1982-2000, Geophysical Research Letters, 34, L14705, doi:10.1029/2007GL030042

Overland, J.E., J.E. Walsh, and M. Wang (2007): Why are ice and snow changing? Chapter 3 in Global Outlook for Ice and Snow, United Nations Environment Programme (UNEP), Division of Early Warning and Assessment (DEWA), 29–38.

Overland, J.E., and M. Wang (2007): Future regional Arctic Sea ice declines. Geophys. Res. Lett., 34(17), L17705, doi: 10.1029/2007GL030808.

Richter-Menge, J., J. Overland, A. Proshutinsky, V. Romanovsky, R. Armstrong, J. Morison, S. Nghiem, N. Oberman, D. Perovich, I. Rigor, L. Bengtsson, R. Przybylak, A. Shiklomanov, D. Walker, and J. Walsh (2007): 5. The Poles; a. Arctic — in *State of the*

Climate in 2006, A. Arguez (ed.). Bull. Am. Meteorol. Soc., 88 (suppl.)(6), S62–S71.

Trites, A.W., A.J. Miller, H.D.G. Maschner, M.A. Alexander, S.J. Bograd, J.A. Calder, A. Capotondi, K.O. Coyle, E. Di Lorenzo, B.P. Finney, E.J. Gregr, C.E. Grosch, S.R. Hare, G.L. Hunt, J. Jahncke, N.B. Kachel, H.-J. Kim, C. Ladd, N.J. Mantua, C. Marzban, W. Maslowski, R. Mendelssohn, D.J. Neilson, S.R. Okkonen, J.E. Overland, K.L. Reedy-Maschner, T.C. Royer, F.B. Schwing, J.X.L. Wang and A.J. Winship. 2007. Bottom-up forcing and the decline of Steller sea lions (Eumetopias jubatus) in Alaska: Assessing the ocean climate hypothesis. Fisheries Oceanography, 16(1):46–67.

Wang, M., N.A. Bond, and J.E. Overland (2007): Comparison of atmospheric forcing in four sub-arctic seas. Deep-Sea Res. II, 54(23–26), 2543-2559.

Wang, M., J.E. Overland, V. Kattsov, J.E. Walsh, X. Zhang, and T. Pavlova (2007): Intrinsic versus forced variation in coupled climate model simulations over the Arctic during the Twentieth Century. J. Climate, 20(6), 1093–1107.

2008

Overland, J.E., and M.C. Serreze (2008): Advances in arctic atmospheric research. Chapter 2 in Arctic Climate Change—The ACSYS Decade and Beyond. [In preparation]

Bond, N.A., J.E. Overland, and S.A. Salo (2008): Influence of the regional atmospheric circulation on the observed shortwave radiation at the North Pole. J. Geophys. Res. [Submitted]

Overland, J.E. (2008): The case for global warming in the Arctic. In 40th Liege Colloquium, Ocean Dynamics and Advanced Research Workshop on Oceanography of the Rapidly Changing Arctic and Sub-Arctic. [Submitted]

Overland, J.E. (2008): Meteorology of the Beaufort Sea, J. Geophys. Res. [In review]

Wood, K. R. and J. E. Overland (2008): Early 20th century Arctic warming in retrospect. Inter. J. Climatology [In review]

Overland, J.E., M. Wang, and S. Salo (2008): The recent Arctic warm period. Tellus. [In press]

Overland, J., J. Turner, J. Francis, N. Gillett, G. Marshall, and M. Tjernstrom (2008): The Arctic and Antarctic: Two faces of climate change. Eos Trans. AGU, 89(19), 177–178.

Arctic Climate Observatories

Peer-Reviewed 2007_

Verlinde, J., J.Y. Harrington, G.M. McFarquhar, V.T. Yannuzzi, A. Avramov, S. Greenberg, N. Johnson, G. Zhang, M.R. Poellot, J.H. Mather, D.D. Turner, E.W.

Eloranta, B.D. Zak, A.J. Prenni, J.S. Daniel, G.L.Kok, D.C. Tobin, R. Holz, K. Sassen, D. Spangenberg, P. Minnis, T.P.Tooman, M.D. Ivey, S.J. Richardson, C.P. Bahrmann, M. Shupe, P.J.Demott, A.J. Heymsfield, and R. Schofield, 2007: The Mixed-Phase Arctic Cloud Experiment (M-PACE). /Bull. Amer. Met. Soc./, 88, 205-220.

Schofield, R., J. S. Daniel, R. W. Portmann, H. L. Miller, S. Solomon, C. S. Eubank, M. L. Melamed, A. O. Langford, M. D. Shupe, and D. D. Turner, 2007: Retrieval of effective radius and liquid water path from ground-based instruments: A case study at Barrow, Alaska. /J. Geophys. Res., 112, /D21203, doi:10.1029/2007JD008737/./

Shupe, M.D., 2007: A ground-based multiple remote-sensor cloud phase classifier./ Geophys. Res. Lett./, 34, L22809, doi:10.1029/2007GL031008.

Cohen L., Helmig, D., Neff, W, Grachev, A., and Fairall, C. 2007: Boundary-Layer Dynamics and its Influence on Atmospheric Chemistry at Summit, Greenland. Atmospheric Environment. 41(24), 5044 - 5060.

Grachev, A. A., Andreas, E. L, Fairall, C. W., Guest, P. S., and Persson, P. O. G.: 2007a, 'SHEBA Flux-Profile Relationships in the Stable Atmospheric Boundary Layer', Boundary-Layer Meteorology. 124(3), 315 - 333.

Grachev, A. A., Andreas, E. L, Fairall, C. W., Guest, P. S., and Persson, P. O. G.: 2007b, 'On the Turbulent Prandtl Number in the Stable Atmospheric Boundary Layer', Boundary-Layer Meteorology. 125(2), 329 - 341.

Esau, I. N. and A. A. Grachev: 2007, 'Turbulent Prandtl Number in Stable Stratified Atmospheric Boundary Layer: Intercomparison between LES and SHEBA Data', e-WindEng, 2007 (006). pp. 01-17. ISSN 1901-9181.(http://ejournal.windeng.net/).

Conferences:

Shupe, M., P. Kollias, G. McFarquhar, M. Poellot, and E. Eloranta, 2007: Vertical motions in Arctic mixed-phase stratus. /Proc. 9th Conf. on Polar Met. and Ocean./, AMS, St. Johns, Newfoundland, May 28 – June 1.

Shupe, M., T. Uttal, D. Wolfe, and D. Welsh, 2007: Cloud occurrence at Arctic atmospheric observatories. /Proc. 9th Conf. on Polar Met. and Ocean./, AMS, St. Johns, Newfoundland, May 28 – June 1.

Eloranta, E., T. Uttal, M. Shupe, and V. Walden, 2007: The measurements of particle size in Arctic clouds using high spectral resolution lidar and millimeter wavelength radar data. /Proc. 9th Conf. on Polar Met. and Ocean./, AMS, St. Johns, Newfoundland, May 28 – June 1.

Solomon, A., O. Persson, M. Shupe, H. Morrison, and J.-W. Bao, 2007: Mesoscale simulations of polar clouds during M-PACE. /Proc. 9th Conf.on Polar Met. and Ocean./, AMS, St. Johns, Newfoundland, May 28 – June 1.

Uttal, T., M. Shupe, V. Walden, E. Eloranta, O. Persson, and D. Hazen, 2007: Radar, radiometers, interferometers and lidar in Eureka, Canada for cloud and aerosol studies. /Proc. 9th Conf. on Polar Met. and Ocean./, AMS, St. Johns, Newfoundland, May 28 – June 1.

Kollias, P., E. Luke, and M. Shupe, 2007: Cloud phase identification using radar Doppler spectra. /Proc. 9th Conf. on Polar Met. and Ocean./, AMS, St. Johns, Newfoundland, May 28 – June 1.

Eloranta, E. W., T. Uttal, and M. Shupe, 2007: Cloud particle size measurements in Arctic clouds using lidar and radar data. /International Geoscience and Remote Sensing Symposium/, IEEE, Barcelona.

Eloranta, E. W., T. Uttal, and M. Shupe, 2007: A 2-year climatology of Arctic clouds for Eureka Canada prepared from High Spectral Resolution Lidar data. /American Geophysical Union/, San Francisco, CA.

Persson, O. and R. Stone, 2007: Evidence of Forcing of Arctic Regional Climate by Mesoscale Processes. / AMS/ Jan. 15-16, 2007, San Antonio, TX.

Grachev, A., E. Andreas, C. Fairall, P. Guest, O. Persson: 2007, 'Influence of stability on the turbulent Prandtl number in the stable atmospheric boundary layer' (EGU2007-A-04471), EGU General Assembly 2007, Vienna, Austria, 15 – 20 April 2007, Session: AS2.04 Boundary Layers in High Latitudes: Observations and Modeling.

Fairall, C. and A. Grachev: 2007, 'An Analysis of Turbulent and Radiative Flux Gradient Relationships in the Highly Stable Polar Surface Layer' (EGU2007-A-04662), EGU General Assembly 2007, Vienna, Austria, 15– 20 April 2007, Session: AS2.04 Boundary Layers in High Latitudes:Observations and Modeling.

Neff, W., D. Helmig, A. Grachev, D. Davis: 2007, 'An overview of the effect of boundary layer processes on surface [NO] concentrations during ANTCI 2003' (EGU2007-A-09238), EGU General Assembly 2007, Vienna, Austria, 15 – 20 April 2007, Session: CR70 Snow dynamics and snow-atmosphere exchange over Greenland and Antarctica.

Uttal T. 2007 Tiksi Hydrometeorological Observatory Planning and Implementation Update May, 2007, ESRL, NOAA -Roshydromet Workshop Report http://tf.tribes.cc/telfort/px/url/287/www.esrl.noaa.gov/psd/psd3/arctic/meetings/tiksi/

Accepted in 2007 but published in 2008

Matrosov, S. Y., M. D. Shupe, and I. V. Djalalova, 2008: Snowfall retrievals using millimeter-wavelength cloud radars. /J. Appl. Meteor. Clim./, 47, 769-777.

Shupe, M.D., P. Kollias, M. Poellot, and E. Eloranta, 2008: On deriving vertical air motions from cloud radar Doppler spectra./ J. Atmos. Ocean. Technol./, 25, 547-557.

Shupe, M. D., P. Kollias, P.O.G. Persson, and G. M. McFarquhar, 2008: Vertical motions in Arctic mixed-phase stratiform clouds. /J. Atmos. Sci./, 65, 1304-1322.

Tjernstrom, M., J. Sedlar, and M. D. Shupe, 2008: How well do regional climate models reproduce radiation and clouds in the Arctic? An evaluation of ARCMIP simulations. /J. Appl. Met. Clim/., accepted.

Arctic Observing Network

Arctic Observing Network: Toward a U.S. Contribution to Pan-Arctic Observing, 2007, Arctic Research of the U.S. v. 21 pp 1-94. Managing Editorial Committee: M. Jeffries, F. Korsmo, J. Calder and K. Crane

Crane, K., and J. Grebmeier, 2007, Monitoring the Arctic Ocean North of the Pacific Ocean, *EOS*, Vol. 88, No. 39, P. 384

First IPY Workshop on Sustaining Arctic Observing Networks: Workshop Report, 2007, Arctic Council and IPY, Stockholm 12-14, November 2007pp.1-34

Arctic Reanalysis

Bromwich, D.H., R.L. Fogt, K.I. Hodges and J.E. Walsh. 2007. A tropospheric assessment of the ERA-40, NCEP, and JRA-25 global reanalyses in the polar regions. Journal of Geophysical Research, 112(D10):D10111, doi:10.1029/2006JD007859

Fan, X., J.E. Walsh and J.R. Krieger. 2007. A one-year experimental Arctic reanalysis and comparisons with ERA-40 and NCEP/NCAR reanalyses. Proceedings of the 7th International Conference on Global Climate: Connections to Arctic (GCCA-7), Fairbanks, Alaska, 19–20 February 2007, pp. 37–40.

Hines, K.M., D.H. Bromwich and L.-S. Bai. 2007. Polar-optimized WRF. Preprints, 8th Annual WRF User's Workshop, Boulder, Colorado.

RUSALCA *Benthic Ecosystems Biodiversity and Change Observations*

Iken K, Bluhm BA, Dunton K. Benthic food web structure serves as indicator of water mass properties in the southern Chukchi Sea. Deep Sea Research II, special issue, in prep in 2007, submitted Mar 2008

Presentations
Iken K, Grebmeier JM, Norcross BL, Sirenko BI, Bluhm BA, Cooper LW, Dunton K, Gagaev S, Holladay B. Benthic studies in the Chukchi Sea: The contribution by the Russian-American Long-Term Census of the Arctic (RUSALCA) program. Arctic Frontiers Conference, Tromsø, Norway, Jan 21-26, 2007 (talk)

Gradinger R, Bluhm BA, Hopcroft RR. Arctic Ocean Diversity Census of Marine Life project and IPY. 1st Arctic Marine Biodiversity IPY Cluster Meeting, Frankfurt, Germany, Feb 2007 (talk)

Reports:
Hopcroft R, Bluhm B, Gradinger R, Whitledge T, Weingartner T, Norcross B, Springer A. Arctic Ocean synthesis: analysis of climate change impacts in the Chukchi and Beaufort Seas with strategies for future research. First submitted to the North Pacific Research Board (funding agency for this report) in 2006, revised version in progress in 2007

RUSALCA *Benthic-Water Column Fluxes*

Grebmeier, J.M. and J.P. Barry (2007). Benthic processes in polynyas, pp. 363-390. In: W.O. Smith, Jr. and D.G. Barber (eds), Polynyas: Windows to the World, Elsevier Oceanography Series, Volume 74.

Lalande, C., K. Lepore, L.W. Cooper, J.M. Grebmeier, and S.B. Moran (2007), Export fluxes of particulate organic carbon in the Chukchi Sea: A comparative study using 234Th/238U disequilibria and drifting sediment traps. Marine Chemistry, 103: 185-196.

Lalande, C., Grebmeier, J.M., Wassmann, P., Cooper, L.W., Flint, M.V., Sergeeva, V.M. (2007). Export fluxes of biogenic matter in the presence and absence of seasonal sea ice cover in the Chukchi Sea. Continental Shelf Research, 27:2051-2065.

Coakley, B., H.N. Edmonds, K. Frey, J.-C. Gascard, J.M. Grebmeier, H., Kassens, J. Thiede, and C. Wegner (2007). Past, present and future, A science program for the Arctic Ocean linking ancient and contemporary observations of change through modeling. EOS 88 (28), 287.

Crane, K., and J.M. Grebmeier (2007). Monitoring the Arctic Ocean North of the Pacific Ocean, Pacific Arctic Group Meeting, Shanghai, China, October 11-12, 2006, Eos, Vol. 88 (39), 384.

Lepore, K., S.B. Moran, J.M. Grebmeier, L.W. Cooper, C. Lalande, W. Maslowski, V. Hill, N.R. Bates, D.A. Hansell, J.T. Mathis, R.P. Kelly (2007), Seasonal and Interannual Changes in particulate organic carbon export and deposition in the Chukchi Sea, Journal of Geophysical Research, Vol. 112, C10024, doi:1029/2006JC003555.

Cooper, L.W., C. Lalande, R.P. Levy, I.L. Larsen, and J.M. Grebmeier (2008), Sedimentation and water column indicators of organic carbon processing in the Bering Strait shelf region: evidence for seasonal and decadal shifts, 2nd SBI Special Issue, Deep-Sea Research II (in press).

Grebmeier, J.M., and L.W. Cooper, Sediment Biogeochemical Tracers and Carbon Cycling in the Bering and Chukchi Seas during 1988 and 1993 (2008), In: Results of the Fourth Joint US-Russia Bering & Chukchi Seas Expedition (BERPAC), Summer 1993. U.S. Fish and Wildlife Service, Washington, DC. (in press).

Pirtle-Levy, R., J.M. Grebmeier, L.W. Cooper, and I.L Larsen (2008) Seasonal variation of chlorophyll a in Arctic sediments implies long persistence of plant pigments, 2nd SBI Special Issue, Deep-Sea Research II (in press).

Sukhanova, I.N., M.V. Flint, L.A. Pautova, D. A. Stockwell, J.M. Grebmeier, and V. M. Sergeeva (2008), Phytoplankton of the Western Arctic in the Vegetation Season of 2002: Structure and Seasonal Changes, 2nd SBI Special Issue, Deep-Sea Research II (in press).

RUSALCA *Bering Strait Fluxes*

Woodgate, R.A., K.Aagaard, J.H.Swift, W.M.Smethie and K.K.Falkner, 2007, Atlantic Water Circulation over the Mendeleev Ridge and Chukchi Borderland from Thermohaline Intrusions and Water Mass Properties, Journal of Geophysical Research, 112, C02005, doi:10.1029/2005JC003416.
http://psc.apl.washington.edu/HLD/CBL/Atlanticwaterzigzagpaper.html

Woodgate, R., K.Aagaard, J.Swift, B.Smethie and K.Falkner, Temperature-salinity Zigzags:Tracing Atlantic Water through the Arctic using Double-Diffusive Intrusions, 2007, Poster at Gordon Conference.

Woodgate, R.A., K.Aagaard and T.Weingarter, 2007, First steps in calibrating the Bering Strait Throughflow, APL internal report, 20pp,
http://psc.apl..washington.edu/BeringStrait.html

White, D., L. Hinzman, L. Alessa, J. Cassano, M. Chambers, K. Falkner, J. Francis, B. Gutowski, M. Holland, M. Holmes, H. Huntington, D. Kane, A. Kliskey, C. Lee, J. McClelland, B.Peterson, F. Straneo, M. Steele, R. Woodgate, D. Yang, K. Yoshikawa, T. Zhang, 2007, The Arctic Freshwater System: changes and impacts, Journal of Geophysical Research, 112, G04S54, doi:10.1029/2006JG000353..

Nechaev, D., G. Panteleev, R.Woodgate, 2007,Variational reconstruction of the Chukchi Sea circulation in October-December 1990. abstract for AGU Dec 2007.

Gieger B., "Our Changing Climate – The Poles",2008, outreach book from Sally Ride Science, includes feature on Woodgate and polar research.

Woodgate, R.A., 2008, Mooring cruise report for RUSALCA Sever to the Bering Strait, August/Sept 2007, http://psc.apl.washington.edu/BeringStrait.html

Melling, H., K.K.Falkner, R.A.Woodgate, S.Prinsenberg, A.Muenchow, D.Greenberg, T.Agnew, R.Samelson, C.Lee, B.Petrie, Freshwater Fluxes via Pacific and Arctic Outflows across the Canadian Polar Shelf, 2008, ASOF (Arctic Subarctic Ocean Fluxes) special volume, Springer-Verlag.

Dmitrenko, I. A., S. A. Kirillov, V.V. Ivanov, and R. A. Woodgate, 2008, Mesoscale Atlantic Water Eddy off the Laptev Sea continental slope carries the signature of upstream interaction, J. Geophys. Res., doi: 10.1029/ 2007JC00449, in press.

Woodgate, R.A., The Ocean's role in the 2007 Arctic Sea-ice Minimum, invited talk at NY Sea-ice retreat workship, Palisades, New York, April 2008

Mizobata, K., K.Shimada, R.Woodgate, S-I. Saitoh and J. Wang, submitted 2008, Estimation of heat flux through the eastern Bering Strait, Journal of Oceanography.

RUSALCA *Biogeochemistry*

Lein, A. Yu., A.S. Savvichev, I.I. Rusanov, G.A. Pavlova, N.A. Belyaev, K. Crane, N.V. Pimenov and M.V. Ivanov, 2007, Biogeochemical Processes in the Chukchi Sea, *Lithology and Mineral Resources*, Vol. 42, No. 3. pp. 221-239

Savvichev, A.S., I.I. Rusanov, N.V. Pimenov, E.E. Zakharova, E.F. Veslopolova, A. Yu. Lein, K. Crane and M.V. Ivanov, 2007, Microbial Processes of the Carbon and Sulfur Cycles in the Chukchi Sea*, Microbiology*, vol. 76, No. 5, pp. 603-613

Savvichev A.S., I.I. Rusanov, Pimenov, N.V., Lein A. Yu, Ivanov, M.V., 2006 Biogeochemical Assessment of Water Column and Bottom Sediments of the Chukchi Sea, Modern Ecological Problems of the North. Proceedings of the International Conference 10-12 October, Apatity, 2004, p. 105-107

RUSALCA *Fish Biodiversity and Change Observations*

Busby, M. S. and R. L. Cartwright. Paraliparis adustus and Paraliparis bullacephalus (Teleostei: Liparidae): Two new snailfishes from Alaska(Ichthyological Research) submitted.

Mecklenburg, C.W., D.L. Stein, B.A. Sheiko, N. V. Chernova, T. A. Mecklenburg, and B.A. Holladay, 2007, Russian-American Long-Term Census of the Arctic: Benthis Fishes Trawled in the Chukchi Sea and Bering Strait, August 2004, Northwestsern Naturalist, v. 88 pp. 168-187

Norcross, B. L. , Holladay, B. A., Busby, M. S., and K. L. Mier. Frontal structure in the Chukchi Sea determines small demersal and larval fish communities (Deep Sea Research II) submitted

Norcross, B.L, B.A. Holladay, and C.W. Mecklenburg. 2008. Current and historic distribution and ecology of demersal fishes in the Chukchi Sea Planning Area. CMI Annual Review, Fairbanks, AK, February 2008.

Norcross, B.L., B.A. Holladay, M. Busby and K. Mier. Oceanography,Ichthyoplankton, and Bottom Fishes of Bering Strait and Chukchi Sea. Gilbert Ichthyological Society, Newport, OR, September 2006.

Norcross, B.L., B.A. Holladay, M. Busby and K. Mier. Oceanography, Ichthyoplankton, and Bottom Fishes of Bering Strait and Chukchi Sea., American Fisheries Society, Early Life History Section, Larval Fish Conference, Lake Placid, NY, September 2006.

RUSALCA, ***Marine Geology-Baseline Observation***

Astakhov, A.S., R. Wang, M.V. Ivanov and K. Crane, The Sediment Geochemistry of the Chukchi Sea and Adjacent Arctic Basin: Multivariate Statistical Analysis, Chemical Partitioning. Signs of Recent Geodynamic Activity, Marine Geology, submitted

Glasby, G.P., G.A. Cherkashov, G.M. Gavrilenko, v.A. Rashidov, and I.B. Slovtsov, 2006, Submarine hydrothermal activity and mineralization on the Kurile and western Aleutian island arcs, N.W. Pacific Marine Geology, v. 231 pp 163-180

RUSALCA Water Column Zooplankton Biodiversity and Change Observations

Berline L., Spitz Y.H., Ashjian C.J., Campbell R.G., Maslowski W., Moore S.E. Euphausiid transport in the Western Arctic Ocean. Marine Ecology Progress Series 360: 163-178..

Campbell, R.G., Sherr, E.B., Ashjian, C.J., Plourde, S. Sherr, B.F., Hill, V., Stockwell, D.A. Mesozooplankton prey preference and grazing impact in the Western Arctic Ocean. In Press, Deep-Sea Research II.

Kosobokova, K.N., H.-J. Hirche & R.R. Hopcroft. 2007. Egg production of deep-water copepods in the Arctic Ocean. Mar. Biol. 151:919-934.

Moore, S.E., George, J.C., Sheffield, G., Bacon, J., Ashjian, C.J., SNACS Team. Bowhead whale distribution and feeding in the western Alaskan Beafuort Sea during late summer, 2005-2006. Submitted to Arctic.

Okkonen, S.R., Ashjian, C.J., Campbell, R.G., Potter, R. Intrusion of warm Bering/Chukchi waters onto the shelf in the western Beaufort Sea. In Revision, J. Geophys. Res.

Beckendorf, K., Ashjian, C., Moore, S., Braund, S. 2008. In search of whale food. Science Scope 31: 42-47.

NABOS/CABOS

Principal Investigator/s:
Igor Polyakov, International Arctic Research Center, Fairbanks, AK, USA

Published:

Ivanov, V., and P. Golovin, Observations and modeling of dense water cascading from the north-western Laptev Sea shelf, *J. Geophys. Res*., 112, C09003, doi:10.1029/2006JC003882, 2007.

Dmitrenko, I. A., I. V. Polyakov, S. A. Kirillov, L. A. Timokhov, I. E. Frolov, V. T. Sokolov, H. L. Simmons, V. V. Ivanov, and D. Walsh (2008), Toward a warmer Arctic Ocean: Spreading of the early 21st century Atlantic Water warm anomaly along the Eurasian Basin margins, *J. Geophys. Res., 113*, C05023, doi:10.1029/2007JC004158, 2008 .

Polyakov, I. V. , V. Alexeev, G. I. Belchansky, I. A. Dmitrenko, V. Ivanov, S. Kirillov, A. Korablev, M. Steele, L. A. Timokhov, I. Yashayaev, Arctic Ocean freshwater changes over the past 100 years and their causes, *J. Climate,21(*2), 364–384, 2008.

Walsh, D., I. Polyakov, L. Timokhov, and E. Carmack, Thermohaline structure and variability in the eastern Nansen Basin as seen from historical data, *J. Marine Research*, *65*, 685–714, 2007.

Polyakov, I. V. and Co-Authors, Observational program tracks Arctic Ocean transition to a warmer state, *Eos, Transactions, American Geophysical Union, Vol. 88*, 398-399, 2007.

In press:

Ivanov, V., and Co-authors, Seasonal variability of properties in the boundary current north of Svalbard, *Deep-Sea Research*.

Submitted:

Bauch, D., Wegner, C., Hölemann, J., Kirillov, S., Dmitrenko, I., Pivovarov, S., Timokhov, L., Kassens, H., Seasonal succession and inter-annual variability of the Laptev Sea hydrology and exchange with Arctic Halocline waters based on 1993 to 2003 expedition data. *J. Geophys. Res*.

Dmitrenko, I., S. Kirillov, and B. Tremblay, The long-term and interannual variability of summer fresh water storage over the eastern Siberian shelf: Implication for climatic change, *J. Geophys. Res*.

Polyakov, I. and Co-authors, North Atlantic warming: Fingerprints of global warming and long-term variability, *Climate Dynamics.*

Simmons, H. L. The geography of subharmonic instability of the semi-diurnal internal tide, *J. Phys. Oceanogr*.

Polyakov, I. V., U. S. Bhatt, and V. A. Alexeev, Suppressed polar amplification of long-term variations in recent decades: Fingerprint of climate change? *Geophys. Res. Lett.*

NABOS Technical Report # 5.

Siberian Shelf Studies (Methane and Carbon Fluxes)

Shakhova, N., and I.Semiletov, 2007. Methane release and coastal environment in the East-Siberian Shelf. Journal of Marine Systems, 66, 227-243.

Semiletov, I., I.I. Pipko, I.A. Repina, Shakhova N., 2007. Carbonate dynamics and carbon dioxide fluxes across the atmosphere-ice-water interfaces in the Arctic Ocean Pacific sector of the Arctic, Journal of Marine Systems, 66, 204-226.

Shakhova, N., I. Semiletov, A. Salyuk, N. Belcheva, and D. Kosmach, 2007a, Anomalies of methane in air above the sea surface in the East-Siberian Arctic shelf, Transactions of Russian Academy of Sciences, 414 (6), (translated in English by Springer).

Shakhova, N., I. Semiletov, and N. Belcheva, 2007b, The Great Siberian Rivers as a source of methane on the Russian Arctic shelf, Transactions of Russian Academy of Sciences, 414 (5), (translated in English by Springer).

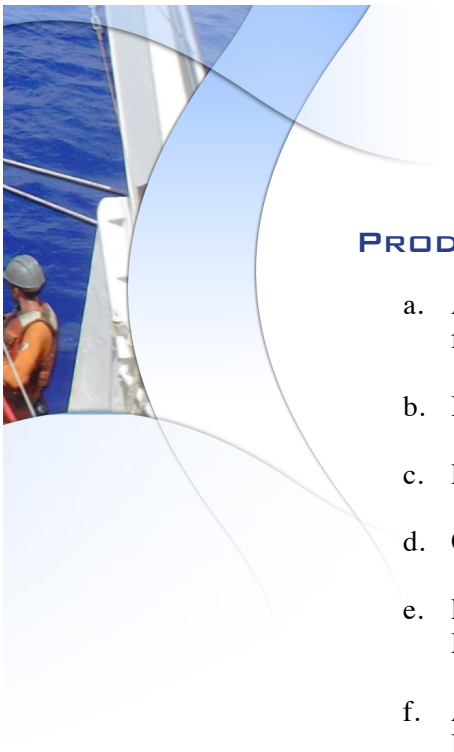
Repina, I.A., I. Semiletov, A.S. Smirnov (2007), Direct measurement of CO2 fluxes in the Laptev Sea in summer, Transactions of Russian Academy of Sciences, 413 (5), (translated in English by Springer).

Semiletov, I.P. and I.I. Pipko, 2007, Sinks and sources of carbon dioxide in the Arctic Ocean, Transactions of Russian Academy of Sciences, in press.

Van Dongen B.E., I.P. Semiletov, J.W.H. Weijers, and Ö. Gustafsson. 2007, Contrasting lipid biomarker composition of terrestrial organic matter exported from across the Eurasian Arctic by the five Great Russian Arctic Rivers, Global Biogeochemical Cycles, in press.

Vetrov, A.A., I.P. Semiletov, O.V. Dudarev, V.I. Peresipkin, and A.N. Charkin (2007), Study of composition and origin of organic matter in the East-Siberian Sea bottom sediments, Geokhimiya (Geochemistry), in press.

Elmquist M., I. Semiletov, L. Guo and Ö. Gustafsson. 2007, Pan-Arctic patterns in black carbon sources and fluvial discharges deduced from radiocarbon and PAH source apportionment markers in estuarine surface sediments, Global Biogeochemical Cycles, in press.



Product Delivery, Analysis/Reanalysis

a. A Web Site for NCEP's Global Ocean Data Assimilation System for Global Ocean Monitoring, Ocean Monitoring Products, and Data Validation

b. In Situ and Satellite Sea Surface Temperature (SST) Analyses

c. Development of Global Heat and Freshwater Anomaly Analyses

d. Ocean Heat and Freshwater Content Variability Estimates

e. Evaluating the Ocean Observing System: Performance Measurement for Heat Storage.

f. A Fifty-Year Analysis of Global Ocean Surface Heat Flux to Improve the Understanding of the Role of the Ocean in Climate

g. Climate Variability in Ocean Surface Turbulent Fluxes

h. Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses

i. Evaluating the Ocean Observing System: Surface Currents

j. Quarterly Reports on the State of the Ocean: Meridional Heat Transport Variability in the Atlantic Ocean

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

l. Satellite Altimetry

m. Global Carbon Data Management and Synthesis Project

n. Determination of the Information Content in Long-Occupied Voluntary Observing Ship (VOS) Expendable Bathythermograph (XBT) Transects

o. Arctic Ice Thickness: State of the Arctic Report

p. Observing System Research Studies

q. Simulation of the ARGO Observing System

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

Yan Xue
Climate Prediction Center/NCEP/NWS, Camp Springs, MD

Project Summary:

The purpose of this project is to maintain and develop a comprehensive web site for global ocean monitoring based on the Global Ocean Data Assimilation System (GODAS) at the National Centers for Environmental Prediction (NCEP). The first objective of the web site is to provide the user community an easy access to the GODAS data sets, comparison of analysis with observations, and various maps of climatology and anomalies of oceanic fields in the past two decades; the second objective is to deliver real time global oceanic monitoring products derived from the GODAS analysis.

The current version of the GODAS was developed by the Environmental Modeling Center of NCEP for initialization of the oceanic component of the NCEP's Climate Forecast System. A retrospective ocean analysis for 1979-present has been produced, and the monthly and pentad (5 day mean) fields are made available for dissemination to the general public through the GODAS web site supported by this project. The Climate Prediction Center (CPC) of NCEP is charged by NOAA's Office of Climate Observations (OCO) to maintain and develop the website, and CPC acts as the NCEP point of contact for the GODAS user community. With the support provided by the OCO, the GODAS web site underwent a significant expansion in FY07 and started an operational product referred to as "Monthly Ocean Briefing" providing a real time assessment of the state of the global ocean and its interactions with atmosphere.

CPC strives to continuously improve the GODAS web site and "Monthly Ocean Briefing" by engaging participations and contributions from both research and operational communities.

Background:

The in situ ocean observation network managed by the NOAA's OCO has greatly enhanced our knowledge of the state of the global ocean and is critical for the ocean reanalysis efforts in the past decade. The National Centers for Environmental Prediction (NCEP) is the operational agency responsible for producing ocean analysis for the Global Ocean by assimilating in situ observations into an oceanic general circulation model forced by atmospheric fluxes. Currently, assimilated observations include temperature profiles from XBT**,** profiling floats and TAO moorings. The Global Ocean analysis is used to initialize the oceanic component of the NCEP's Climate Forecast System (CFS) (Saha et al. 2007) and was developed in 2003 (Behringer and Xue 2004). The retrospective global ocean reanalysis for 1979-2004, and its real time updates, constitute a unique dataset that can be used to diagnose the past oceanic variability and to monitor the recent trend and current oceanic conditions in support of climate attribution and prediction activity.

To gain a broader dissemination of GODAS data products, and to increase research community's involvement in the assessment of GODAS towards increasing the

effectiveness of the NOAA's ocean observing systems, the NOAA's OCO currently supports the Climate Prediction Center of NCEP to maintain a comprehensive web site for the GODAS. The web site contains data link, data validation, and oceanic monitoring products. Since the web site aims to serve a broad user community that includes operational forecast centers, scientific research groups, and the general public, CPC solicits feedbacks from all users, answer their questions in a timely manner, and improve the web site according to the needs of user community.

Website: http://www.cpc.ncep.noaa.gov/products/GODAS/

Parternership:

This project has been coordinated with the production of the GODAS data set by the Environmental Modeling Center of NCEP. CPC also works with various expert teams supported by the OCO to validate, and to enhance, the GODAS products with in situ observations.

Accomplishments:

1. GODAS web statistics

The GODAS web site has been significantly improved in FY06. One of the major improvements is a revised home page that contains animations and plots that describe the recent conditions of the state of the ocean (Fig. 1). The GODAS home page contains cursor activated animations of the pentad means for the past three months and plots of the monthly means for the past 30 days for selected variables such as SST, heat content and Tropical Cyclone Heat Potential. The modified home page is particularly useful for monitoring the recent trends and current conditions of the ocean. The monthly hits to the GODAS web increased five fold from June 2006 to July 2006 due to the improvement in the home page. Another significant increase in the number of the monthly hits to the GODAS web site happened in May 2007 when CPC introduced an operational oceanic monitoring product, referred to as "Monthly Ocean Briefing" (Fig. 1). Details about the new product are described in the next section.

2. Monthly Ocean Briefing

The GODAS home page contains many plots and animations that are useful for forecasters and researchers to assess the current oceanic conditions and infer their impacts on the atmosphere. However, community can be better served by providing a synthesis of plethora of such products and by summarizing (a) how the state of the ocean evolved recently, (b) what is interaction with the atmosphere, and (c) how it will likely evolve in near future. Since CPC have access to the real time oceanic and atmospheric reanalysis data and the climate outlooks made by the NCEP's CFS, CPC is well positioned to provide the user community with a real time assessment of the state of the global ocean, its interaction with the atmosphere, and an assessment of how model predictions verify. To accomplish this, an operational oceanic monitoring product referred to as "Monthly Ocean Briefing" was initiated in May 2007 at the CPC. The "Monthly Ocean Briefing" is conducted with a PowerPoint Presentation using a conference call, and is held around the 7th day of each month. The schedule of the ocean

briefing is sent by email to a distribution list that contains both internal and external colleagues. The conference call is open to anyone who is interested in the briefing. During the past 7 months, the ocean briefing has been well received by internal and external participants, and feedback received so far indicates that the ocean briefing is very informative and useful, and further, is becoming a valuable tool for both research and operational community. The past PPT presentations have been archived and made available to the general public at the GODAS web site.

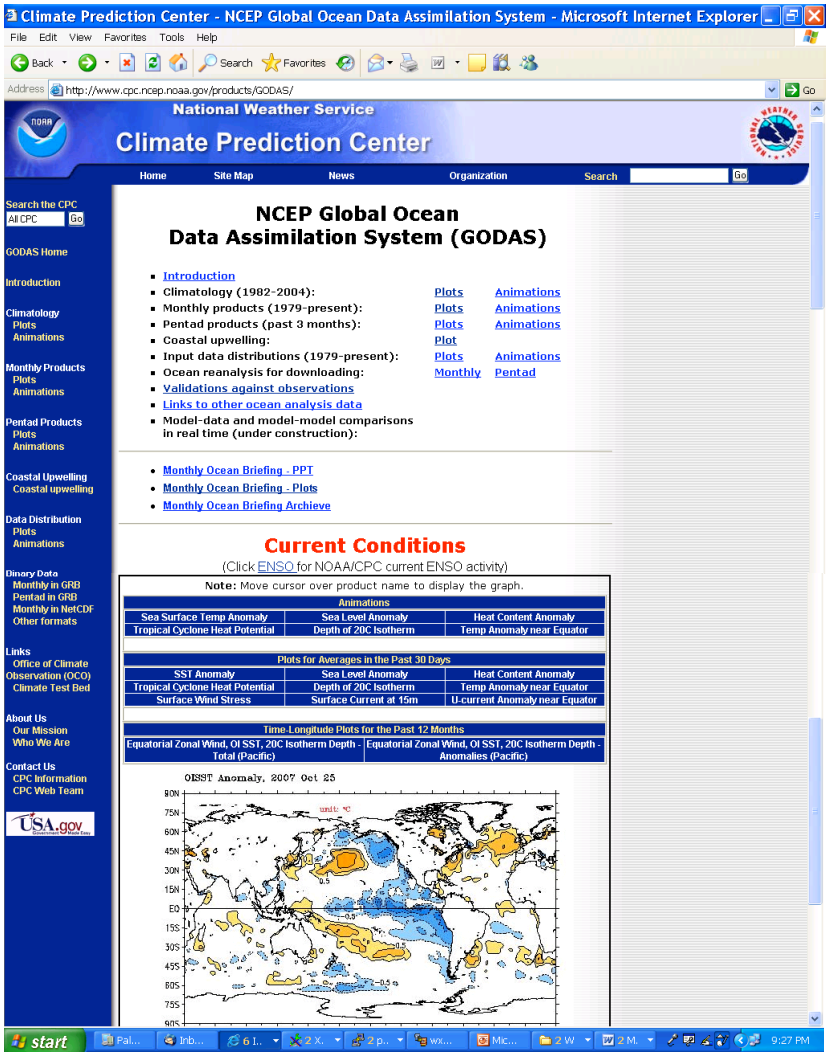


Fig. 1 The home page of the GODAS web site.

Through the interaction with the user community, the content of the PPT presentation has improved with time, and it has been structured to contain a set of fixed monitoring products and additional analyses that are used to address some oceanic events of current interest. Contributions from external community are highly encouraged. The NOAA's Pacific Marine Environmental Laboratory has been contributing to the ocean briefing a

few slides on the SST heat budget analysis, Warm Water Volume and depth-longitude section of temperature for the tropical Pacific.

3. Uncertainties in NCEP fluxes

The CLIVAR's Global Synthesis and Observations Panel organized the Second CLIVAR/GODAE Meeting on Ocean Synthesis Evaluation at MIT on September 24-25. CPC was invited to give a presentation on "Uncertainties in NCEP Fluxes". In response to this invitation, we systematically evaluated the biases of fluxes in NCEP's CDAS, CDAS2 and GDAS. The momentum flux was validated against the FSU in situ objective pseudo wind stress and FSU QuickScat winds; the heat flux was against the blended flux product (OAflux) from WHOI, the in situ objective flux product from FSU and the ISCCP radiation flux. The study suggests that the momentum flux from CDAS and CDAS2 have large errors in the far eastern tropical Pacific and the tropical Atlantic. The momentum flux of GDAS agrees with observations much better since it is an operational atmospheric analysis that uses a much improved version of the atmospheric model and assimilates the QuickScat winds. The heat fluxes of CDAS are slightly more accurate than those of CDAS2. Both CDAS and CDAS2 have too little short wave (SW) radiations, resulting in net heat flux biases as large as -60W/m^2. The variability of SW is poorly simulated by both CDAS and CDAS2. The CDAS2 has too large net heat flux variability due to too large latent heat (LH) flux variability. However, the correlation of the LH of CDAS and CDAS2 with OAflux is above 0.6 over the global ocean. Based on the comparison results, we decided to use the CDAS heat flux in our "Monthly Ocean Briefing" to assess the attributions of SST changes in the global ocean. It turned out that the CDAS heat flux product provides very useful information on the SST variability in the extra-tropics where oceanic latent heat fluxes are the major forcings for SST.

4. Impacts of Argo salinity in NCEP GODAS

Several experimental runs have been made to assess the impacts of Argo salinity in the NCEP GODAS. It was found that the ocean currents in the tropical Pacific significantly improved due to corrections of the model density field made by Argo salinity (Behringer 2007). The impacts of Argo salinity in the tropical Indian are also examined, and the results have been described in a journal paper accepted by Journal of Geophysical Research (Huang et al. 2007).

References:

Behringer, D.W., and Y. Xue, 2004: Evaluation of the global ocean data assimilation system at NCEP: The Pacific Ocean. *Eighth Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface*, AMS 84th Annual Meeting, Washington State Convention and Trade Center, Seattle, Washington, 11-15.

Behringer, D.W, 2007: The Global Ocean Data Assimilation System (GODAS) at NCEP. *11th Symposium on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface*, AMS 87th Annual Meeting, San Antonia, TX, 14-18.

Huang, B., Y. Xue, and D. Behringer, 2007: Impacts of Argo salinity in NCEP Global Ocean Data Assimilation System: The tropical Indian Ocean. *J. Geophys. Res*., accepted.

Saha, S., S. Nadiga, C. Thiaw, J. Wang, W. Wang, Q. Zhang, H. M. van den Dool, H.-L. Pan, S. Moorthi, D. Behringer, D. Stokes, M. Peña, S. Lord, G. White, W. Ebisuzaki, P. Peng, P. Xie , 2006 : The NCEP Climate Forecast System. *J. Climate*, **19**, 3483-3517.

In Situ and Satellite Sea Surface Temperature (SST) Analyses

Richard W. Reynolds
NOAA National Climatic Data Center, Asheville, NC

1. PROJECT SUMMARY

The purpose of this project is to focus on improvements to the climate-scale sea surface temperature (SST) analyses produced at NOAA. The major effort has been the development of a new daily optimum interpolation analysis, which was designed use multiple satellite data sets as well as in situ data. At present there are two products. One product uses infrared satellite data from the Advanced Very High Resolution Radiometer (AVHRR). The second product uses AVHRR and microwave satellite data from the Advanced Microwave Scanning Radiometer (AMSR) on the NASA Earth Observing System. The AVHRR-only product began in January 1985 and the AMSR+AVHRR product began in June 2002 when the microwave satellite data became available. Both products include a large-scale adjustment of satellite biases with respect to the in situ (ship and buoy) data. Two products are needed because there is an increase in signal variance when microwave satellite data became available due to its near all-weather coverage.

Additional efforts have been carried out to improve the Extended Reconstruction SST analysis. This analysis presently uses in situ data and begins in 1854. The reconstructions were produced from a low frequency (or decadal-scale component) and from a residual high-frequency component. The high frequency analysis was performed by fitting the observed high frequency anomalies to a set of large-scale spatial-covariance modes. A new version is produced which improves the damping in the late 19th century. In addition, beginning in 1985, coverage is improved by the use of bias-adjusted satellite data.

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 2007 PROGRESS

2.1 The High-Resolution Daily SST Analyses

During FY2006, two new daily 1/4° SST analyses were developed: the AVHRR-only daily optimum interpolation (OI) from January 1985 to present and the AMSR+AVHRR daily OI from June 2002 to present. During FY2007 a Journal of Climate paper was written to describe the product (see Reynolds et al., 2007). Both analyses use in situ data and use a satellite bias correction. In FY2007 a web server was developed: http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php. This server allows users to get information on how the analyses were generated and to download the analyses. The data are available in NetCDF and IEEE binary. The user interface also allows users to generate plots as needed and to generate digital output files in different formats including ASCII.

2.1.1 Operations

To monitor operations a system was developed to report on the success of each step. This results in a short email to the operator that summarizes each analysis step. At each step there are three possibilities indicated by a color, a successful completion (green), a warning (yellow) or a fatal error (red). Processing continues with a warning but ends with a fatal error. The color email allows the operator to tell at a glance the status of the operation. Problems can then be assessed and corrected. Examples of emails are shown in Figures 1 and 2.

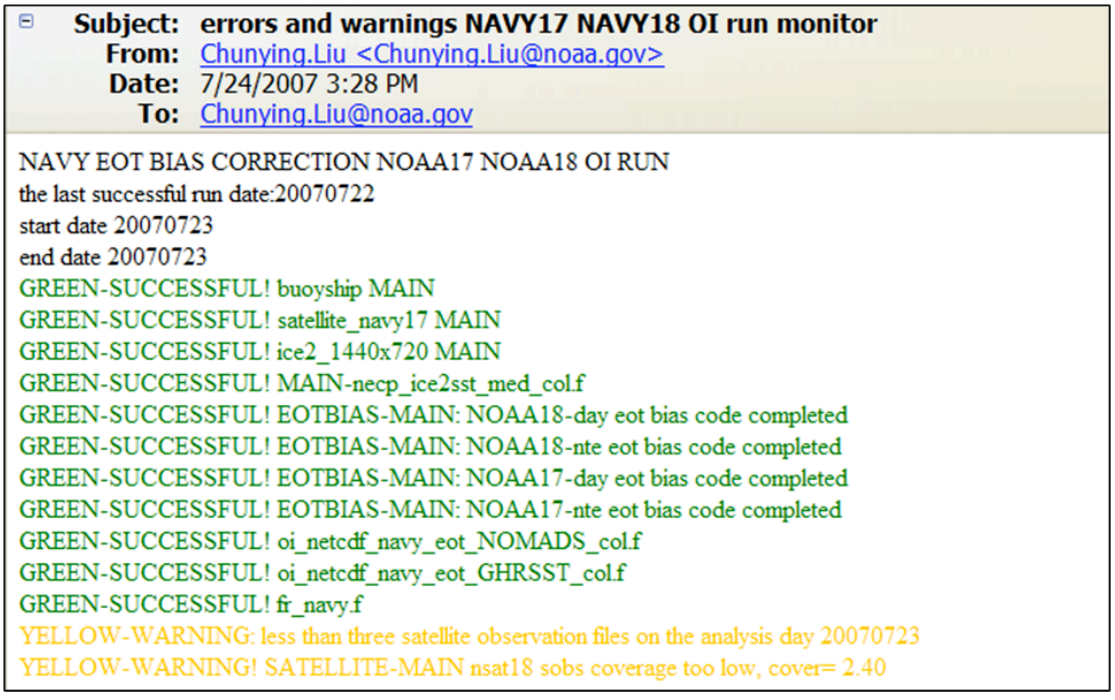


Figure 1. Example of an operational email summary of the analysis procedure with successful steps and warning steps. Successful steps are indicated by the color green, warnings by yellow and fatal errors by red.

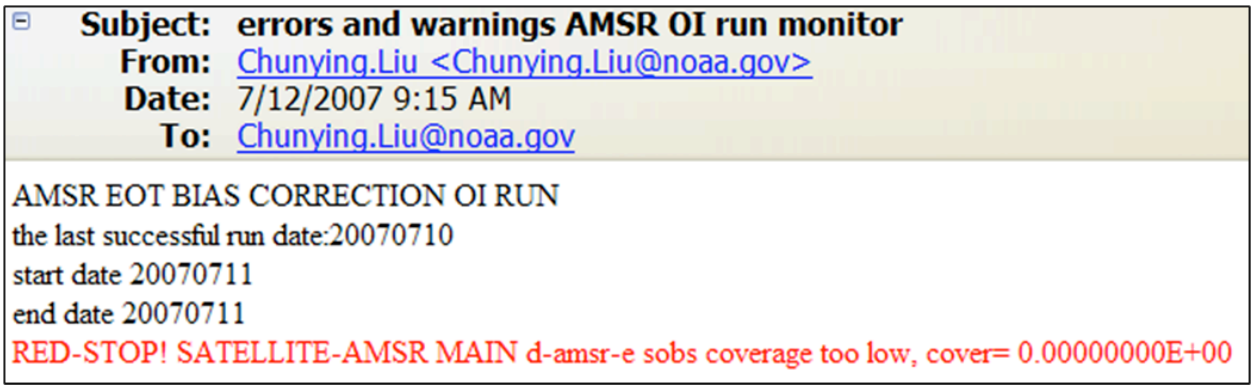


Figure 2. Example of an operational email summary of the analysis procedure with an immediate fatal error. Otherwise as in Figure 1.

2.1.2 Version 2

Once version 1 was completed, several problems were noted. These problems were corrected in version 2 which has now been completed but is not yet operational.

The major problem with version 1 was that there was day-to-day noise. This was particularly evident in the Gulf Stream region (Figure 13, Reynolds et al., 2007) and was due to limited sampling. To reduce the noise the analysis was modified to use 3-days of data instead of 1. To determine if this procedure made was done correctly. Spectra were computed at the location of 43 moored buoys which had daily SST observations for at least 99% of the time for a three year period (2003-05). Buoy spectra and analysis spectra using 1 day and 3 days of data were computed. The average spectra are shown in Figure 3. The figure shows that the highest frequency values in the daily OI using 1-day of data are larger than in the buoy data. These values are reduced in the daily OI using 3-days of data to values closer to the buoy values. Version 2 uses 3 days of data in the daily OI.

Ship data is noisy and biased with respect to buoy data. However, correcting for these biases is difficult because the buoy coverage is sparse until roughly 1990 and because both sets of data are relatively sparse compared to satellite data. Initial attempts to develop even global annual time series failed to produce any clear time dependence. However, scatter plots showed that there was a consistent long term bias. An example of this is shown in Figure 3 for two separate 9 year periods. The linear fits to the data, show that ship SSTs should be reduced by roughly 0.14°C to reduce the overall ship bias with respect to buoys. This ship bias correction has been done in version 2.

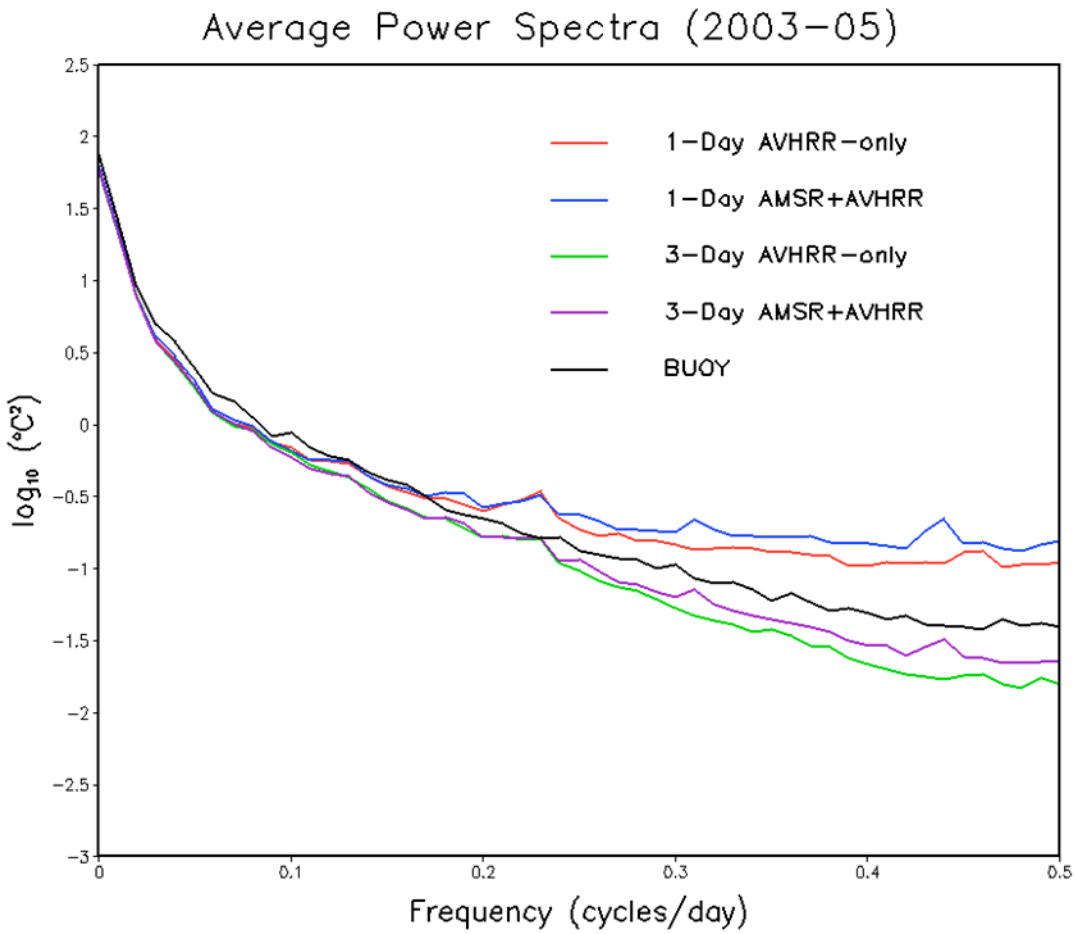


Figure 3. Average of spectra from daily buoy data and from the OI analyses for 2003-05. The spectra are computed at 43 moored buoy locations which had a daily SST value 99% of the time. At the same locations spectra are computed using the daily OI analyses using 1 and 3 days of data. Two daily OI products are considered: AVHRR-only and AMSR+AVHRR.

There are several other corrections that were made to Version 2. This includes smoothing using five 7-day satellite bias correction fields. This smoothing is needed to reduce a strong 7-day period in the bias correction. In addition, a zonal satellite bias correction is made at high latitudes where in situ data are sparse. There have also been improvements in the AMSR data to reduce the errors in SST retrievals near rain events. These improved AMSR data are used in Version 2. Finally some minor corrections were made in the land-sea tables in Version 2 to eliminate a few small errors. Most of these corrections mask out some lakes and narrow fjord channels which cannot be properly analyzed on a 1/4° grid analysis

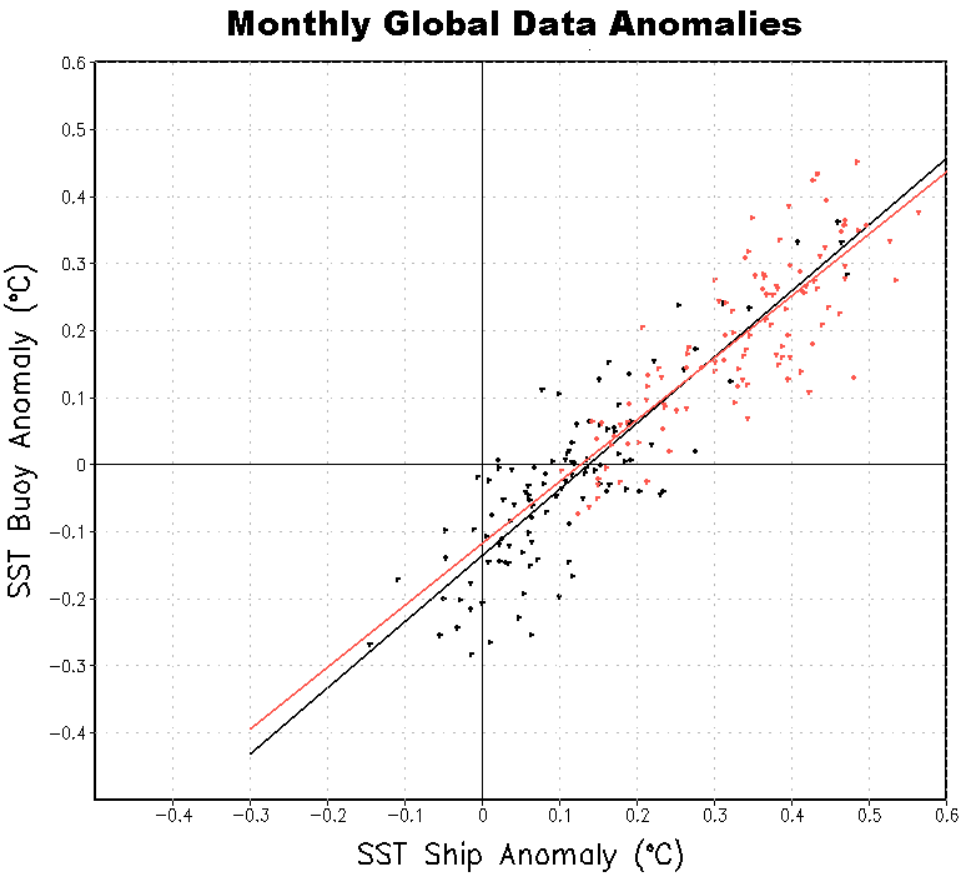


Figure 4. Monthly global data anomalies for ships and buoys. Data for 1989-1997 is in black; data for 1998-2006 is in red. A least squares fit for the two periods is also shown.

2.2 The Historic ERSST Analysis and Merged SST and Land 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.

Beginning in FY06, simulated SST anomaly data from the Geophysical Fluid Dynamics Laboratory (GFDL) Climate Model 2.1 (CM2.1) were used to tune both low frequency and high frequency parameters. During FY07 the tuning procedure was completed. In addition, beginning in 1985 bias-adjusted SST satellite data were added to the in situ data. New fields using the

improved tuning and satellite data were generated (version 3). The full procedure is described in Smith et al. (2007) and was also applied to in situ land surface temperatures. The merged SST and land surface temperatures are shown as global annual averages in figure 5 for the new version (version 3) and the older version (version 2). In addition, a merged analysis produced jointly by the U.K. Met Office Hadley Centre and the University of East Anglia's Climatic Research Unit (HadCRUT3v, Brohan et al. 2006) is also shown. Comparisons show that all anomalies have similar global variations throughout the analysis period. Differences are less than the 95% confidence limits of the merged version 3 analysis. Note that the confidence limits are wide early in the 20th century due to insufficient sampling and bias uncertainty. They decrease greatly between 1930 and 1950 due to increased sampling, and they increase slightly after 1950 due to increasing urbanization bias uncertainty.

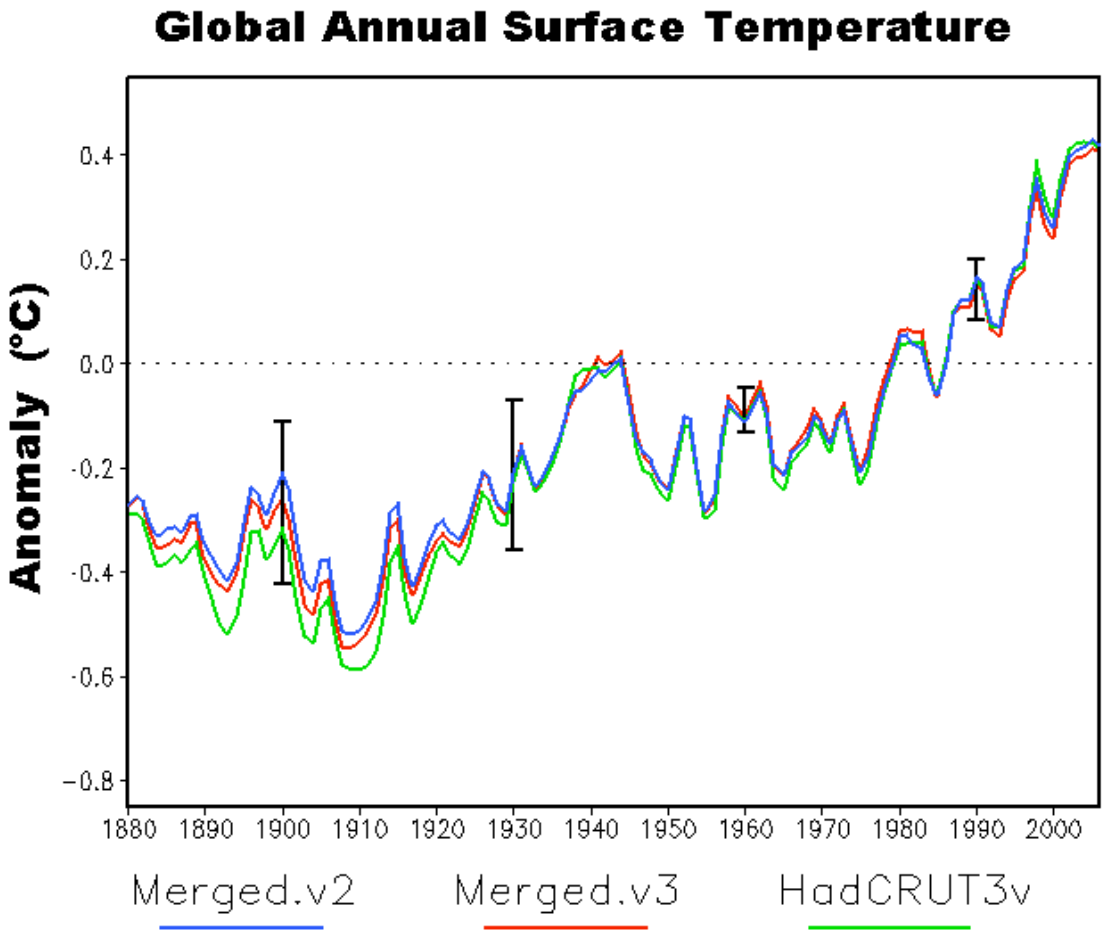


Figure 5. Global and annual merged temperature anomalies from Version 2 (Merged.v2), the improved analysis Version 3 (Merged.v3), and from UK HadCRUT3v. The base periods are adjusted to match the 1971-2000 base used in the improved analysis. A 1-2-1 smoother has been applied to each time series of annual averages. The 95% confidence limits reflecting all errors estimated for Merged.v3 are drawn for the years 1900, 1930, 1960, and 1990.

The SST analyses (ERSST.v2 and ERSST.v3) are available to uses in ASCII and NetCDF. They can be accessed from the web page: http://www.ncdc.noaa.gov/oa/climate/research/sst/sst.html

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).

References

Reynolds, R. W., T. M. Smith, C. Liu, D. B. Chelton, K. S. Casey, and M. G. Schlax, 2007: Daily high-resolution blended analyses for sea surface temperature. *J. Climate,* **20***,* 5473-5496.

Smith, T.M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore, 2007: Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880-2006). *J. Climate* (in press).

Smith, T. M., and R. W. Reynolds, 2004: Improved Extended Reconstruction of SST (1854-1997). *J. Climate*, **17**, 2466-2477.

Zhang, H.-M., R. W. Reynolds, and T. M. Smith, 2006: Adequacy of the in situ observing system in the satellite era for climate SST. *J. Ocean. Atmos. Tech.,* **23**, 107–120.

Development of Global Heat and Freshwater Anomaly Analyses

Gregory C. Johnson[1], John M. Lyman[2] and Josh K. Willis[3]
[1] NOAA Pacific Marine Environmental Laboratory, Seattle WA
[2] University of Hawaii/JIMAR, NOAA Pacific Marine Environmental Laboratory, Seattle WA
[3] Jet Propulsion Laboratory, Pasadena CA

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 are 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 sampling errors inherent in estimating a global average of upper ocean heat content from an incomplete data set. We can also exploit the relationship to improve maps of ocean heat content from in situ data by using the altimeter data with local correlation coefficients applied as a first guess at upper ocean heat content in poorly measured regions.

This project, a part of the NOAA Office of Climate Observations Ocean Observing System Team of Experts, by providing analyses of ocean data, helps NOAA to use and assess the effectiveness of the sustained ocean observing system for climate. The work is primarily carried out at NOAA's Pacific Marine Environmental Laboratory by the PMEL and JIMAR investigator, but in very close consultation with the co-investigator at NASA's Jet Propulsion Laboratory.

Project Accomplishments:

In FY2007 a good deal of effort was expended on identifying one set of instrument errors, quantifying another, and working to quantify the size of both errors in recent upper ocean heat content estimates (Willis et al., 2007b, c). In addition, the effects of sparse historical in situ ocean temperature sampling patterns on global integrals of upper ocean heat content changes were investigated (Lyman and Johnson, 2007). Yearly ocean heat content maps were made by combining in situ temperature profiles with sea surface height anomalies from satellite altimeter data for 1993 through 2006 (Johnson et

al. 2007a). Sea surface salinity maps were made for 2005 and 2006 (Johnson and Lyman, 2007).

We detected one instrument error early in CY2007 in the process of analyzing ocean heat content anomalies. Incorrect pressures were ascribed to otherwise valid temperature and salinity data in a small subset of Argo floats, deployed mostly in the Atlantic Ocean. In terms of ocean heat content, the error introduced a large cold bias in a small fraction of Argo float data. The error is fully correctable for most of the affected floats and approximately correctable for the remainder. As of the writing of this report, the erroneous Argo float data had almost all been recently corrected. However, for heat content analyses published earlier in the year (Johnson et al., 2007a), the worst of the erroneous data were simply removed from the data set.

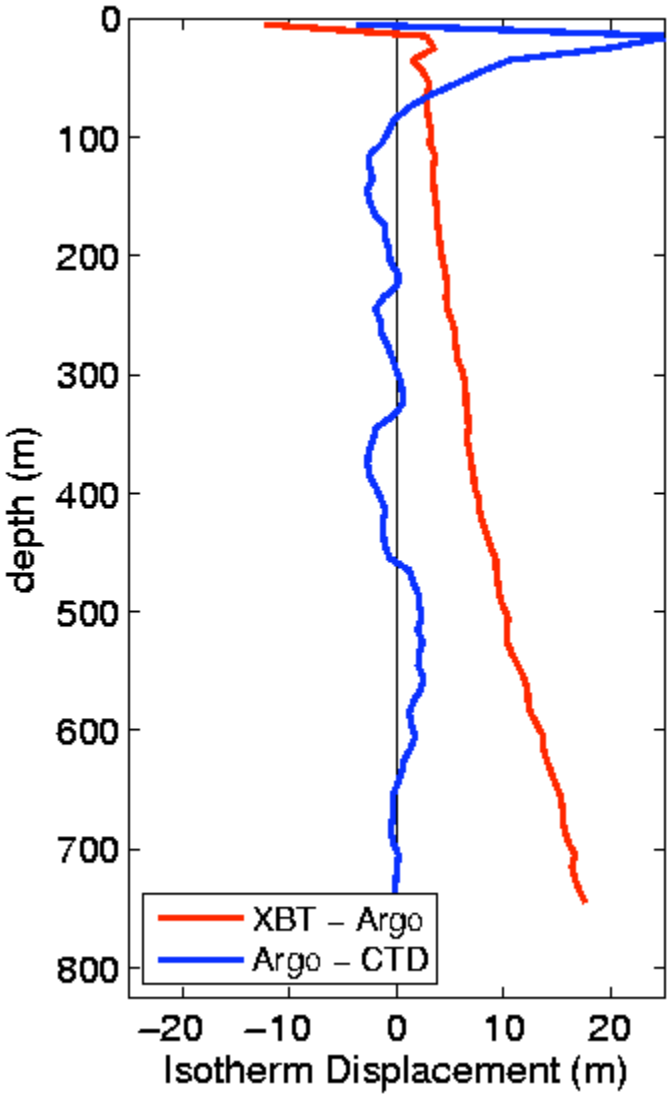


Figure 1. Depth errors due to XBT fall rate equation errors inferred from the median difference between isotherm displacements computed from 23,400 nearby XBT and Argo pairs collected between Jan. 1, 2003 and Dec. 31, 2006 (red line). The median difference between isotherm displacements computed from 2,000 nearby CTD and Argo pairs collected between Jan. 1, 2000 and Dec. 31, 2006 (blue line) is also computed excluding

all floats with known incorrect pressure data. Positive displacements reflect deeper isotherms, hence a generally warm bias. Figure after Willis et al. (2007c).

The other error is a smaller but more prevalent warm bias in eXpendable BathyThermograph (XBT) data. This error came to light after Johnson et al. (2007a) had been completed and appears to arise from variations in XBT fall rate (e.g. Figure 1). XBT fall rate equations are used to infer depths, which can be biased if there are errors in the fall rate equation parameters. While all the factors that cause this error are not known, the fall rates appear to vary with XBT model and date of deployment. For 2003-2006, this error resulted in erroneously deep report of XBT depths on the order of 2% (Figure 1; Willis et al. 2007c). A correction noting the detrimental effect of both of these errors on earlier results has been published (Willis et al, 2007b), and further analysis quantifying the significant effects of these errors on global integrals of upper ocean heat content has been submitted for publication (Willis et al., 2007c). Analyses of XBT biases over the entire historical record presently underway suggest significant interannual variations in XBT fall rates. These variations are very likely to have significant ramifications for accurate estimates of upper ocean heat content anomalies. It will take some time and effort to correct for this problem.

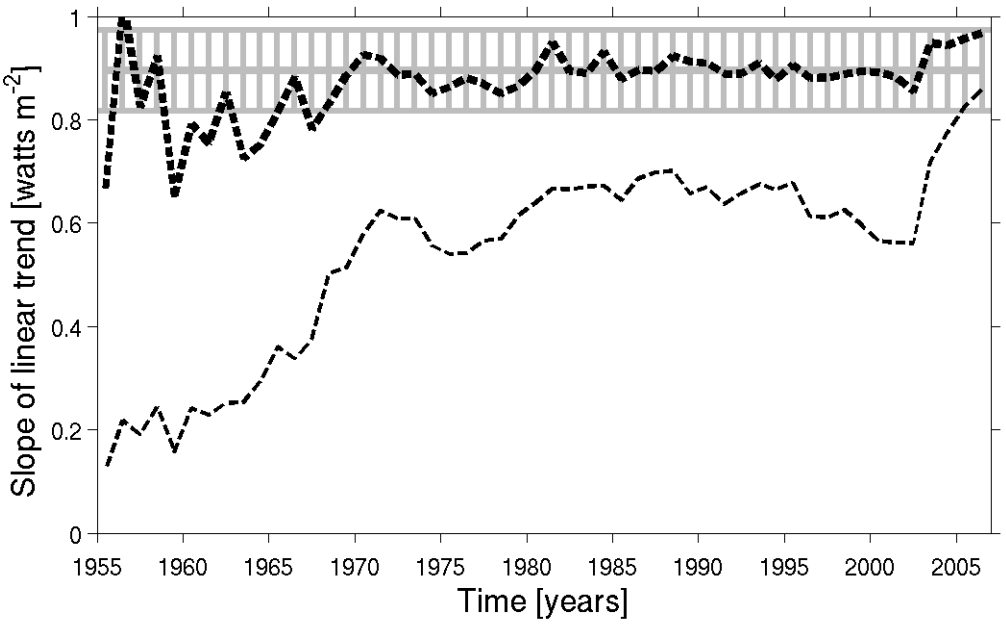


Figure 2. Warming trends of a synthetic upper ocean heat content record created from satellite altimetry data for the 13-year period from 1993 through 2006 calculated using the full record (grey line with error bars) and by resampling the 13-year record using each year's data distribution from 1955 through 2006 from both simply integrating the resulting objective maps (thin dashed line) and estimating representative integrals (thick dashed lines). Figure after Lyman and Johnson (2007).

Sparse in situ temperature profile distributions in pre-Argo years can also create difficulties in estimating global integrals of upper ocean heat content anomalies. An assumption used often in creating global integrals of this quantity is that unsampled

regions have zero anomaly. Objective maps generally build in this assumption by increasingly relaxing back to a climatological mean value at locations and times where data coverage is increasingly sparse. We compared results using this assumption (that we term the integral of the maps) to results using another one: that unsampled regions have an anomaly equal to the spatial average of sampled regions in any given year (that we term the representative integral; Lyman and Johnson, 2007).

To do these comparisons quantitatively we developed a methodology to estimate the fractional area for which an objective map will replicate a globally uniform anomaly for any given data distribution, noise to signal ratio, and correlation function (Lyman and Johnson, 2007). We also used appropriately scaled set of high temporal and spatial resolution sea-surface height anomaly maps from 1993 – 2006 as a proxy for a fully sampled upper ocean heat content record. We resampled each year of this proxy using in situ sampling patterns for every year from 1955 – 2006. We compared how well the 13-year trend in the global integral of the fully resolved proxy was recreated for integrals based on objective maps of the proxy resampled for any given year's historical sampling pattern under the two different assumptions (Fig. 2). There are at least four significant conclusions. The historical sampling distributions for years prior to 1967 are inadequate for computing global integrals with confidence using either method. Also, estimates of global integrals of upper ocean heat content anomalies from integrals of the maps are likely to underestimate trends in global upper ocean heat content, especially early in the record. Representative integrals appear to do good a job of reproducing the actual trend. Finally, only in the last few years of the record, with Argo reaching near-global coverage, do the two methods agree within uncertainties.

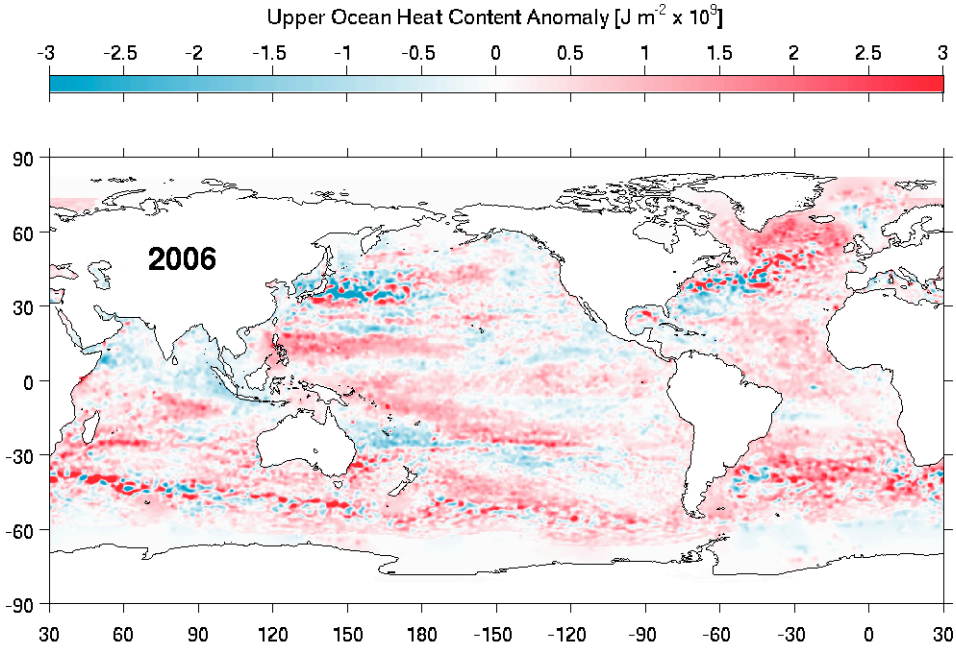


Figure 3. Combined satellite altimeter and in situ ocean temperature data upper (0 – 750 m) ocean heat content anomaly OHCA (J m^{-2}) map for 2006 (top panel) analyzed following Willis et al. (2004), but relative to a 1993 – 2006 baseline. Figure after Johnson et al. (2007a).

In addition to these investigations, we updated maps (e.g. Fig. 3) of annual upper (0-750 m) ocean heat content primarily for the ice-free portions of the globe from 1993 through 2006 combining in-situ and satellite altimetry data (following Willis et al. 2004) to better resolve smaller (sub-gyre) scale spatial variability over shorter (year-to-year) time-scales for the 2006 State of the Climate Report (Johnson et al., 2007a). The analyses were discussed in that report, and those discussions are not repeated here. While the Argo float profile data with serious pressure biases were removed from these estimates, no correction was made for XBT fall rate errors, which were not well known at the time.

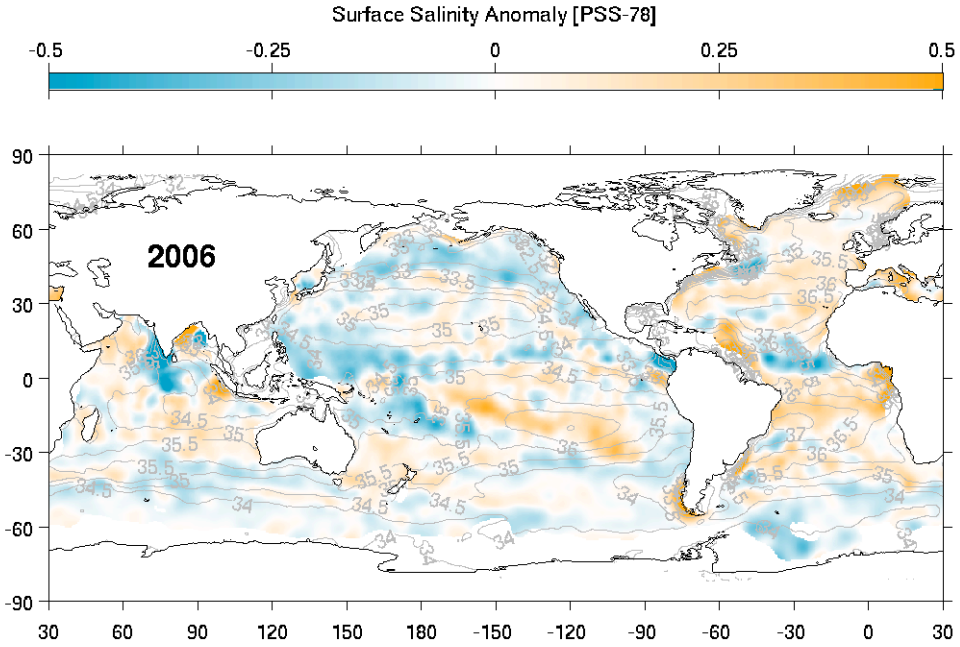


Figure 4. Map of the 2006 annual surface salinity anomaly estimated from Argo data [colors in PSS-78] with respect to a climatological salinity field from WOA 2001 [gray contours at 0.5 PSS-78 intervals]. White areas are either neutral with respect to salinity anomaly or are too data-poor to map. While salinity is often reported in practical salinity units, or PSU, it is actually a dimensionless quantity reported on the 1978 Practical Salinity Scale, or PSS-78. Figure after Johnson and Lyman (2007).

Finally, we began producing annual average maps of Sea-Surface Salinity (SSS) anomalies with respect to the World Ocean Atlas 2001 Climatology for the 2006 State of the Climate Report (Johnson and Lyman, 2007). These maps (e.g. Fig. 4) were only possible for 2005 and 2006, when Argo provided near-global coverage of SSS data. Again, the analyses were discussed in that report, and those discussions are not repeated here.

Manuscripts related to this project that were published or submitted for publication in FY2007 are listed below. The project web page is http://oceans.pmel.noaa.gov/.

FY2007 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., and J. M. Lyman. 2007. Global Oceans: Sea Surface Salinity. In State of the Climate in 2006, A. Arguez, Ed., *Bulletin of the American Meteorological Society*, **88**, **6,** S34-S35

Johnson, G. C., J. M. Lyman, and J. K. Willis. 2007a. Global Oceans: Heat Content. In State of the Climate in 2006, A. Arguez, Ed., *Bulletin of the American Meteorological Society*, **88**, **6**, S31-S33.

Johnson, G. C., J. M. Toole, and N. G. Larson. 2007b. Sensor corrections for Sea-Bird SBE-41CP and SBE-41 CTDs. *Journal of Atmospheric and Oceanic Technology*, **24**, 1117-1130.

Lyman, J. M, and G. C. Johnson. 2007. Estimating global upper ocean heat content despite irregular sampling. *Journal of Climate*, submitted.

Lyman, J. M., G. C. Johnson, and W. S. Kessler. 2007. Distinct 17-day and 33-day tropical instability waves in subsurface observations. *Journal of Physical Oceanography*, **37**, 855-872.

Willis, J. K., D. P. Chambers, and R. S. Nerem. 2007a. Closing the Globally Averaged Sea Level Budget on Seasonal to Interannual Time Scales. *Journal of Geophysical Research - Oceans*, submitted

Willis, J. K., J. M. Lyman, G. C. Johnson, and J. Gilson. 2007b. Correction to "Recent cooling of the upper ocean". *Geophysical Research Letters*, **34**, L16601, doi:10.1029/2007GL030323.

Willis, J. K., J. M. Lyman, J. M., G. C. Johnson, and J. Gilson. 2007c. In situ data biases and recent ocean heat content variability. Geophysical Research Letters, submitted.

Ocean Heat and Freshwater Content Variability Estimates

Sydney Levitus
NOAA National Ocean Data Center, Silver Spring, MD

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 ahs been used in the IPCC 2007 Assessment. The IPCC has received the Nobel Peace Prize for 2007. Our work has also been used in an NRC Report to President Bush.

ACCOMPLISHMENTS FY2007

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 end of 2007. 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 2006. After reaching a relative maximum in heat content during 2003, world ocean heat content has approximately stayed level.

Our goal has been to prepare estimates of ocean heat content every three months and make them available online. This has not been possible because of the discovery of systematic time –varying errors in the drop rates of XBTs and in biases found in profiling floats (PFL). We are processing all temperature profile data received every three months but are still working on corrections to the XBT and PFL data. We hope to begin updating heat content on a routine basis within three months.

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 have published work during this year on this subject) (see Boyer et al., 2007) . 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 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.

Boyer, T., S. Levitus, J. Antonov, R. Locarnini, A. Mishonov, H. Garcia, 2007: Changes in freshwater content in the North Atlantic Ocean 1955-2006, 34, L16603, doi:10.1029/2007GL030126.

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.

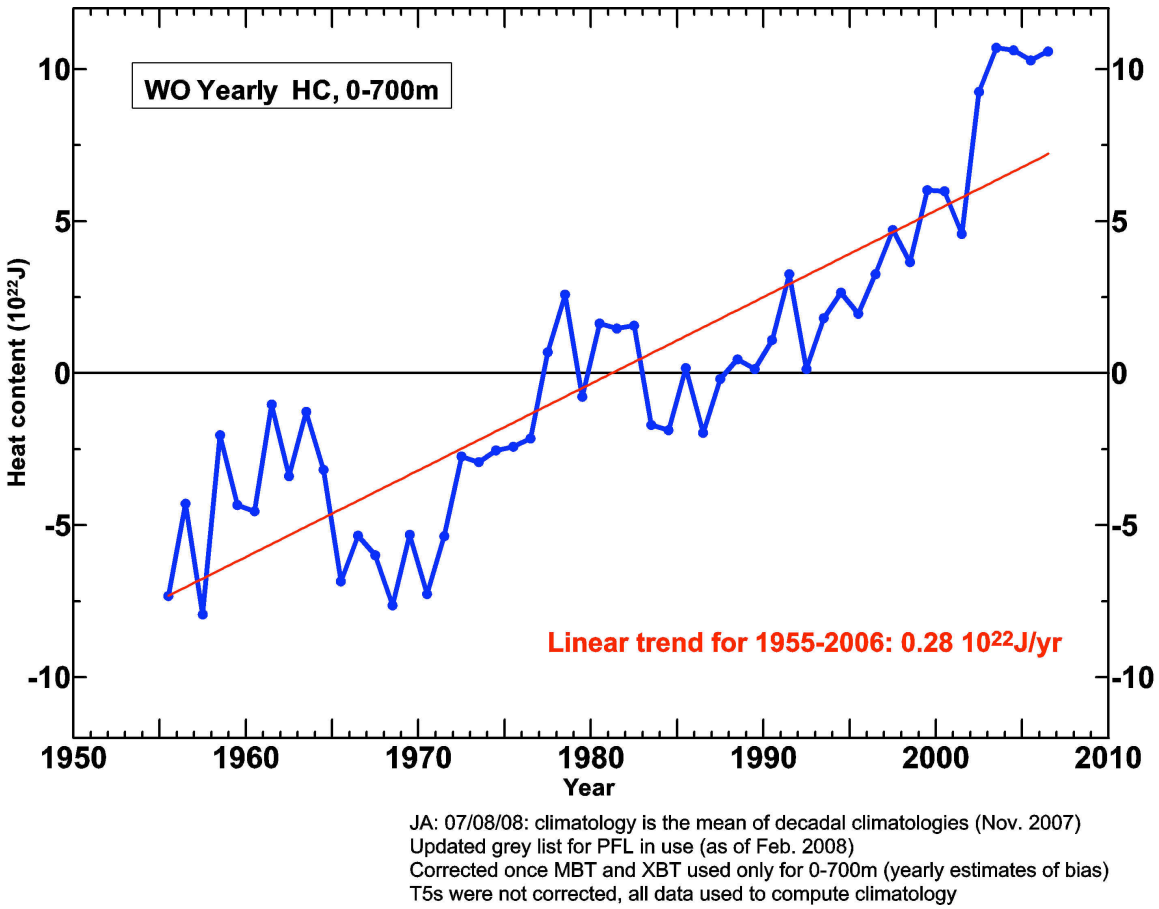


Figure 1. Time series (1955-2006 of yearly ocean heat content (10^{22}J) for the upper 700 m of the world ocean.

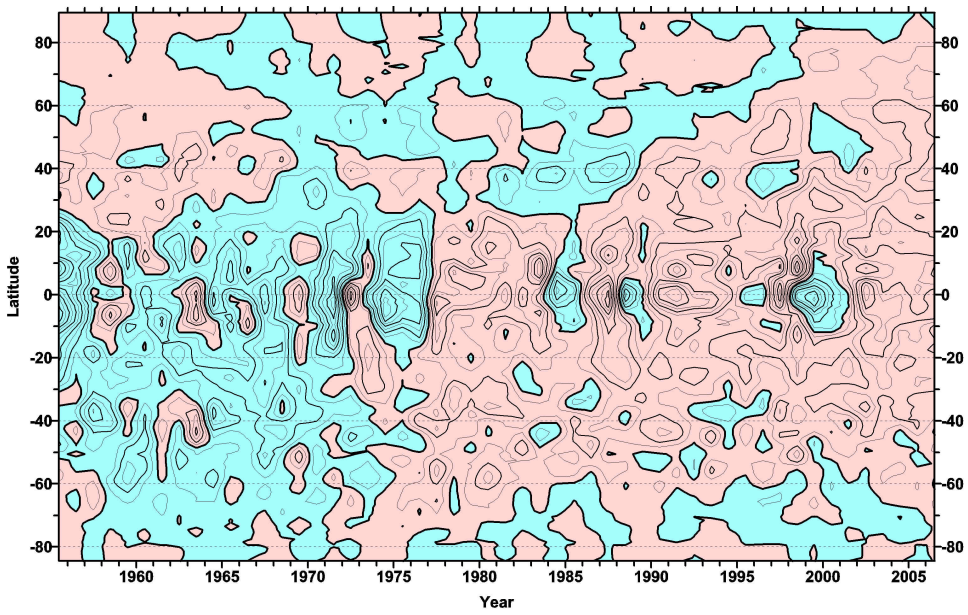


Figure 2. Zonally integrated global ocean heat content (10^{20} J) for the 0-100 m layer as a function of latitude.

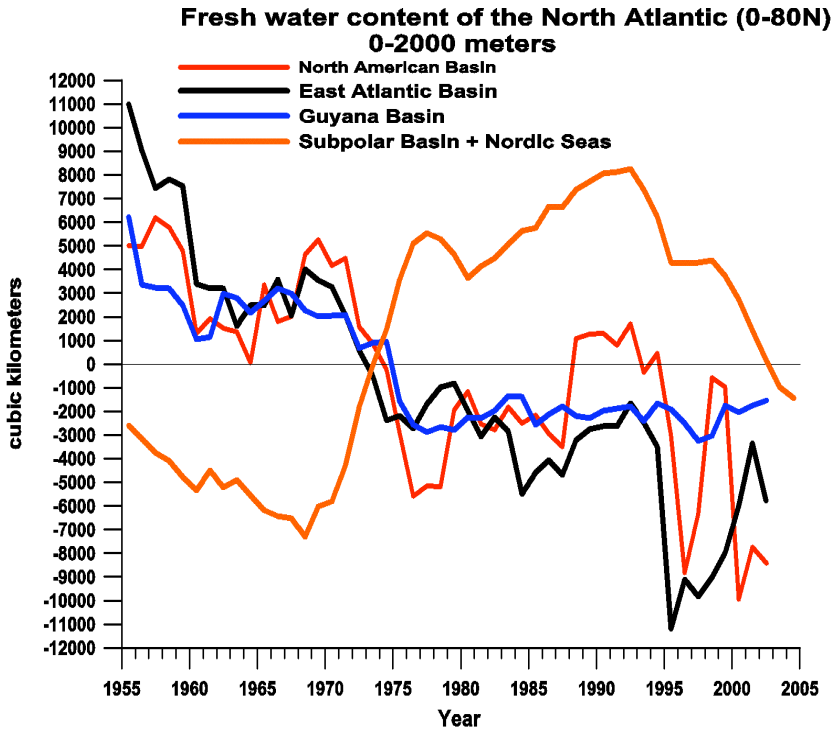


Figure 3. Variability of the Equivalent Freshwater Content of the North Atlantic Ocean and different subregions within the N. Atlantic Ocean.

Evaluating the Ocean Observing System: Performance Measurement for Heat Storage.

Claudia Schmid and Gustavo Goni
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 comparisons between altimetry- and hydrographic-derived estimates of upper ocean heat storage are conducted. They allow us to investigate the extent in depth of the sea height signal in different regions of all ocean basins. The local changes in upper ocean heat storage are estimated from altimetry-derived sea height anomaly fields, using regressions based on historical in-situ observations. For example, similar estimates of altimetry-derived heat storage are currently used to identify long periodic climate signals, such as the variability of the warm pool in the western Pacific Ocean associated with El 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/

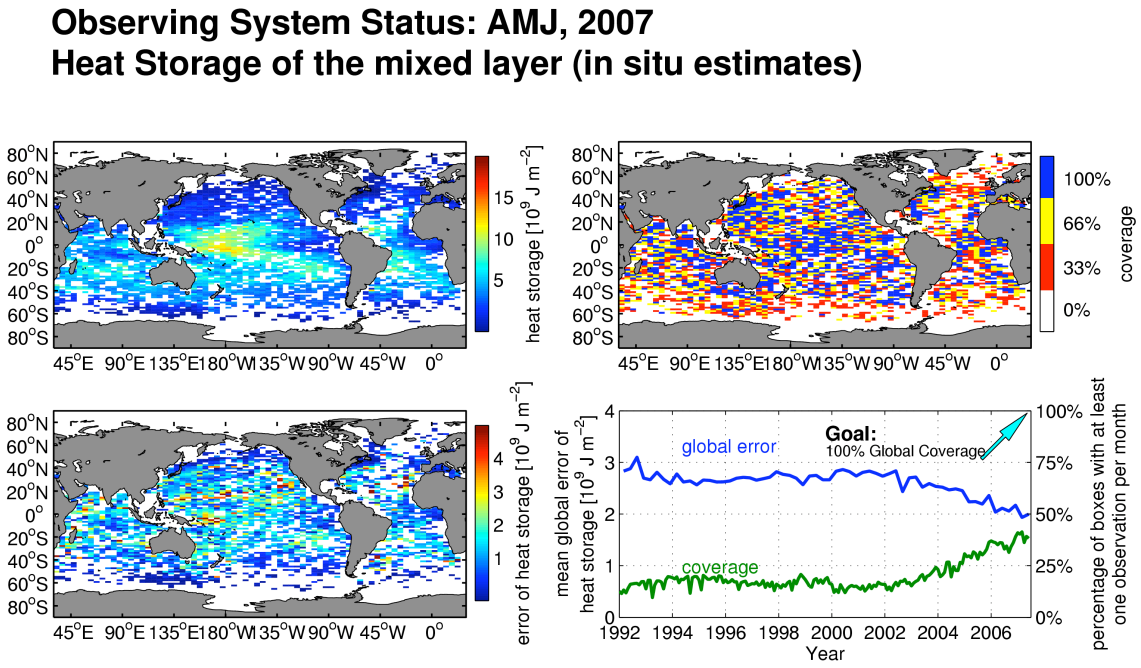


Figure 1: Example of Quarterly System Status Report for heat storage of the mixed layer, covering the time period April through June 2007. The goal of this additional task is to generate quarterly reports for the upper ocean heat storage of the global ocean.

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 exceed 0.6 for layer depths of 100m or more (Fig. 3).

The trend of the heat storage for each layer is derived from the heat storage fields for the 15-year long record (fig. 4). In some regions, these trends are related to shifts of currents (e.g. Kuroshio, Gulf Stream). In other regions the changes may be due to heat storage or haline effects.

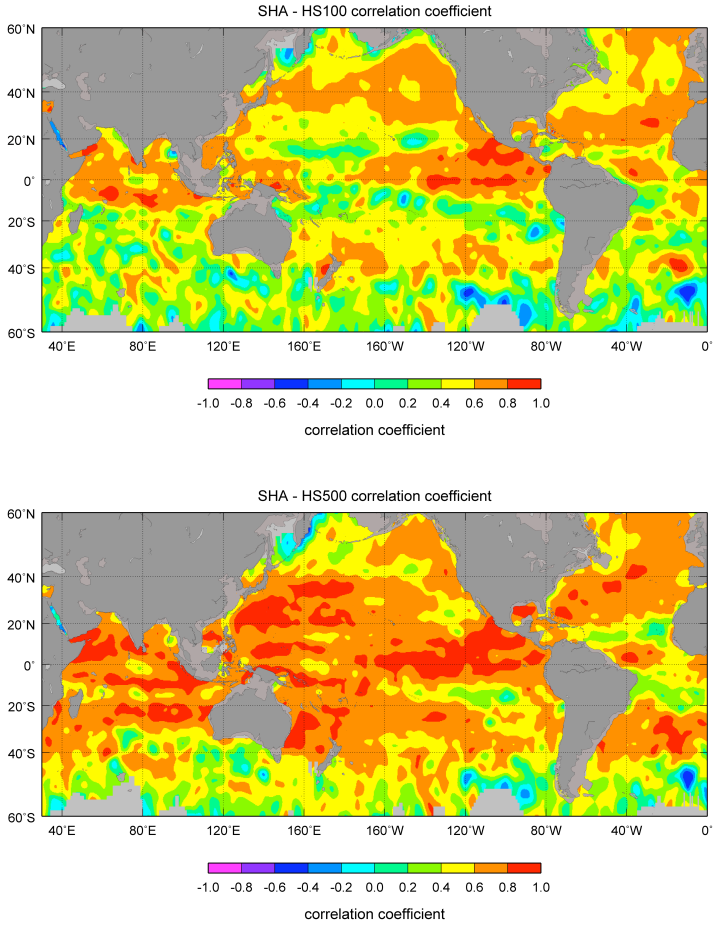


Figure 2: Correlations coefficients between the sea height anomaly and the observed upper ocean heat storage for the upper 100m (top) and for the upper 500m (bottom).

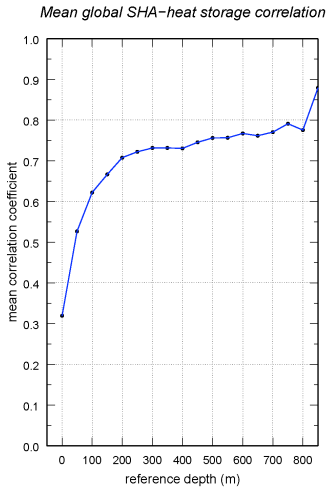


Figure 3: Global mean correlation coefficient between altimetry-derived heat storage and in-situ observations for selected depths, starting with the mixed layer depth.

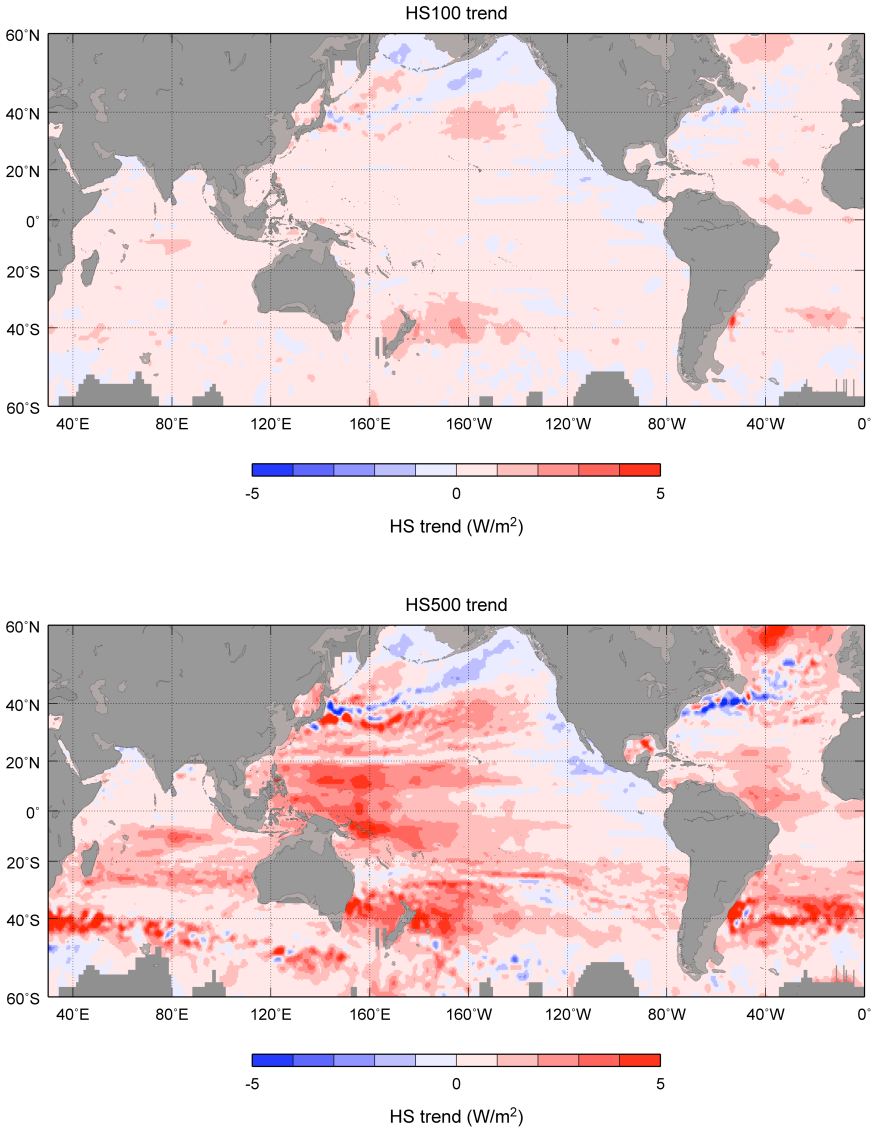


Figure 4: Trend of heat storage for the upper 100m (top) and the upper 500m (bottom).

Research Highlights.

- Improved software to produce global quarterly fields of the heat storage from in-situ observations.
- Improved method and software to derive the error of the global heat storage from in-situ observations.
- Produce status reports (Figure 1)
- Improved identification of regions where altimetric sea height anomalies are correlated to in-situ observations of heat storage (Figure 2).
- Improved quantification of the error of the altimetry-derived heat storage.
- Develop software to derive trends of the heat storage from the weekly fields derived with the combined data set (altimetry and in situ).

Publications:

Goni, G., P. DiNezio, C. Schmid (2007): Global trends in the heat storage and eddy kinetic energy. In preparation.

Lentini, C, G. Goni and D. Olson (2006): Investigation of Brazil Current rings in the Confluence Region. *J. Geophys. Res.,* 111, C06, doi=10.1029/2005JC002988.

Schmid, C., R. Lumpkin (2007): Variability of the mixed layer heat budget in tropical Atlantic. In preparation.

Schmid, C., R. L. Molinari, R. Sabina, Y.-H. Daneshzadeh, X. Xia, E. Forteza and H. Yang (2007): The Real-Time Data Management System for Argo Profiling Float Observations. *J. Atmos. Ocean. Technol*., 24(9), 1608-1628, doi=10.1175/JTECH2070.1

Schmid, C. (2005): The impact of combining temperature profiles from different instruments on an analysis of mixed layer properties. *J. Atmos. Ocean Technol*., 22(10), 1571-1587, doi=10.1175/JTECH1785.1.

Meetings:

Schmid:
Argo Trajectory Workshop in Seoul in October 27-28, 2006.
Argo Data Management Meeting in Tianjin in October 31 - November 3, 2006
U.S. Argo Science and Implementation Panel Meeting at AOML in November 29-30, 2006.
Office of Climate Observations Review Workshop, Silver Spring, MD, June 5-7, 2007.
24th Assembly of the International Union of Geodesy and Geophysics (IUGG) July 3-13, 2007 Perugia, Italy.

Goni:
Ocean Surface Topography Science Team, Hobart, Tasmania, April 2007.
Office of Climate Observations Review Workshop, Silver Spring, MD, June 5-7, 2007.

Community Service:

C. Schmid: Argo Data Management Team, Executive Committee. Member of US Argo Panel
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

Lisan Yu and Robert A. Weller
Woods Hole Oceanographic Institution, Woods Hole, MA

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. 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.

A nearly 50-year (1958-present) analysis of global surface latent and sensible heat fluxes with monthly and daily resolutions has been completed. The datasets are to be released by the end of 2007 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.

Accomplishments

(i) Datasets of air-sea latent and sensible heat fluxes (1958-2006)

We have completed the global analysis of air-sea latent and sensible heat fluxes along with error field estimates for the years from 1958 to 2006 (Fig.1).

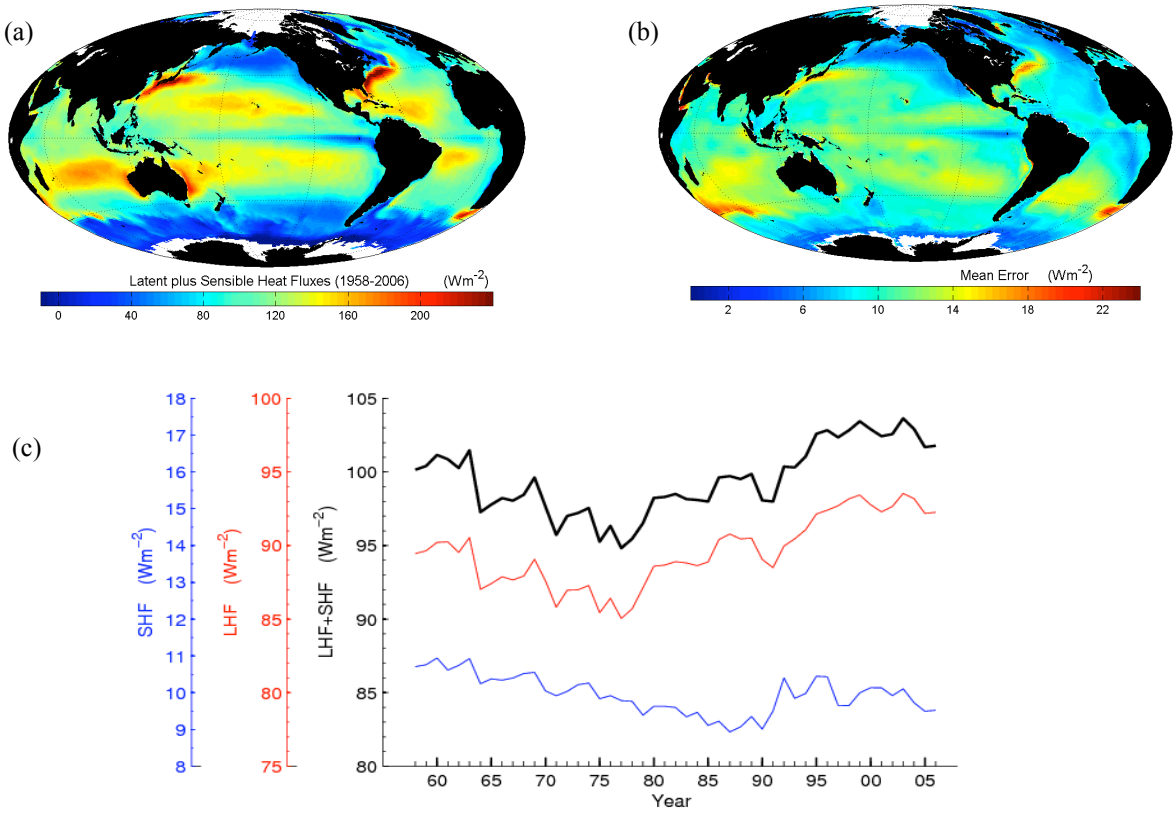


Fig.1 (a) Annual mean latent plus sensible heat fluxes averaged over the 49 year period (1958-2006). (b) Mean error (standard deviation) of the latent plus sensible heat fluxes. (c) Time series of annual-mean latent (red), sensible (blue), and latent plus sensible heat fluxes averaged over global oceans.

The 49-year global daily flux analysis is developed from synthesizing 22 sets of daily variable fields. The 22 input data sets originate from three NWP reanalyses (ERA40, MCEP1, NCEP2) and multiple satellite platforms (AVHRR, SSM/I, QuikSCAT, AMSR-E). The methodology, strategy, and procedure used in developing the 49-year time series were detailed in a technical report (Yu et al. 2007). Also discussed in the report is the accuracy of the OAFlux

products. We have conducted long-term mean comparison using COADS-based (1950-2005) climatological flux atlases, and validated the OAFlux daily time series with in situ daily flux measurements at 107 locations (105 buoys plus 2 ships). The OAFlux estimates have good agreement with long-term means of COADS-based climatologies. Daily latent plus sensible heat flux estimates are unbiased and have the smallest mean error: the mean OAFlux-buoy difference is of 1.0 Wm^{-2} and the mean OAFlux-buoy difference in absolute measure is of 7.4 Wm^{-2}. By comparison, NWP reanalyzed fluxes are largely overestimated (Fig.2).

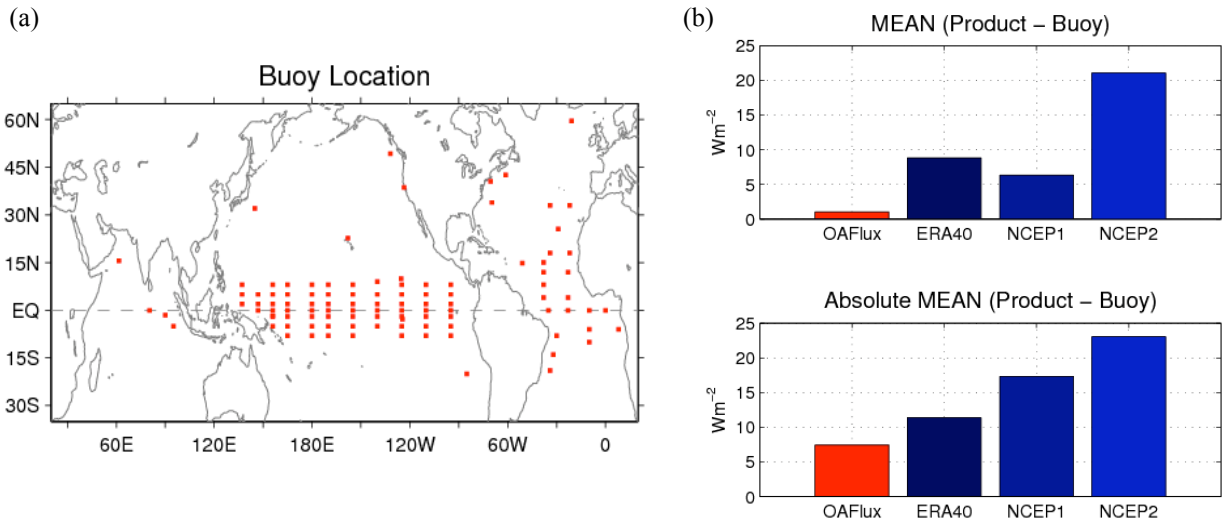


Fig.2 (a) Location of the 105 buoys used in validation analysis. (b) Differences in latent-plus-sensible heat fluxes between product (OAFlux, ERA40, NCEP1, and NCEP2) and buoy averaged over the 107 (105 buoys pus 2 ships) in situ locations. Top panel: mean average (positive and negative signs cancel each other; a measure of bias); Bottom panel: mean average in absolute measure (signs are ignored; a measure of mean variance).

The technical report will support the public release of the 49-year global flux time series at the end of 2007 (http://oaflux.whoi.edu/). This will be the third release[1] of the OAFlux data products that include global latent and sensible heat fluxes, flux-related surface meteorological fields, and error estimates for each flux and variable fields. Monthly products will be available for the entire 49-year period, and daily products will be available from 1985 to 2006, the period that satellite observations became dominant input datasets during OAFlux synthesis.

(ii) Understanding the long-term variability of global heat and water cycle

The 49-year time series (Fig. 1c) shows that the decadal change of the global latent heat flux is marked by a distinct transition from a downward trend to an upward trend around 1977-78. The upward trend coincided with the rapid rise of global sea surface temperature in the 1980s–1990s, suggesting a response of the atmosphere to oceanic forcing (Yu and Weller 2007).

The air-sea latent heat exchange releases not only heat energy but also water vapor to the atmosphere. The ocean evaporation accounts for 86% of global evaporation and is a key

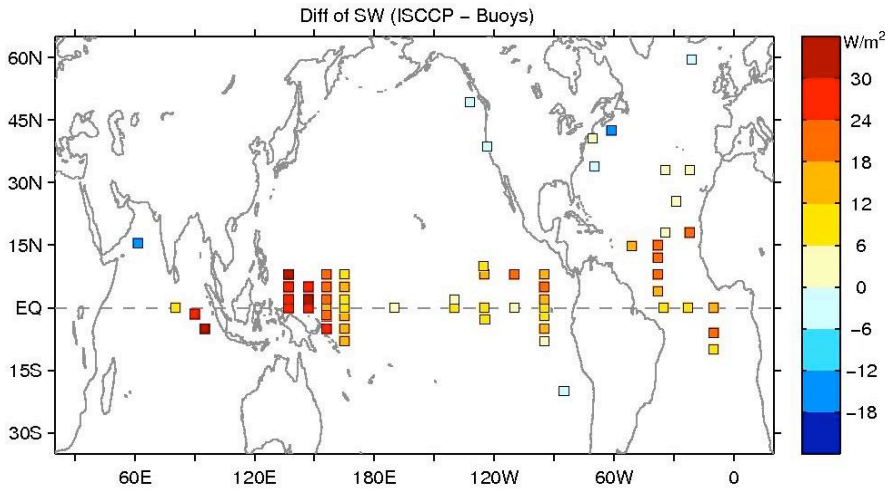
[1] The first version of the OAFlux products was made for the Atlantic Ocean (1988-1999) and released in March 2004. The second version was for the global oceans (1981-2002) and released in December 2005.

component of global water cycle. An increased latent heat flux means increased ocean evaporation and is an indicative of a changing global water cycle (Yu 2007). Evidence of a changing water cycle has been shown in seawater salinity variations. The saltier northern and southern subtropics of the Atlantic Ocean from the 1950s to the 1990s implied a 5–10% increase in net evaporation (i.e., evaporation minus precipitation). Our time series from 1958 to 2006 shows that the ocean evaporation in 1990s is higher than that in early 1960s, consistent with the pattern of change projected by salinity observations.

(iii) Sea-surface shortwave and longwave radiation

Extensive efforts have been made to (1) understand the problems in existing sea-surface shortwave and longwave radiation over the global basins and to (2) develop daily surface radiation products with improved accuracy. Currently, there exist two surface radiation products computed from satellite observations and ancillary data; one is from the International Satellite Cloud Climatological Project (ISCCP) and the other from the NASA/GEWEX Surface Radiation Budget (SRB). These products are not error free. We identified three major biases in the products after comparison analysis with ship-based climatological atlases and with pyranometers (downward shortwave measurements) at 62 buoy locations (Fig.3) and pyrgeometers (downward longwave measurements) at 24 buoy locations (not shown).

(a)



(b)

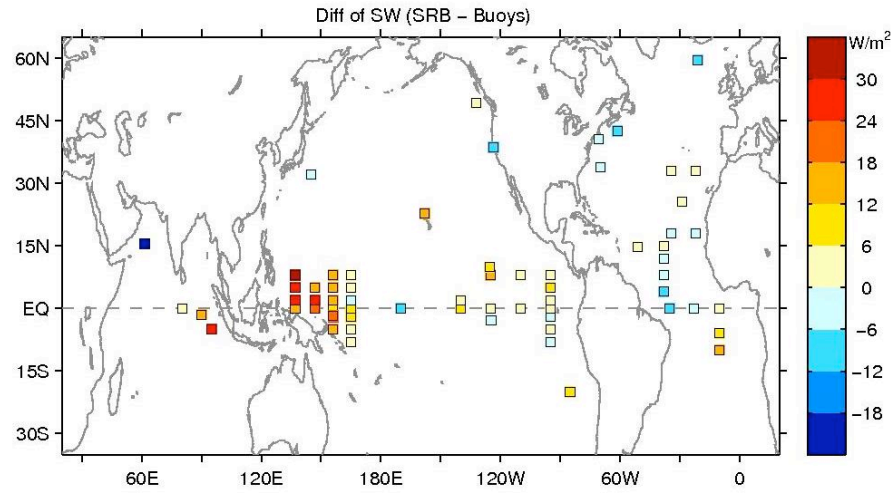


Fig.3 (a) Mean difference between ISCCP and buoy shortwave radiation. (b) Mean difference between SRB and buoy shortwave radiation.

The first problem is the large overestimation of ISCCP incoming solar radiation in the equatorial oceans. ISCCP is severely biased, with the largest bias (>30Wm^{-2}) over the western tropical Pacific and eastern Indian warm water regions. Outside of the equatorial regions, the ISCCP net shortwave radiation is slighted underestimated. By comparison, SRB does a better job in estimating solar radiation. Although there is a similar overestimation bias over the Indo-Pacific warm pool regions, the SRB-buoy differences over other buoy locations are comparatively small (±6Wm^{-2}). The second problem is the spurious reduction in the timeseries of longwave radiation averaged over the global oceans in both ISCCP and SRB datasets (Fig.4). There discontinuities are caused by spurious change of the atmospheric temperature products from the NOAA operational TOVS. The third problem is the so-called the "Indian Ocean Gap" (Fig.5), due to lack of coverage from geostationary satellites over an area centered on 70°E for all of the July 1983 - June 1998 time period, except for April 1988 – March 1989, when data from the INSAT satellite is available to cover the gap. In July of 1998, Meteosat-5 was moved over the gap area, eliminating the gap. Because of the three problems, neither ISCCP nor SRB surface radiation products are ready for climate analysis and modeling study.

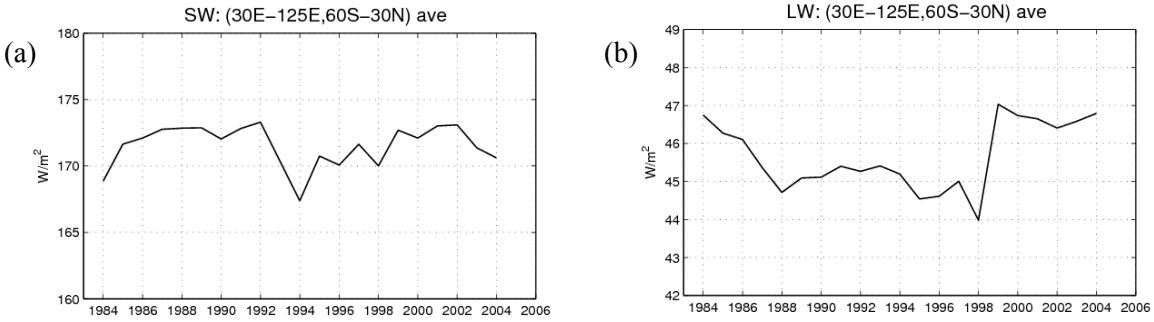


Fig.4 Time series of yearly-mean (a) shortwave (SW) and (b) longwave (LW) radiation averaged over the Indian Ocean. The sudden changes in LW in 1988 and 1999 are spurious.

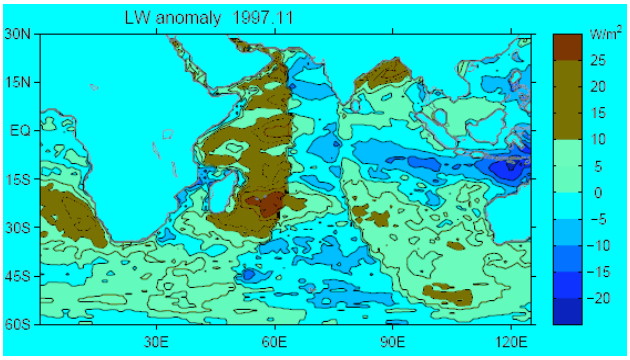


Fig.5 The spatial structure of "The Indian Ocean Gap" in the longwave radiation in November 1997.

Our analyses show that SRB is better than ISCCP in that (1) the mean shortwave radiation is close to buoy mean within ±6Wm^{-2} over most buoy locations except the Indo-Pacific warm pool regions, (2) the time series of SRB longwave radiation is less spurious, and (3) SRB shows better interannual variability (Nof and Yu 2007). But SRB is no any better than ISCCP in the Indian Ocean gap region. In developing an improved daily surface radiation product, the strategy of OAFlux is to use SRB daily estimates as the base and to implement a series of corrections to the base data. Preliminary progress has been made in correcting the Indian Ocean gap (Fig.6). The jump between the inside and outside regions of the gap is caused by two factors. One is the temporal resolution of satellite. The polar orbiting satellites used in filling the gap have only one or two daytime overpasses per day, while geostationary satellites that cover the rest areas have 3-5 times overpasses per daytime depending upon the latitude (between 55 degrees North and South) and the time or year. The other factor is the mean drift in satellite cloud observations. The gap boundaries may suffer from spuriously high cloud amounts due to large view angles. This results in an abrupt drop-off of cloud fraction in the gap as compared to the gap boundaries, and results in a flux discontinuity (Yu 2007b). All in all, the gap is caused by a drift in the mean when there is no coverage from geostationary satellites.

We implemented a smoothing approach to adjust the mean in the gap using EOF modes. The mean adjustment was based on the monthly-mean datasets. We performed EOF analysis for monthly time series for each month, and for each mode we tuned the mean in the gap to match the means of the eastern and western regions outside of the gap, and after that, we reconstructed the field using the mean-adjusted modes. The original SRB radiation fields in the Indian Ocean and the fields after adjustment are shown in Fig.5.

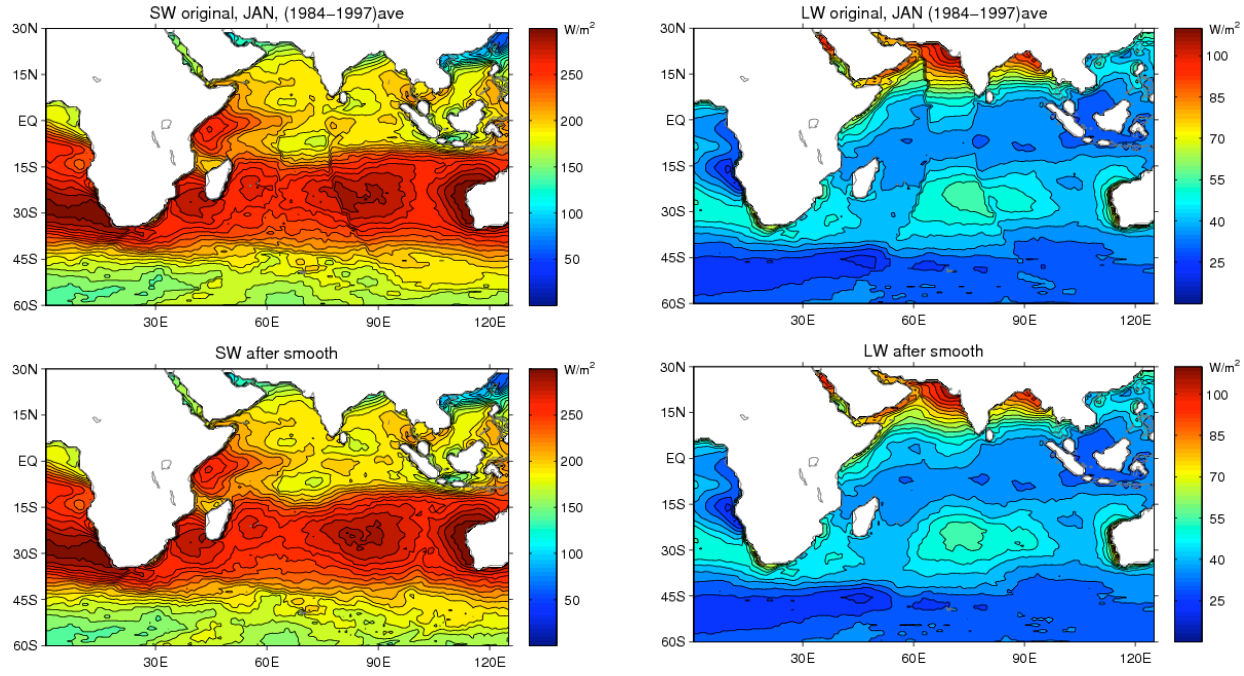
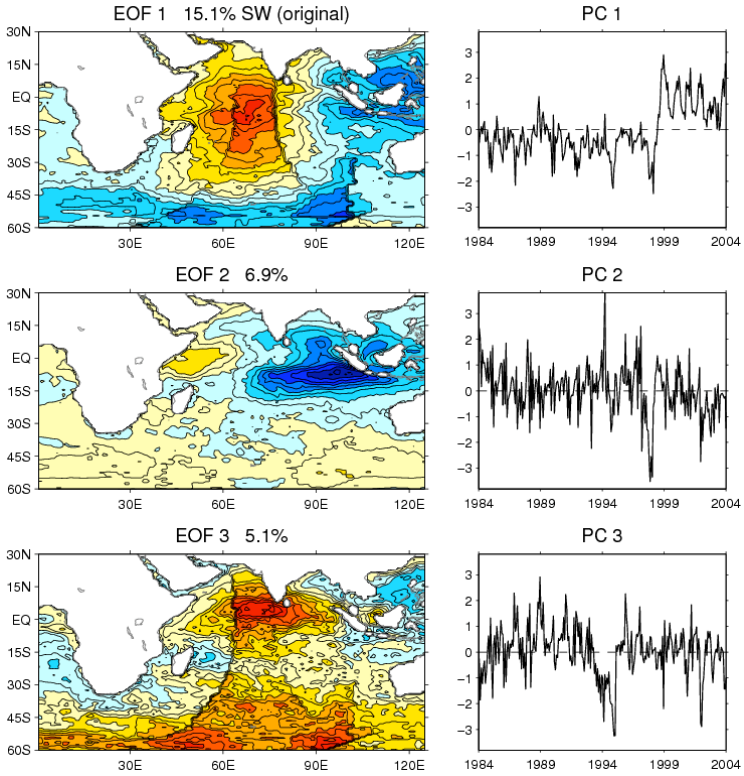


Fig.6 (a) Shortwave and (b) longwave radiation fields in the Indian Ocean from SRB (top panels) and after OAFlux correction (bottome panels).

A key question is whether the mean adjustment alters the variability of the original datasets. Fig.7 shows the first three EOF modes derived from the SRB monthly datasets and from the mean-adjusted monthly datasets. It is apparent that our approach improves the spatial pattern of the modes while retains the variance of the mode and the corresponding principle component (PC) variability.

(a)



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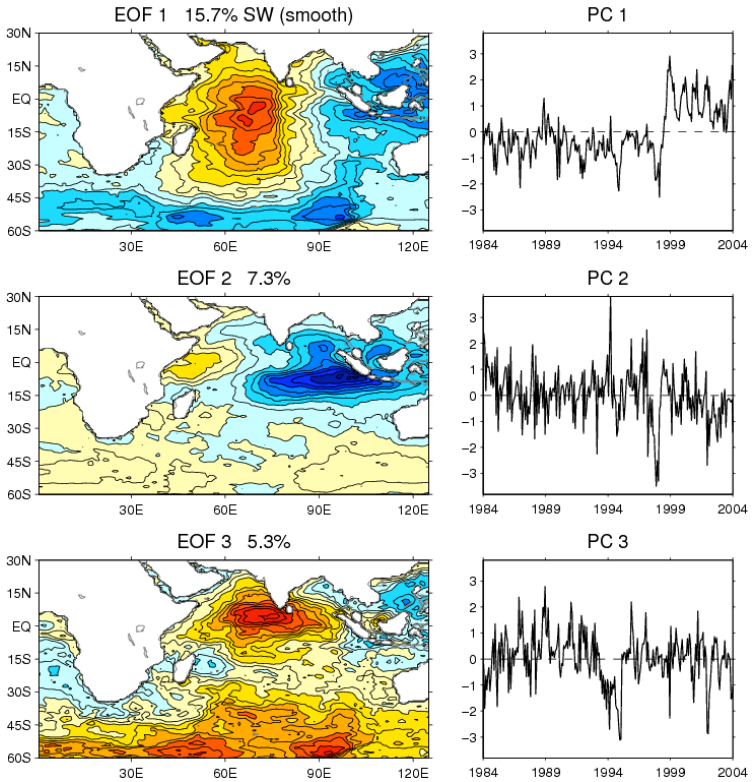

Fig.7 The first three EOF modes derived from the SRB monthly datasets and from the mean-adjusted monthly datasets for the shortwave radiation in the Indian Ocean.

In summary, we have achieved the following in the past year:

(1) Completion of a nearly 50-year global analysis of latent and sensible heat fluxes over global oceans.
(2) Completion of validation analysis using 107 in situ measurement time series.
(3) Completion of error estimation for flux analysis and flux related variables.
(4) Public release of the OAFlux datasets (global latent and sensible heat fluxes and flux-related surface meteorological variables and their error estimates) by the end of 2007.
(5) Completion of 7 refereed manuscripts and 1 WHOI technical report.
(6) Completion of validating ISCCP and SRB shortwave and longwave radiation with 64 pyranometers and 24 pyrgeometers, from which three major error types are identified and a strategy for improving radiation estimates is developed.
(7) Invention of an EOF-mode based smoother to reduce the flux discontinuity caused by the "Indian Ocean Gap".

Publications and reports

Yu, L., and R.A. Weller, 2007: Objectively analyzed air–sea heat fluxes for the global ice-free oceans (1981–2005). *Bull. Amer. Meteor. Soc.*, **88**, 527–539.

Yu, L., X. Jin, and R.A. Weller, 2007: Annual, Seasonal, and Interannual Variability of Air–Sea Heat Fluxes in the Indian Ocean. *J. Climate*, **20**, 3190–3209.

Arguez, A., et al., 2007: State of the Climate in 2006. *Bull. Ameri. Meteor. Soc.*, 88, s1-s135.

Yu, L., 2007a: Global variations in oceanic evaporation (1958-2005): The role of the changing wind speed. *J.Climate*.

Yu, L., 2007b: Sea surface exchanges of momentum, heat, and freshwater determined by satellite remote sensing. *Encyclopedia of Ocean Sciences,* Steve A. Thorpe and Karl K. Turekian, Eds. Accepted.

Nof, D., and L. Yu, 2007: Is radiation important for the variability of the MOC in the North Atlantic? *Ocean Science*. Submitted.

Bernard, B., A. J. Busalacchi, E. Campos, F. Hernandez, R. Lumpkin, M. J. McPhaden, A. D. Moura, P. Nobre, S. Planton, J. Servain, J. Trotte, L. Yu, 2007: The PIRATA Program: History, Accomplishments, and Future Directions. *Bull. Ameri. Meteor. Soc.* Revised.

Yu, L., X. Jin, and R. A. Weller, 2007: Global flux datasets from the Objectively Analyzed Air-sea Fluxes (OAFlux) project: Latent and sensible heat fluxes and related surface meteorological variables (1958 – 2006). WHOI Technical Report - 2007. 64pp.

Climate Variability in Ocean Surface Turbulent Fluxes

Mark A. Bourassa, Shawn R. Smith and Eric Chassignet
Center for Ocean-Atmospheric Prediction Studies (COAPS), The Florida State University, Tallahassee, FL

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[1] and East Coast storm intensity and storm tracks[2]. On smaller spatial and temporal scales they can be related to the storm surge, and tropical storm intensity. On longer temporal scales, several well-known climate variations (e.g., El 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 associated impact on regional weather patterns could be extremely useful to the agricultural community. Agricultural decisions in the southeast U.S. sector based on ENSO predictions could benefit the U.S. economy by over $100 million annually[3]. A similar, more recent estimate for the entire U.S. agricultural production suggests economic value of non-perfect ENSO predictions to be over $240 million annually[4]. These impacts could easily be extended to other economic sectors, adding further economic value. Moreover, similar economic value could be foreseen in other world economies, making the present study valuable to the global meteorological community.

ENSO, PDO, and NAO (AO) each have atmospheric and oceanic components that are linked through the surface of the ocean. Changes in the upper ocean circulation result in modifications to the SST and near surface wind patterns. Variations in SSTs can be related to ENSO and other

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[1] Enfield, D. B., A. M. Metas-Nuñez, and P. J. Trimble, 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. *Geophy. Res. Let.*, **28**, 2077-2080.

[2] Hurrell, J.W., and R.R. Dickson, 2004: Climate variability over the North Atlantic. Marine Ecosystems and Climate Variation - the North Atlantic. N.C. Stenseth, G. Ottersen, J.W. Hurrell, and A. Belgrano, Eds. Oxford University Press, 2004.

[3] Adams, R. M., K. J. Bryant, B. A. McCarl, D. M. Legler, J. O'Brien, A. Solow, and R. Weiler, 1995: Value of improved long-range weather information. *Contemporary Economic Policy*, **13**, 10-19.

[4] Solow, A. R., R. F. Adams, K. J. Bryant, D. M. Legler, J. J. O'Brien, B. A. McCarl, W. Nayda, and R. Weiler, 1998: The value of improved ENSO prediction to U. S. agriculture. *Climate Change*, **39**, 47-60.

climate patterns; however, it is the fluxes of heat and radiation near the ocean surface that transfer energy across the air-sea interface. It is an improved understanding of these turbulent fluxes and their variability that motivates our research (radiative fluxes are difficult to accurately estimate from in situ data; however, satellite-based estimates are available). By constructing high quality fields of surface fluxes we provide the research community the improved capabilities to investigate the energy exchange at the ocean surface.

FSU produces both monthly in-situ based (the FSU3) and hybrid satellite/numerical weather prediction (NWP) fields of fluxes and the flux-related variables. Our long-term monthly fields are well suited for seasonal to decadal studies, and our hybrid satellite/NWP fields are ideal for daily to annual variability and quality assessment of the monthly products. The flux-related variables are useful for ocean forcing in models, testing coupled ocean/atmospheric models, and for understanding climate related variability (e,g., the monthly Atlantic surface pressure is a good indicator of extreme monthly air temperatures over Florida).

The flux project at FSU targets the data assimilation milestones within the Program Plan. Our assimilation efforts combine ocean surface data from multiple Ocean Observing System networks (e.g., VOS, moored and drifting buoys, and satellites). One set of performance measures targeted in the Program Plan is the air-sea exchange of heat, momentum, and fresh water. When the FSU products are combined with ocean models (either at FSU or other institutes), performance measures relating to surface circulation and ocean transports can be addressed. The FSU flux project also focuses on the task of evaluating operational assimilation systems (e.g., NCEP and ECMWF reanalyses) and continues to provide timely data products that are used for a wide range of ENSO forecast systems. All products are distributed in a free and open manner at: http://www.coaps.fsu.edu/RVSMDC/FSUFluxes/.

Accomplishments

Over the past year our focus has deviated from our stated deliverable for FY 2007. The air-sea flux community has produced a number of in-situ, satellite, model-based flux products and there has been great interest in determining how the products compare. An analysis of nine flux products (including the FSU Fluxes) has been completed, and it has revealed a vast difference between these products. We began production of research-quality, in-situ monthly flux fields for the tropical and north Pacific Ocean. During this process, we identified some problems that result in unrealistic fields around the TAO moorings (a similar problem was identified in many of the comparison products). The product release has been delayed until we can modify our analysis to remove this feature. We also continued our operational production of monthly quick-look wind fields for the tropical Pacific and Indian Oceans.

Global and Regional satellite stress products have continued to improve through more effective use of rain-flagged (suspect) observations. We now eliminate far less suspect data, and have more physically consistent fields around tropical cyclones. We have also developed a preliminary technique for the direct calculation of stress from scatterometer backscatter. This approach should address several issues that could result in substantial regional biases in our stress products.

Deliverables for FY 2007 included:

1. Update Atlantic, Indian, and Pacific Oceans using new ICOADS releases (if available)

2. Complete Equatorial and North Pacific 1˚ winds and fluxes
3. Begin operational production and distribution of quick-look, 1˚ in situ fluxes for the Atlantic, Indian, and Pacific Oceans
4. Extend the Atlantic Ocean fluxes back in time from 1978
5. Continue comparisons of FSU winds and fluxes to other available in-situ, satellite, and blended flux products
    - Subtask1: Add GODAS fluxes to comparison
6. Objective estimation of uncertainty in flux fields and related variables
    - Subtask1: First complete uncertainties for wind vector components
7. Production of satellite and NWP hybrid fluxes.
    - Subtask1: Estimate biases in NWP near surface temperatures and humidities

Update products using new ICOADS releases [Deliverable 1]

No updates for ICOADS were made available in FY 2007; therefore, we did not complete any updates or extensions to our products past 2004. We anticipate an ICOADS update to be released in 2008, so this task will be pushed forward.

Complete Equatorial and North Pacific 1˚ in-situ fluxes [Deliverable 2]

In FY 2007, we completed the automated and visual data quality evaluation for the tropical and North Pacific Ocean fluxes for the period 1990-2004. The 1˚ wind and flux products (the FSU3) for the Pacific Ocean revealed a problem with our handling of moored buoys (especially in the tropics) which resulted in the mooring chains being evident in the objective flux fields (Figure 1). We are beginning to test several solutions to this problem, and will implement the successful combination in FY 2008. The problem is due to the sparse longitudinal sampling of the TAO buoys, and to small but widespread and seasonally varying biases relative to the ship observations. We also found that many ship observations had been misclassified (in ICOADS) as moored buoys. We have developed an automated technique for removing the vast majority of such misclassified data, and are in the process of investigating the impacts on our products.

Production of in-situ quick-look products [Deliverable 3]

Although we were unable to implement quick-look versions of the 1˚ objective FSU fluxes, we continue to create an older version (the FSU2) 2˚ tropical Pacific Ocean wind (pseudo-stress) fields based on near-real time in-situ data. Quick-look 2˚ gridded pseudo-stress fields are produced at the beginning of each month using the previous month's GTS-transmitted data. In addition to the Pacific, COAPS continues to produce one-degree pseudo-stress fields for the tropical Indian Ocean using the method of Legler et al.[5]. Related research quality products exist through 2004 for the Pacific and 2003 for the Indian Ocean. We have not updated the FSU2 and Legler research products as we had anticipated switching to the Bourassa 3.0 method. This switch was delayed by the desire of the flux community to have an assessment of multiple flux products (including the FSU3). We also must solve the problem with the mooring data revealed while creating the FSU3 for the tropical Pacific (figure 1). We will push the quick-look FSU3 product forward to FY 2008. Both two-degree fields for the Pacific Ocean and one-degree fields

[5] Legler, D. M, I. M. Navon, and J.J. O'Brien, 1989: Objective analysis of pseudostress over the Indian Ocean using a direct-minimization approach. *Mon. Wea. Rev.*, **117,** 709-720.

for the Indian Ocean FSU winds are available at http://www.coaps.fsu.edu/RVSMDC/SAC/index.shtml.

As part of our continued production of the FSU2 for the tropical Pacific Ocean, we now produce additional monthly graphics for inclusion into the on-line version of the NOAA Climate Diagnostics Bulletin (http://www.cpc.ncep.noaa.gov/products/CDB/).

Extend the Atlantic Ocean fluxes back in time from 1978 [Deliverable 4]

This activity was delayed due to the need for a detailed comparison of available monthly flux products. Due to flat budgets in recent years and shifting priorities in the air-sea flux community, this deliverable has been removed from our FY 2008 work plan. When sufficient resources can be obtained (either via add tasks or other agency funding), we will extend our series back prior to 1978.

Continue comparisons of FSU winds and fluxes to available products [Deliverable 5]

As mentioned above, a detailed comparison of the FSU3 to other freely available air-sea flux products was a priority for FY 2007. We found large differences in scalar wind speed, humidity, and heat fluxes. Examples of these differences are apparent in the zonal quantiles for the Indian and Atlantic Oceans (Figure 2). The magnitude of the LHF differences can reach 80 Wm^{-2} at some latitudes. The magnitude of the differences varies at different quantiles. Examining the quantiles shows additional variability in the spread of the LHF distribution between the nine flux products. We also found substantial differences in the curl and divergence of these products, which are important considerations for ocean forcing (curl) and cloud processes (divergence). In many cases, the observing system (and numerical ring from the NCEP1 product) was easily identified in the derivative fields. This finding indicates serious problems in using these products to force ocean models. We also found that the differences in products were more than offsets and proportionalities: there were very large differences in statistical distributions of the data, which would again be important for ocean forcing. This activity will be ongoing.

Objective estimation of uncertainty in flux fields and related variables [Deliverable 6]

We have made little progress on this task. We have coded the necessary calculations (which are extremely complex), but are still in the process of debugging. This task will be continued in 2008.

Production of satellite and NWP hybrid fluxes. [Deliverable 7]

We produce equivalent neutral pseudostress fields, which can easily be used to determine surface stress. For isolated projects we produce hybrid NWP and satellite fluxes; however, we believe that there are substantial errors in the heat fluxes that should be addressed prior to public release of these products. This task will be continued in 2008.

Publications and Reports

Refereed

Arguez, A., J. J. O'Brien, and S. R. Smith, 2007: Air Temperature Impacts over Eastern North America and Europe Associated with North Atlantic SST Variability. *Int. J. Climatol.*, submitted.

Hughes, P. J., M. A. Bourassa, J. J. Rolph, and S. R. Smith, 2007: Tropical Atlantic flux variability. *J. Atmos. Ocean. Technol.*, in preparation.

Kara, A. B., A. J. Wallcraft, C. N. Barron, E. J. Metzger, H. E. Hurlburt and M. A. Bourassa, 2007: Accuracy of 10 m Wind Speeds from Satellites and NWP Products Near Land–Sea Boundaries, *J. Geophys. Res.*, submitted.

Kennedy, A. J., M. L. Griffin, S. L. Morey, S. R. Smith, and J. J. O'Brien, 2007: Effects of El Niño-Southern Oscillation on sea-level anomalies along the Gulf of Mexico coast. *J. Geophys. Res.*, **112**, C05047, doi:10.1029/2006JC003904.

Morey, S. L., D. S. Dukhovskoy, and M. A. Bourassa, 2007: Connectivity between variability of the Apalachicola River flow and the biophysical oceanic properties of the northern West Florida Shelf. *Continental Shelf Research*, submitted.

Rolph, J. J., R. Banks, M. A. Bourassa, and S. R. Smith, 2007: Indian Ocean flux variability. *J. Climate*, submitted.

Smith, S. R., C. Tartaglione, J. J. O'Brien, and J. Brolley, 2007: ENSO's impact on regional U.S. hurricane activity. *J. Climate*, **20**, 1404-1414.

Technical reports and other publications

Bourassa, M. A., D. Dukhovskoy, S. L. Morey, and J, J. O'Brien, 2007: Innovations in Modeling Gulf of Mexico Surface Turbulent Fluxes. Flux News, Issue 3, World Meteorologica1 Organization, eds. Bernard Barnier and Sergey Gulev, 9.

Bourassa, M. A, R. N. Maue, S. R. Smith, P. J. Hughes, and J. Rolph, 2007: Global winds. *State of the Climate in 2006*. A. Arguez, H. J. Diamond, F. Fetterer, A. Horvitz, and J. M. Levy, Eds., *Bull. Amer. Meteor. Soc.*, 88, S25-S27.

Smith, S. R., A. Bentamy, and C. A. Clayson, 2006: SEAFLUX 3rd Workshop. FLUX NEWS, Newsletter of the WCRP Working Group on Surface Fluxes, WCRP, Issue 2. [Available from http://www.esrl.noaa.gov/psd/psd3/wgsf/].

Conference proceedings/presentations

Bourassa, M. A., and P. J. Hughes, 2006: Sensitivity of surface turbulent fluxes to errors in bulk formula inputs. *HYCOM NOPP GODAE* Meeting. Nov. Tallahassee, FL.

Bourassa, M. A., and S. R. Smith, 2007: Improving air-sea flux estimation with a new wave-dependant parameterization and high-quality research vessel observations. *ONR Progress Review – Southeast Region*, Tallahassee, FL.

Bourassa, M. A., P. J. Hughes, and S. R. Smith, 2006: Comparison of surface turbulent flux products, *Fall AGU Meeting*, Dec., CA.

Bourassa, M. A., P. J. Hughes, J. Rolph, and S. R. Smith, 2007: North Atlantic decadal variability of ocean surface fluxes. *7th Workshop on Decadal Climate Variability*, April, Waikoloa, HI.

Bourassa, M. A., P. J. Hughes, and S. R. Smith, 2007: Comparison of surface turbulent flux products. Joint , Sept., Amsterdam, Netherlands.

Bourassa, M. A., P. J. Hughes, and S. R. Smith, 2007: A fear-inspiring intercomparison of monthly averaged surface forcing. 4th SEAFLUX Workshop, Sept., Amsterdam, Netherlands.

Bourassa, M. A., Paul J. Hughes, Jeremy Rolph, and Shawn R. Smith, 2007: Hurricanes and Atlantic Surface Flux Variability. *NOAA Climate Observation Division 5th Annual System Review*, June, Silver Springs, MD.

Bourassa, M. A, J. Rolph, P. Hughes, and S. R. Smith, 2007: An update of the FSU3 Winds and Fluxes. *Climate Observation Division 5th Annual System Review*, Silver Spring, MD, USA, NOAA, in press.

Dukhovskoy, D.S., M.A. Bourassa, S.L. Morey, and J.J. O'Brien, 2007: Modeling studies of the ocean response to a tropical cyclone. *7th Workshop on Decadal Climate Variability*, April, Waikoloa, HI.

Hughes, P. J., M. A. Bourassa, J. Rolph, and S. R. Smith, 2006: North Atlantic decadal variability of latent and sensible heat fluxes. *Fall AGU Meeting*, Dec., San Francisco, CA

Hughes, P. J., and M. A. Bourassa, 2007: Variability of latent and sensible heat fluxes over the tropical Atlantic. *ONR Review*, May, Tallahassee, FL.

Josey, S. A. (presented by S. R. Smith), 2006: Evaluation of Air-Sea Fluxes. *2nd CLIVAR Global Synthesis and Observation Panel meeting*, La Jolla, CA, USA, 8 and 9 December 2006.

Figures

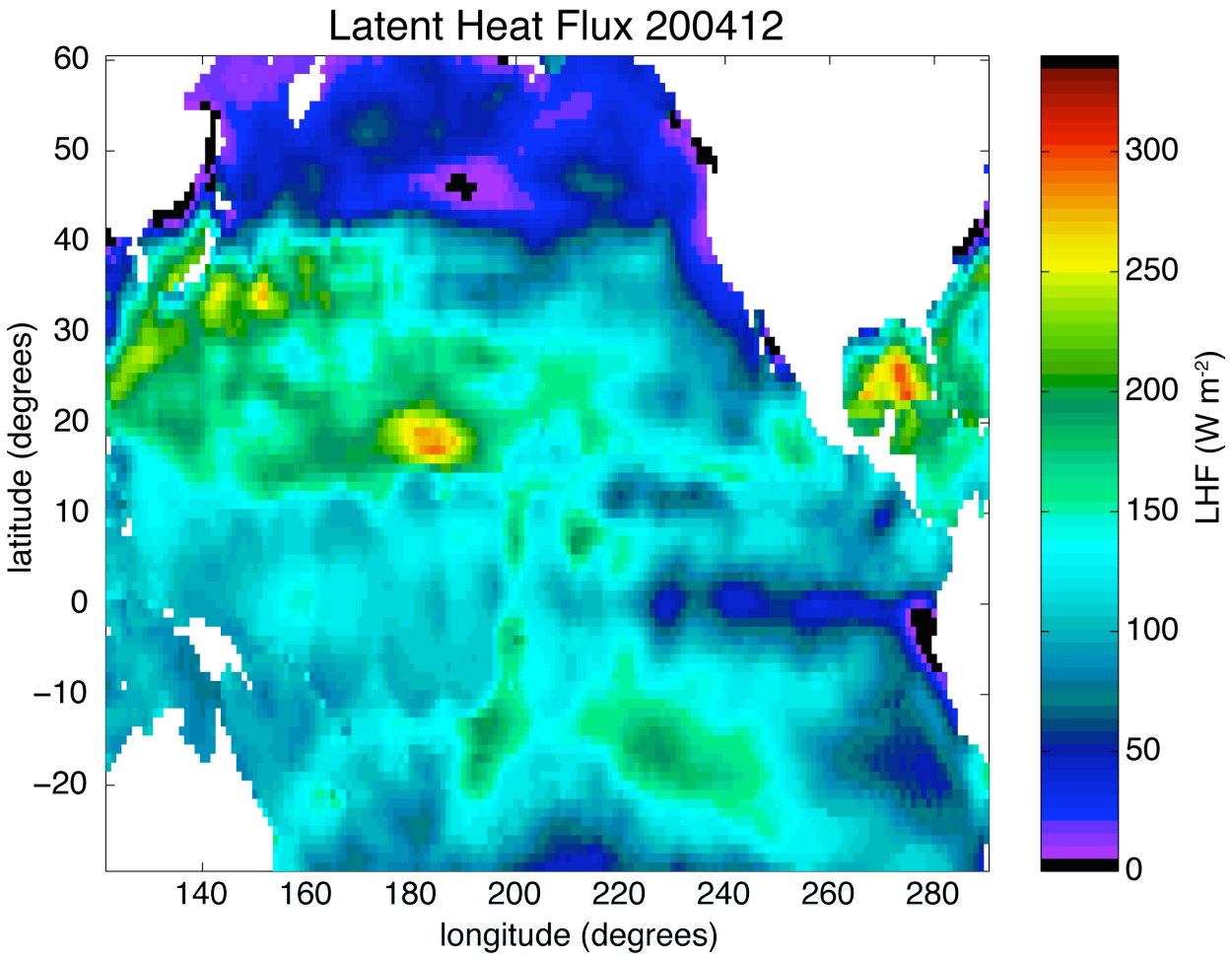
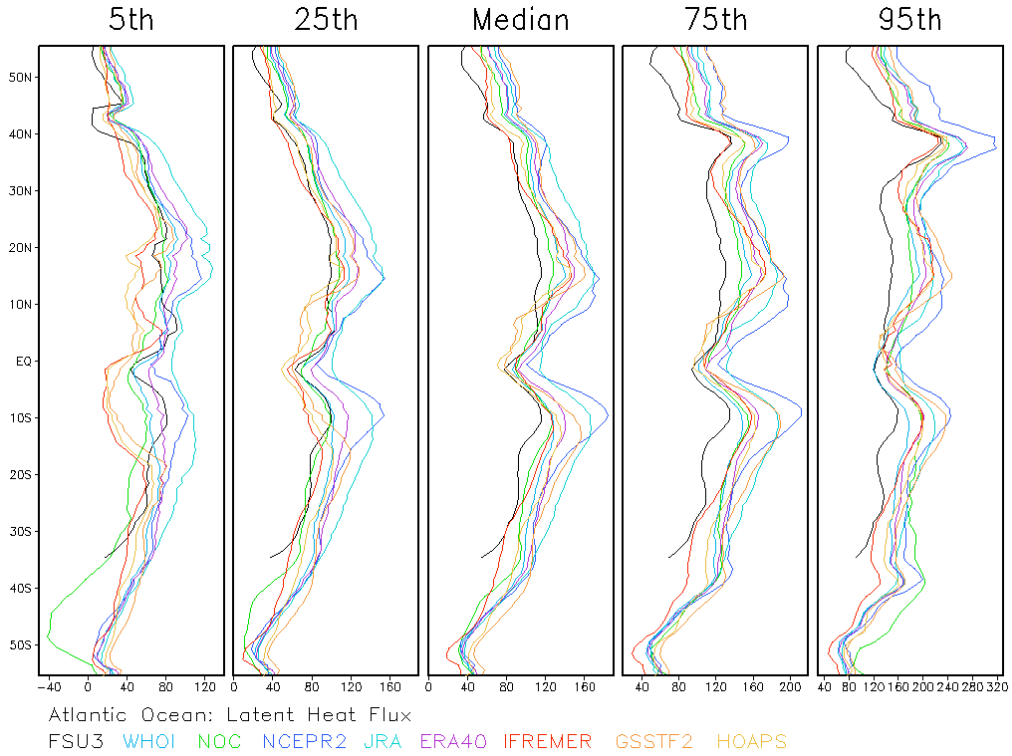


Figure 1. An example of the preliminary FSU3 latent heat flux field for December 2004. The elliptical patterns in the field along the equator are caused by the TAO moorings in the tropical Pacific. These artificial features will be removed through modifications to our objective gridding technique.

(a)



(b)

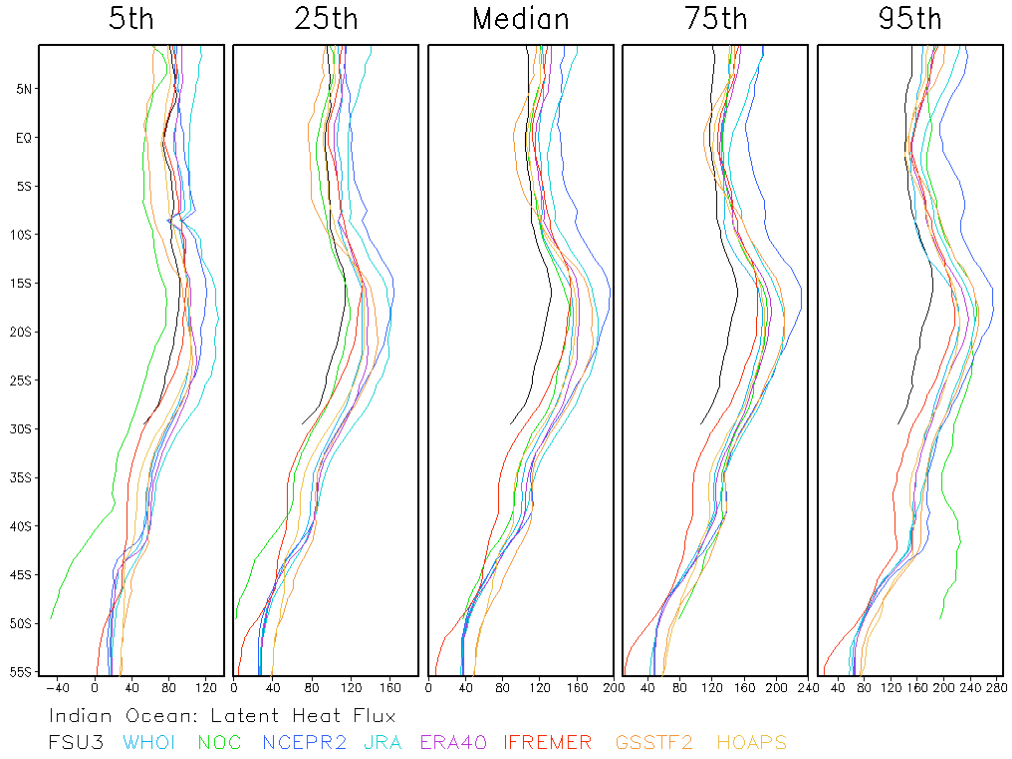


Figure 2. Zonal quantile values for latent heat flux for the (a) Atlantic and (b) Indian Oceans. Values are presented for nine flux products. All products are on a common 1˚ grid and use a common land mask. Substantial differences (upwards of 80 Wm^{-2}) exist between the products.

Air-Sea Exchanges of Fresh Water: Global Oceanic Precipitation Analyses

Pingping Xie[1], John Janowiak[1], and Phillip Arkin[2]
[1] NOAA Climate Prediction Center, Camp Springs, MD
[2] Earth Systems Science Interdisciplinary Center, University of Maryland, College Park, MD

1. PROJECT SUMMARY

Oceanic Fresh water flux is an essential component of the global water cycle and plays an important role in forcing the oceanic circulation. However, its mean state, short-term variability and long-term changes are poorly monitored and documented due to undesirable qualities of the data sets for its two primary components, precipitation (P) and evaporation (E). Two major factors restricting the quality of existing oceanic fresh water flux data sets are 1) the lack of an extensive and continuous network of in-situ observations for calibrating and verifying each component, and 2) insufficient efforts to synthesize analyses for E and P. The availability of many new observation-based and model-produced data sets, especially precipitation, surface air temperature, sea surface temperature, humidity, and wind, makes it possible to quantitatively calibrate, verify and refine the existing P and E products.

In the past decade, two sets of satellite-based precipitation products have been developed at NOAA's Climate Prediction Center (CPC) that are used to monitor precipitation variations over global oceans. The CPC Merged Analysis of Precipitation (CMAP, Xie and Arkin 1997) is defined by merging individual products of satellite estimates derived from infrared (IR) and microwave (MW) observations. The CMAP data sets are created on a 2.5^{o}lat/lon grid over the globe and on monthly and pentad (5-day) time resolution for a 28-year period from January 1979 to the present. The other CPC oceanic precipitation analysis is that generated by the CPC Morphing Technique (CMORPH, Joyce et al. 2004) for high temporal / spatial applications. Cloud/precipitation movement vectors are first computed from high-resolution infrared image data in 30-min intervals observed by geostationary satellites. These movement vectors are then used to separately 'propagate' precipitation systems observed (by more-physically-based but less frequently sampled PMW observations) both forward/backward in time from "past"/"future" PMW scans to get the analyzed fields of precipitation at the targeted times. By weighting the forward and backward propagated rainfall estimates by the inverse of their respective temporal distance from scan time, these separate propagations are then morphed. The CMOPRH precipitation analysis is produced on an 8kmx8km grid over the globe from 60°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 2007 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 and other observation-based data sets of precipitation and evaporation; and 2) Continuous updates and improvements of the current CMAP for better quantitative applications over ocean. In FY2007, we have focused our efforts on the examination of the quantitative uncertainties of the currently available oceanic precipitation and evaporation data sets and applied the observation data to assess the oceanic fresh water budget in several NCEP model-based products with consideration of uncertainties in the observations.

Three sets of widely used precipitation data sets are used here to define the 'best possible' observation of oceanic precipitation. These include the CPC merged analysis of precipitation (CMAP, Xie and Arkin), the Global Precipitation Climatology Project (GPCP) gauge-satellite merged analysis (Adler et al. 2003), and the Tropical Rainfall Measurement Mission (TRMM) merged precipitation analysis. Arithmetic mean of and root mean square (RMS) differences among the three data sets are computed for each grid box and defined as the 'best guess' of oceanic precipitation and the proxy index of its

quantitative uncertainties, respectively. Largest uncertainties of oceanic precipitation analysis are observed over tropics along the rainbands associated with the ITCZ and over high latitude oceans where satellite observations are less reliable (fig.1). On average, uncertainties of the analyses are about 10% of the precipitation amount.

Similar calculations are performed for oceanic evaporations using four popular observation-based data sets, including the satellite-based products of the GSSTF2 of Chou et al. (2003), the HOAPS3 of Grassl et al. (2000), and the J-OFURO2 of Tomita et al. (2007), and the COADS-based SOC climatology of Josey et al. (1998,1999). Uncertainties of the observed seasonal climatology of oceanic evaporation are around 10% of the magnitude of mean climatology, with larger uncertainties over eastern Pacific and oceanic regions around the Maritime Continent (fig.2). Combined, the observed long-term mean of precipitation (P) and evaporation (E) presents net fresh water coming into/out of the ocean in tropics/subtropics, respectively, with a quantitative uncertainty of 10-15% in the annual/seasonal mean climatology defined by the currently available observation data sets (fig.3).

Seasonal and interannual variations of global fresh water flux generated by the NCEP operational Global Data Assimilation System (GDAS), Reanalysis 1, Reanalysis2, Global Forecast System (GFS) atmospheric model and the Climate Forecast System (CFS) coupled ocean-atmosphere model are then examined against the observations described above. NCEP reanalysis 2 is utilized to force the Global Oceanic Data Assimilation System (GODAS) and initialize the CFS climate forecast model, while the GDAS is an analysis system taking advantage of the state-of-the-art modeling technology and newly available observation inputs. Among the five NCEP model-based products examined here, Reanalysis 1 reproduced the magnitude of E and P very well, while all other products tend to produce excessive amount of both E and P over the ocean (fig.4).

Interannual variations (monthly anomaly) of precipitation are reasonably well captured by the NCEP GDAS and the two reanalyses, especially over tropical Pacific and the northern Atlantic (not shown), while those of evaporation presents good agreements with the observations over most of the extra-tropical oceanic areas (fig.5). The state-of-the-art NCEP Global Data Assimilation System generates both the oceanic precipitation and evaporation fields with better agreements with the observations than the NCEP reanalyses, indicating potential of further improvements upon the current generation reanalyses through refined models and enhanced input observation data (figure not shown). Substantial differences in the evaporation over tropical oceans are attributable to multiple factors including differences in the state variables (surface wind, air temperature and humidity) and the bulk algorithms used to compute the evaporation used in both the models and the observation data sets. Further work is underway to determine the contribution of each factor.

To support our efforts of monitoring and examinations of oceanic precipitation, the monthly and pentad CMAP precipitation have been updated throughout FY2007. As of November 2007, the standard version of the monthly and CMAP precipitation data sets have been updated through September 2007, while the real-time version pentad CMAP

data set has been updated on a quasi-real-time basis, available one day after the end of each pentad period.

2.2 CMORPH Global Precipitation Analyses

The overall goal of this part of our project is to improve the CMORPH and to apply the technique to produce high-resolution oceanic precipitation for an extended period. Although the CMORPH analysis are available for recent years when we have microwave observations from multiple satellites, the high space and time resolution of the analysis makes it a powerful means to monitoring and assess the oceanic precipitation of meso- to synoptic scales over the global oceans from 60°S to 60°N.

Our original plan for FY2007 focused more on the back extension of the CMORPH high-resolution precipitation analysis beyond December 2002. Due to the delay in upstream input satellite data and the migration of CPC computer systems, we had to adjust our work plan and carried out other tasks that are critical to the accomplishment of our goal. The following is a list of the tasks we have accomplished during FY2007:

- Improvement of a retrieval algorithm to derive precipitation from AMSU satellite observations

Our CMORPH technique defines precipitation analysis by combining information from estimates made from individual satellites. Refinement of the precipitation estimates from these individual satellites is fundamental to the success of our project. During FY2007, we actively participated in the development of a new algorithm to derive precipitation from satellite microwave observations of AMSU led by our colleagues in NOAA/NESDIS. The new algorithm takes advantage of cloud liquid water derived from the AMSU-A instruments and a convective index computed from the 183GHz channel data, yielding precipitation estimates with much improved quality than those based on AMSU-B instrument observation alone and used as one of the inputs to our CMORPH technique. The new AMSU estimates derived from this new technique will be used to replace the current AMSU data in near future. A paper describing the algorithm has been published in *J. Geophys. Research.*

- Regional validation and global examinations of the new AMSU algorithm

A comprehensive evaluation is performed for the precipitation estimates derived from the new AMSU algorithm described above. Such examination is critical to better understand the quantitative behavior of the estimates before they may be incorporated into our CMORPH merging technique. For this purpose, precipitation estimates derived from both the new and old AMSU algorithms are examined using data from NOAA 15, 16, 17, and 18 for July 2005. These AMSU-based precipitation estimates are then compared against the high-quality surface rainfall estimates generated by the TRMM "2A12" algorithm (Kummerow, 1998). Both the AMSU-based estimates and the TRMM "2A12"

products are remapped to a 0.25^{o} lat/lon grid, and collocated observations from the AMSU and TRMM that occurred within 30 minutes of each other were retained to calculate the statistics.

Our comparison showed that the new AMSU estimates present much better comparison statistics than the old AMSU estimates (Weng et al. 2003). In general, the correlation of the new AMSU estimates with the TRMM data is higher than that of the old estimates, especially over southern hemisphere (fig.6). While the old AMSU algorithm over-/under-estimates precipitation over tropics/high latitudes, respectively, the new algorithm generates precipitation estimates with a latitudinal profile much close to that of the high-quality TRMM product (fig.7). Raining area of the new AMSU estimates, however, is smaller than that of the TRMM estimates, suggesting that the new AMSU algorithm still tends to overestimate heavy rainfall events compared to the TRMM (fig.8).

Differences between the new and old AMSU estimates are examined over various parts of the global oceans. Over the tropical oceanic regions, the new algorithm produces an overall reduction in the rainfall amount (fig.9), while overall rainfall frequency shows an increase, especially in subtropical anticyclonic regions (fig.10). For mid-latitudes, an increase in the amount and frequency of rain events is observed over the ocean with the estimates derived from the new algorithm, especially poleward of 25° in both hemispheres (fig.9&10). It is also notable that the new estimates are in a good agreement over oceanic regions when compared with other PMW techniques (i.e., SSM/I GPROF V6) and high quality collocated retrievals (TMI 2A12) at global and regional scales.

Based on these results, we concluded that the precipitation estimates produced by the new AMSU algorithm present better performance in representing the spatial distribution, temporal variations and frequency of rainfall events with various intensity and will be used to replace the current AMSU estimates.

- Extend the CMORPH period of record back beyond December 2002

Currently, CMORPH high resolution precipitation estimates are available for a period from December 2002 to the present. As an important part of this project, we are in process of extending the CMORPH data record back for the period before December 2002.

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. Precipitation estimates derived from these passive microwave observations are generated by scientists in NASA/GSFC, NOAA/NESDIS and other institutions and used as inputs to our merging processes. To date, we have acquired approximately 90% of the necessary passive microwave data from all available sources back to 1998. Currently we are waiting for the retrospective reprocessing of the GPROF V6 algorithm for the SSMI instruments aboard the DMSP satellites.

In order to extend the CMORPH record to before December 2002, it is also necessary to retrieve global, ½ hourly, native resolution (~ 4 km) IR data from the 5 geosynchronous meteorological satellites that, when combined, afford complete global coverage in longitude. Fortunately, these data were saved by CPC back to late 1998. However, the data were saved in raw ("McIDAS") format on several hundred CDROMs. Thus, a non-trivial effort was expended in FY2007 to copy the data on the CDROMs to tapes. This effort will enable the global merging and QC of the IR data prior to its use in the CMORPH processing.

- Reprocess the entire CMORPH period of record using a frozen system in which all recent improvements have been incorporated

As described before, we had to defer this task to next fiscal year due to the delay in the SSM/I-based precipitation estimates and the technical difficulties caused by the migration of computer systems at CPC.

3. PUBLICATIONS

Vila, D., R. Ferraro, and R. Joyce, 2007: Evaluation and improvement of AMSU precipitation retrievals. *J. Geophys. Res.*, **112**, D20119, doi:10.1029/2007JD008617.

Xie, P., W. Wang, J.E. Janowiak, M. Chen, C.L. Shie, and L. Chiu, 2007: Seasonal and interannual variations of fresh water flux over the global oceans in the NCEP CDAS, CDS2, GDAS, GFS and CFS. *IUGG 2007 General Assembly*, Perugia, Italy, July 2-13, 2007.

Xie, P., W. Wang, J.E. Janowiak, M. Chen, C.L. Shie, and L. Chiu, 2007: Examining fresh water flux over global oceans in the NCEP CDAS, CDAS2, GDAS, GFS and CFS. *NOAA 32nd Climate Diagnostics and Prediction Workshop*, Tallahassee, FL, Oct.22-26,2007.

Xie, P., W. Wang, J.E. Janowiak, M. Chen, C.L. Shie, and L. Chiu, 2008: Examining fresh water flux over global oceans in the NCEP CDAS, CDAS2, GDAS, GFS and CFS. *Third WCRP International Conference on Reanalysis*. Tokyo, Japan, Jan. 28 – Feb.1, 2008.

4. REFERENCES:

Adler, R.F., and co-authors, 2003: The Version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979 – present). *J. Hydrometeor.*, **4**, 1147 – 1167.

Chou, S.-H., E. Nelkin, J. Ardizzone, R. Atlas, and C.-L. Shie, 2003: Surface turbulent heat and momentum fluxes over global oceans based on the Goddard satellite retrievals, version 2 (GSSTF2). *J. Climate*, **16**, 3,256-3,273.

Grassl, H., V. Jost, J. Schulz, M.R. Ramesh Kumar, P. bauer, and P. Schluessel, 2000: The Hamburg Ocean-Atmosphere Parameter and Fluxes from Satellite Data (HOAPS): A climatological Atlas of satellite-derived air-sea interaction parameters over the World Oceans. *Report No. 312, ISSN 0937-1060, Max Planck Institute for meteorology*, Hamburg, pp.130 + figures.

Josey, S.A., E.C. Kent, and P.K. Taylor, 1998: The Southampton Oceanography Centre (SOC) Ocean – Atmosphere Heat, Momentum and Freshwater Flux Atlas. *Southampton Oceanography Centre Rep*. 6, 30pp + figures.

Josey, S.A., E.C. Kent, and P.K. Taylor, 1999: New insights into the ocean heat budget closure problem from analysis of the SOC air-sea flux climatology. *J. Climate*, **12**, 2850 – 2880.

Joyce, R.J., J.E. Janowiak, P.A. Arkin, and P. Xie, 2004: CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *J. Hydrometeor.*, **5**, 487 – 503.
climatology. *J. Climate*, **12**, 2850 – 2880.

Kummerow, C., Olson, W.S., and Giglio, L., 1996: A simplified Scheme for Obtaining Precipitation and Vertical Hydrometeor Profiles from Passive Microwave Sensors. *IEEE Trans. on Geosci. and Remote Sensing , 34* , 1213-1232. Xie, P., and P.A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Amer. Meteor. Soc.*, **78**, 2539 – 255

Tomita, H., M. Kubota, S. Iwasaki, T., Hihara, and A. Kawatsura, 2007: Introduction of J-OFURO version 2 surface heat flux data set and its analysis over the North Pacific. *AGU 2007 Joint Assembly*, Acapula, Mexico, May 22-25, 2007.

Weng, F., L. Zhao, G. Poe, R. Ferraro, X. Li and N. Grody, 2003: A1MSU cloud and precipitation algorithms, *Radio Science, vol. 38(4)*, pp. 8068-8079.

Xie, P., and P.A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bull. Amer. Meteor. Soc.*, **78**, 2539 – 2558.

FIGURES

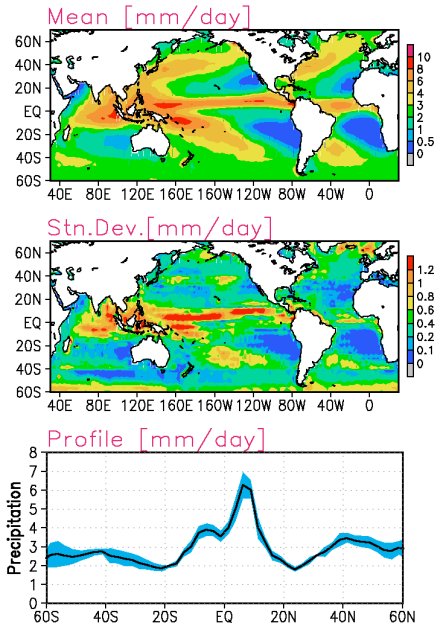


Fig. 1

Global distribution of the arithmetic mean (upper) and standard deviation (middle), together with their zonal means (bottom), among the annual mean precipitation (mm/day) from three sets of widely used observation-based data sets: the CMAP (Xie and Arkin 1997), GPCP (Adler et al. 2003) and the TRMM TMI-PR merged analysis. Arithmetic mean and standard deviation of the zonal means are plotted as solid line and blue shading, respectively, in the bottom panel.

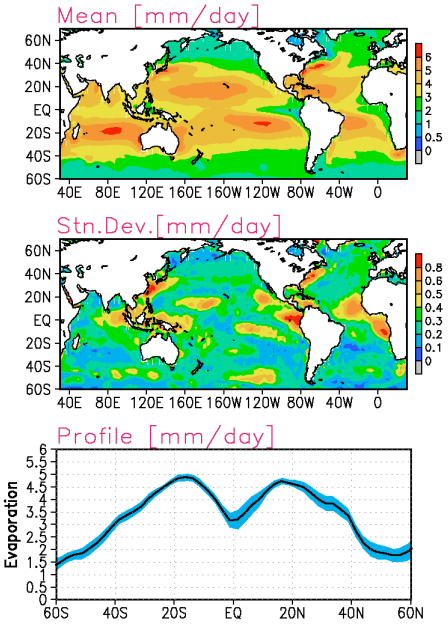


Fig. 2

Same as in figure 1, except for evaporation from four sets of observations data sets: the GSSTF-2 of Chou et al. (2003), the HOAPS3 of Grassl et al. (2000), and the J-OFURO2 of Tomita et al. (2007), and the COADS-based SOC climatology of Josey et al. 1998,1999.

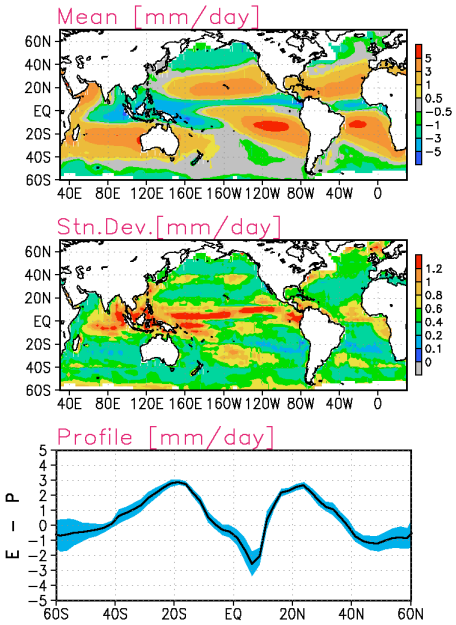


Fig. 3

Same as in figure 1, except for the fresh water flux (evaporation-precipitation, mm/day).

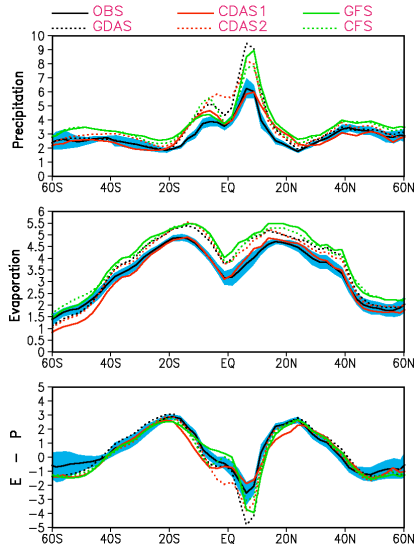


Fig. 4

Latitudinal profile of annual mean zonal mean precipitation (mm/day, upper), evaporation (mm/day, middle), and fresh water flux (mm/day, bottom), as derived from the observations and several NCEP model-based products. The black line indicates arithmetic mean while the blue spread shows the standard deviation among the individual data sets used.

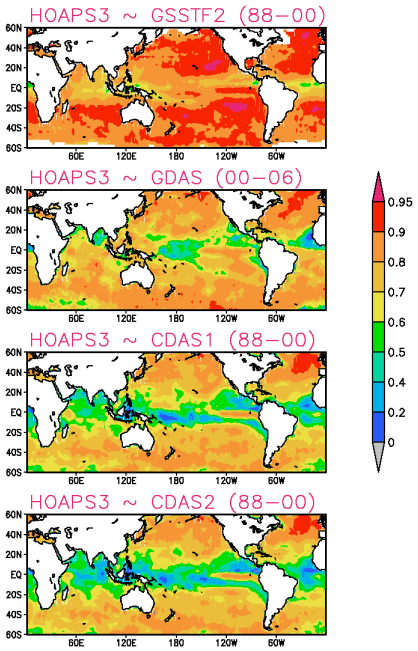


Fig. 5

Anomaly correlation between the monthly evaporations derived from a) the HOAPS3 and GSSTF2 satellite-based estimates (top); b) HOAPS3 and GDAS (2nd from top); c) HOAPS3 and NCEP Reanalysis 1 (3rd from top); and d) HOAPS3 and NCEP Reanalysis 2 (bottom).

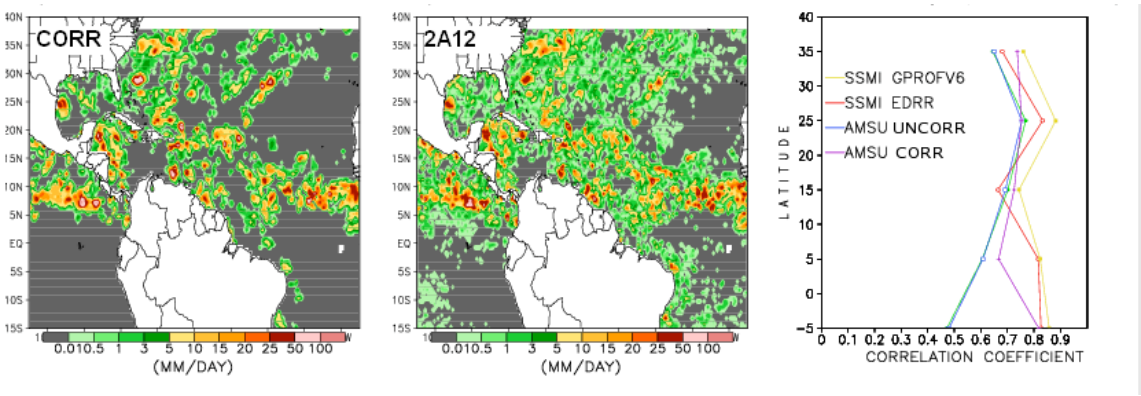


Fig.6: Left panel: Mean rain rate for the new AMSU estimates over Atlantic Ocean from 1-31 July 2005. Central panel: Idem for TMI 2A12. Only scenes within 30 minutes are considered in the average. Right Panel: correlation coefficient of different estimates compared against TMI 2A12. Results for the new and old AMSU are marked as "AMSU CORR", and "AMSU UNCORR", respectively.

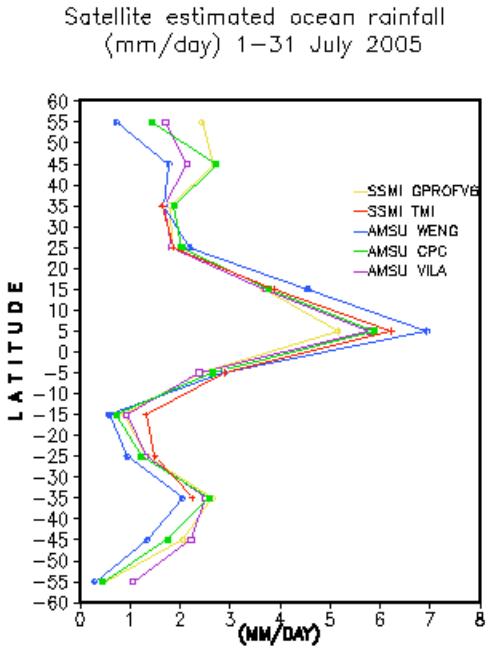


Fig. 7:

Oceanic passive microwave estimated rainfall from various sensor/algorithms for July 2005 averaged in 10 degree latitude bands. The new and old AMSU estimates are marked as "AMSU VILA" and "AMSU WENG", respectively.

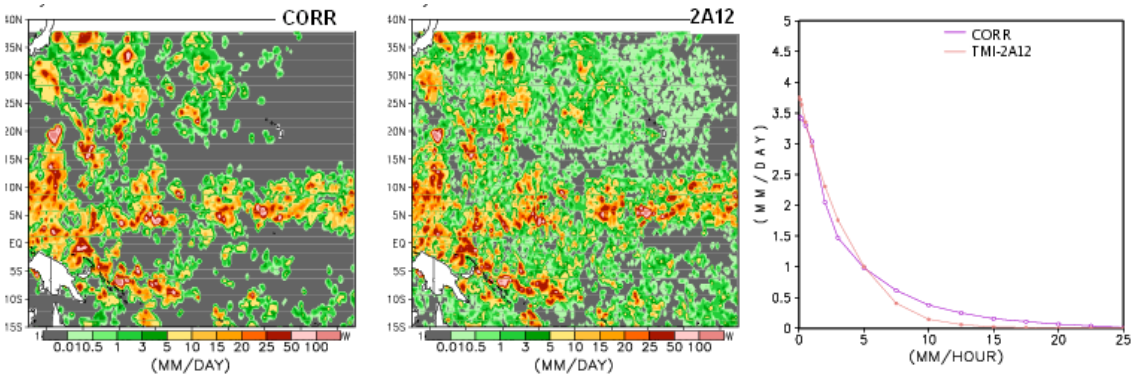


Fig. 8: Left panel: Mean rain rate for new AMSU estimates over western Pacific Ocean from 1-31 July 2005. Central panel: Idem for TMI 2A12. Only scenes within 30 minutes are considered in the average. Right Panel: Rain rate distribution for AMSU CORR and TMI 2A12.

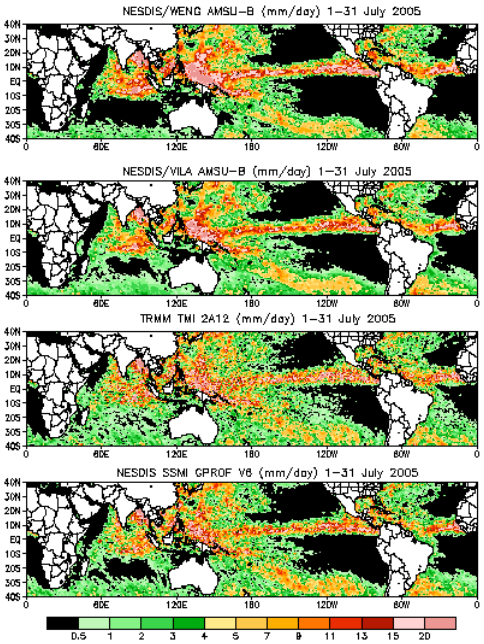


Fig. 9:

Spatial distribution of passive microwave estimated rainfall for July 2005 derived from a) the old AMSU algorithm (top), b) the new AMSU algorithm (2nd from top), c) TRMM TMI 2A12 (3rd from top), and d) the NESDIS SSMI GPROF V6 (bottom).

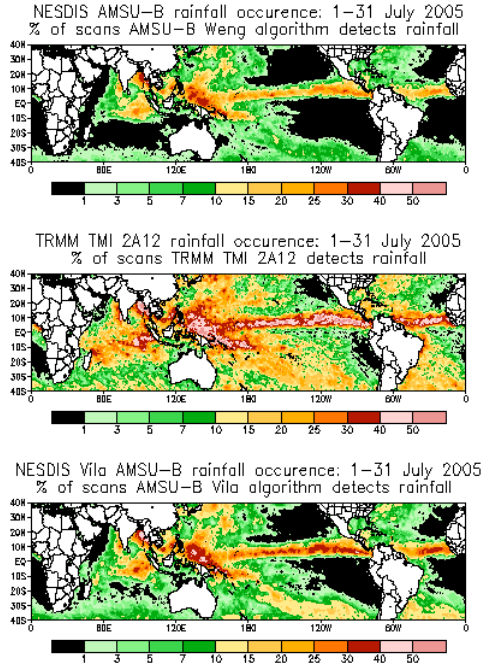


Fig. 10:

Spatial distribution of frequency of rain events for July 2005 detected from a) the old AMSU algorithm (top), b) the TRMM TMI 2A12 (middle), and c) the new AMSU algorithm (bottom).

Evaluating the Ocean Observing System: Surface Currents

Rick Lumpkin and Gustavo Goni
NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

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 FY07 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).

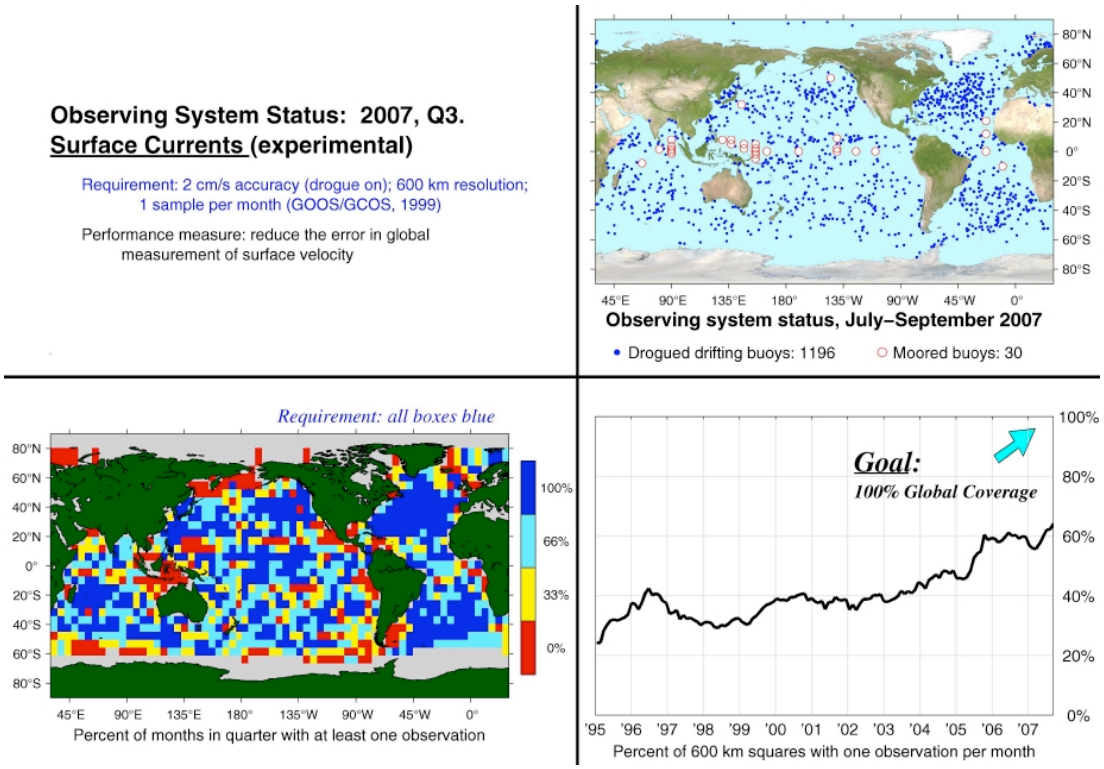


Fig. 1: FY07 Q4 (calendar Q3) report evaluating the IOOS's performance for near surface current measurements.

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.

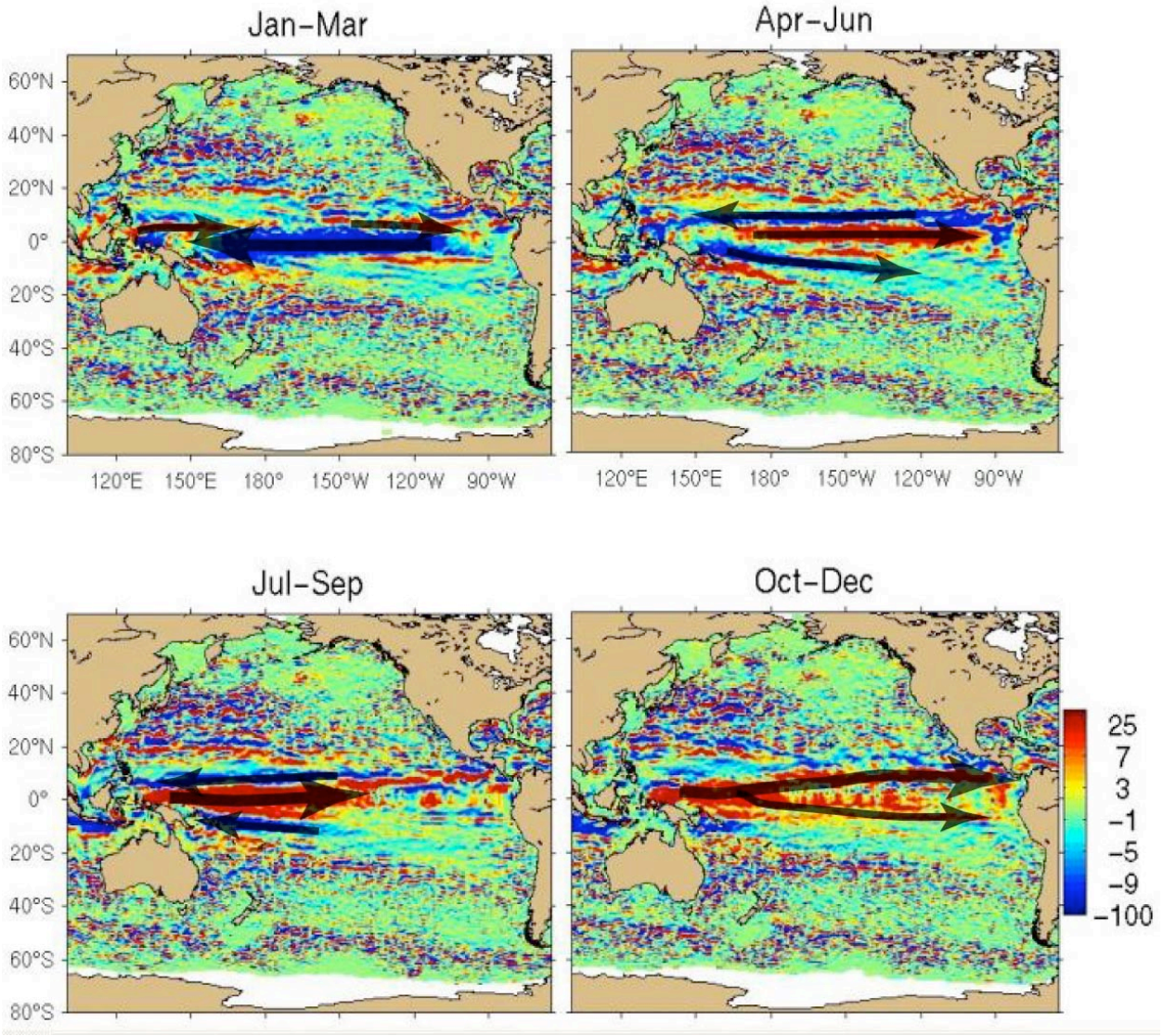


Fig. 2: Seasonally-averaged current anomalies (cm/s; positive eastward) for 2006, calculated from a synthesis of drifters, altimetry and wind products (from Lumpkin and Goni, 2007). Development and evolution of the El Nino is clearly revealed. These fields are being generated as a part of this project; error analysis of their accuracy is the current focus of the study.

We are currently expanding our results from an FY07 focus on the North Atlantic, to the global distribution of correlation and bias. Where correlations are high, we have 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 in all basins; in these regions, sustained in-situ observations are needed to eliminate biases or errors in the satellite-based estimates. In some poorly-sampled regions, more drifter observations are needed to be able to produce more matches between altimetry and drifter observations at 1º 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.

The PIs of this project, Lumpkin and Goni, contribute the "Surface Currents" section for the State of the Ocean report using results generated in this study. For the first time in FY07, the authors used the synthesized drifter/altimetry/wind fields to describe the evolution of surface current anomalies around the world (Fig. 2), as opposed to separate drifter, mooring and altimetry analysis.

Publications and Reports:

Lumpkin, R. and G. Goni, 2007: State of the Ocean in 2006: Surface Currents. In "State of the Climate in 2006", ed. A. Arguez, *Bulletin of the American Meteorological Society*, 88 (June).

Goni, G. J., P. N. DiNezio, F. Bringas, C. Shmid and R. Lumpkin, 2008: Global trends in heat storage and eddy kinetic energy. To be submitted to *Geophys. Res. Letters.*

Quarterly Reports on the State of the Ocean: Meridional Heat Transport Variability in the Atlantic Ocean

Molly Baringer, Silvia Garzoli, Gustavo Goni, Carlisle Thacker and Rick Lumpkin
NOAA Atlantic Oceanographic and Meteorological Laboratory,Miami FL 33149

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 electricity produced by *one million* of the largest nuclear power plants in existence today (the largest nuclear plants produce about 1 gigaWatt of electrical power).

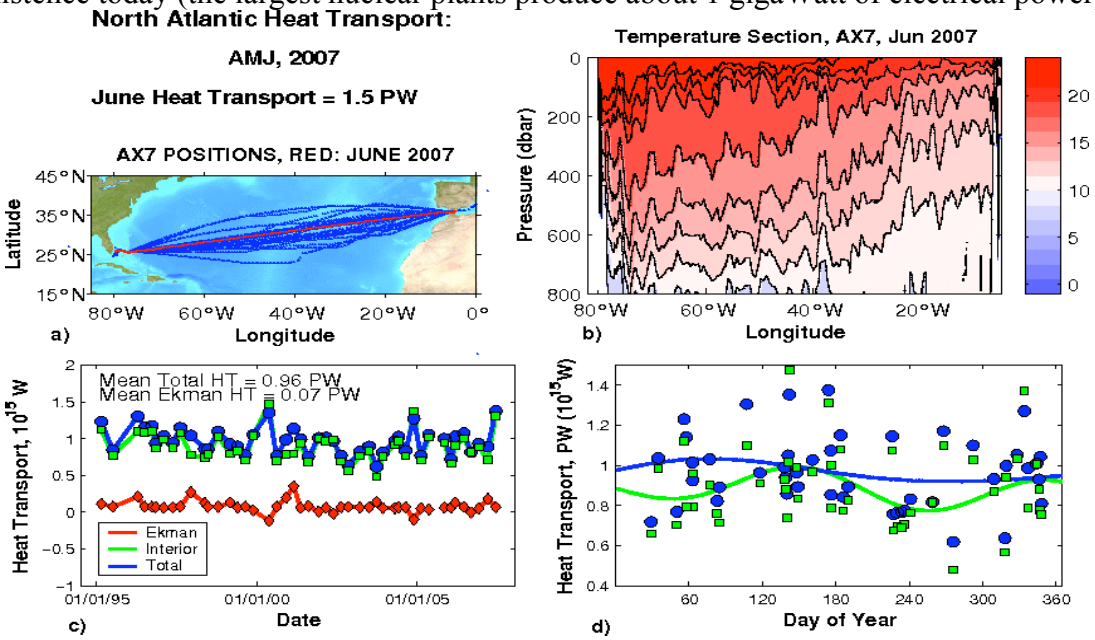


Figure 1: Report for the April-May-June quarter of 2007 for North Atlantic Meridional Heat transport along the AX7 high density XBT line. Transport results based on June 2007 XBT section (positions shown in top left, temperature section shown in top right). Heat transport estimates were decomposed into the geostrophic (interior) and Ekman components and their total (lower left). Heat transports contain an insignificant seasonal signal (lower right) with only a slight suggestion that spring sections have a higher heat transport than fall sections. The heat transport during this quarter was significantly higher than the mean heat transport and appears to alter the recent trend towards reduced heat transports.

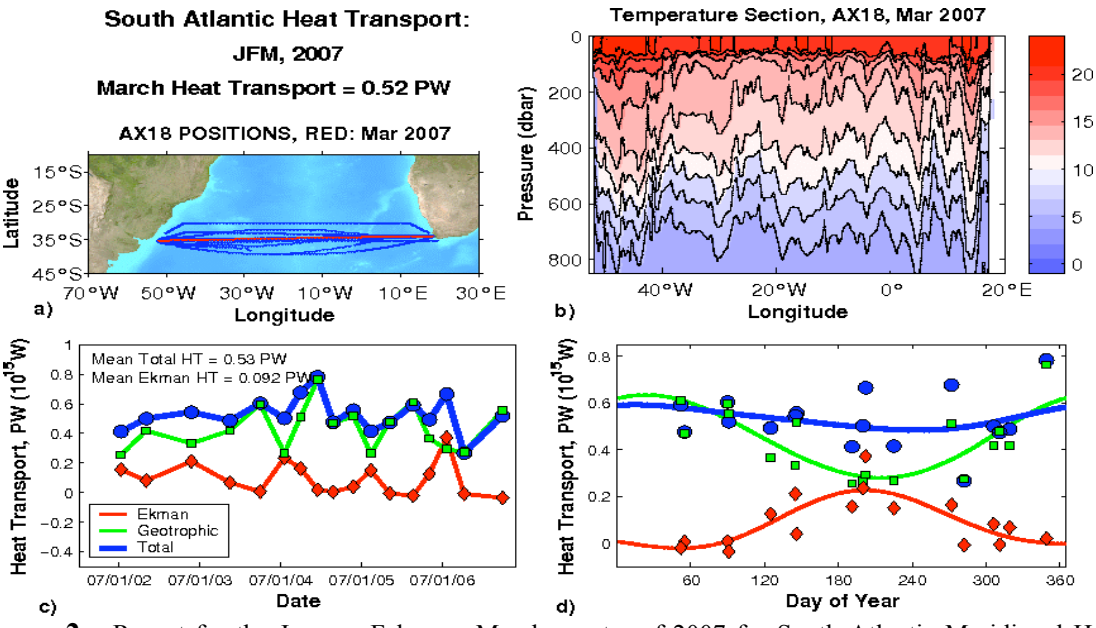


Figure 2: Report for the January-February-March quarter of 2007 for South Atlantic Meridional Heat transport along the AX18 high density XBT line. Transport results based on March 2007 AX18 XBT section (positions shown in top left, temperature section shown in top right). Heat transports were

estimated using a shallow (green squares) and deep (red diamonds) reference level (lower left). Total heat transports demonstrate no significant seasonal signal because the seasonal signal in the Ekman layer is directly out of phase with the geostrophic signal (lower right). The July heat transport was close to the mean transport observed over the past four years.

Scientific Findings:

This year, Thacker (2007) and Thacker and Sindingler (2007) published 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.

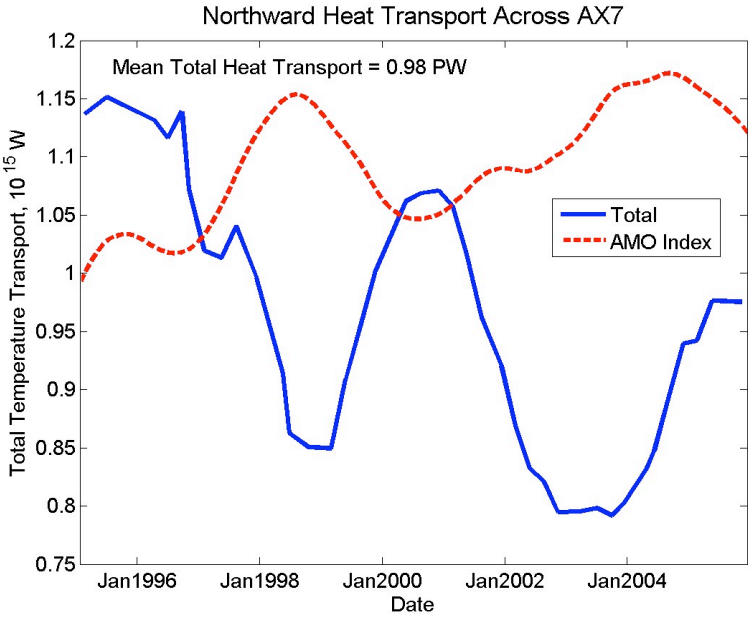


Figure 3: Time series of total heat transport in the center of the subtropical gyre in the North Atlantic Ocean along the XBT lined designated AX7. In the North Atlantic, there has been an apparent decrease in heat transport over the past 10 years (solid blue). Heat transport is inversely related to the Atlantic Multidecadal Oscillation (AMO) Index (red dashed)

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

South Atlantic: The methodology described above was applied to the South Atlantic data and an intensive study of the errors was completed (Baringer and Garzoli, 2007). 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 (2007) 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

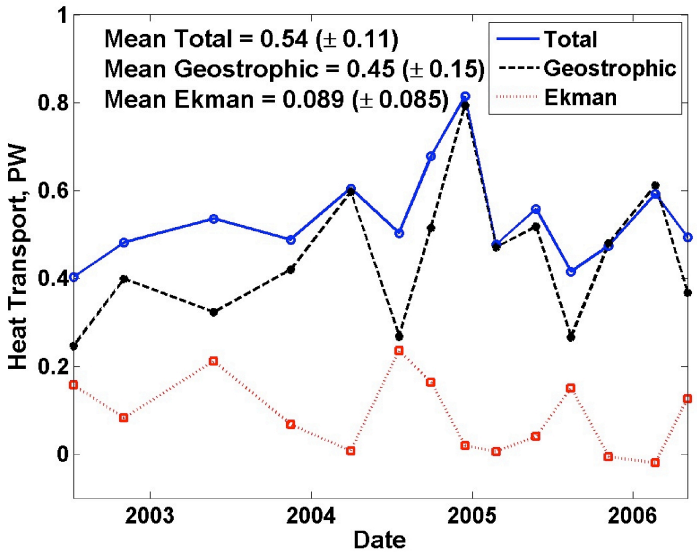


Figure 3: Variability with latitude of the computed total (red) and geostrophic (blue) fluxes. The lines are the linear fit between the total heat transport (red) and geostrophic heat transport (blue) with latitude.

December 2004 and a decrease thereafter (Figure 3). 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 (Figure 4) 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 (2007) (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.

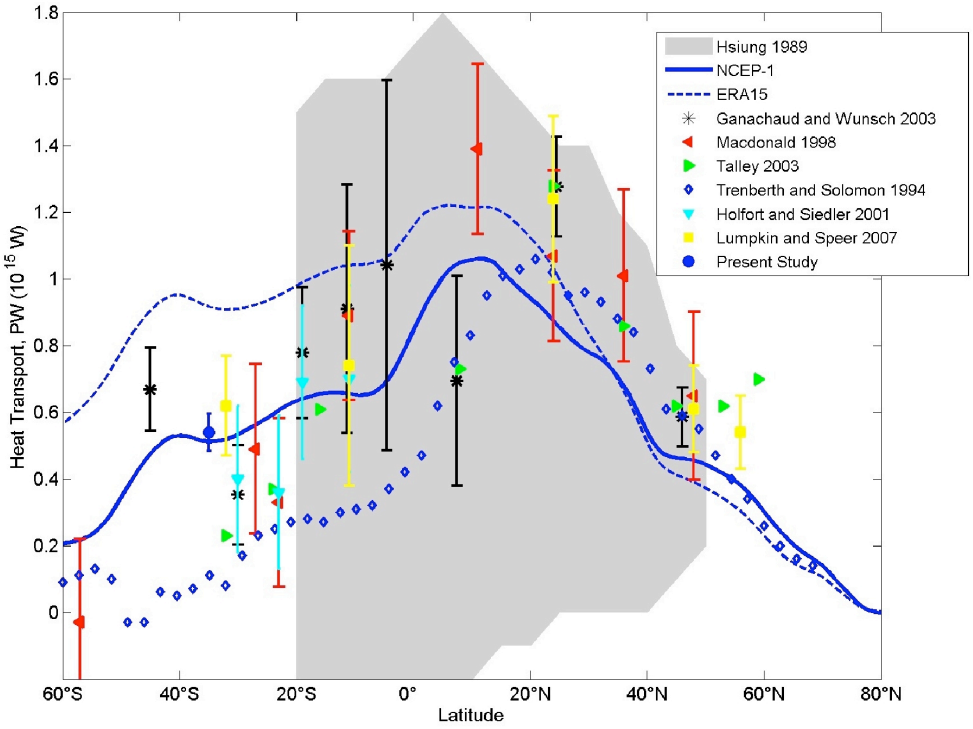


Figure 4: Oceanic Heat transport implied from integrating air-sea flux products (NCEP-1 and ERA15) starting from North Atlantic compared to several direct estimates of the heat transport from trans-basin sections (see legend). The AX18 mean heat transport (blue circle) compares favorably with the NCEP surface fluxes. The NCEP-1 annual mean was obtained from an average climatology of the years 1949 to 2003, (Kalnay, 1996). The ERA15 annual mean was derived from the ECMWF climatology based on 1979 – 1993, (Gibson *et al*., 1997)

Publications

Peer-reviewed:

1. Thacker, W.C., 2007. Estimating salinity to complement observed temperature, Part 1: Gulf of Mexico. *Journal of Marine Systems*, 65 (1-4), 224-248.
2. Thacker, W. C. and L. R. Sindlinger, 2007. Estimating salinity to complement observed temperature, Part 2: Northwestern Atlantic. *Journal of Marine Systems*, 65 (1-4), 249-267.
3. Baringer, Molly O. and Silvia L. Garzoli, 2007. Meridional Heat Transport using Expendable Bathythermographs. Part I: Error Estimates from model and hydrographic data, *Deep Sea Research, (Part 1)*, DOI information doi:10.1016/j/dsr.2007.03.011.

4. Garzoli, Silvia L. and Molly O. Baringer, 2007. Meridional Heat Transport using Expandable Bathythermographs Part II: South Atlantic Transport. *Deep Sea Research (Part 1)*, DOI information doi:10.1016/j.dsr.2007.04.013.

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

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

Project Summary

The objective of this project by the NOAA National Ocean Service (NOS) Center for Operation Oceanographic Products and Services (CO-OPS is to develop and implement a routine annual sea level and extreme event analysis reporting capability that meets the requirements of the Climate Observation Program

The fundamental URL's are:

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

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

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.

FY2007 Accomplishments

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

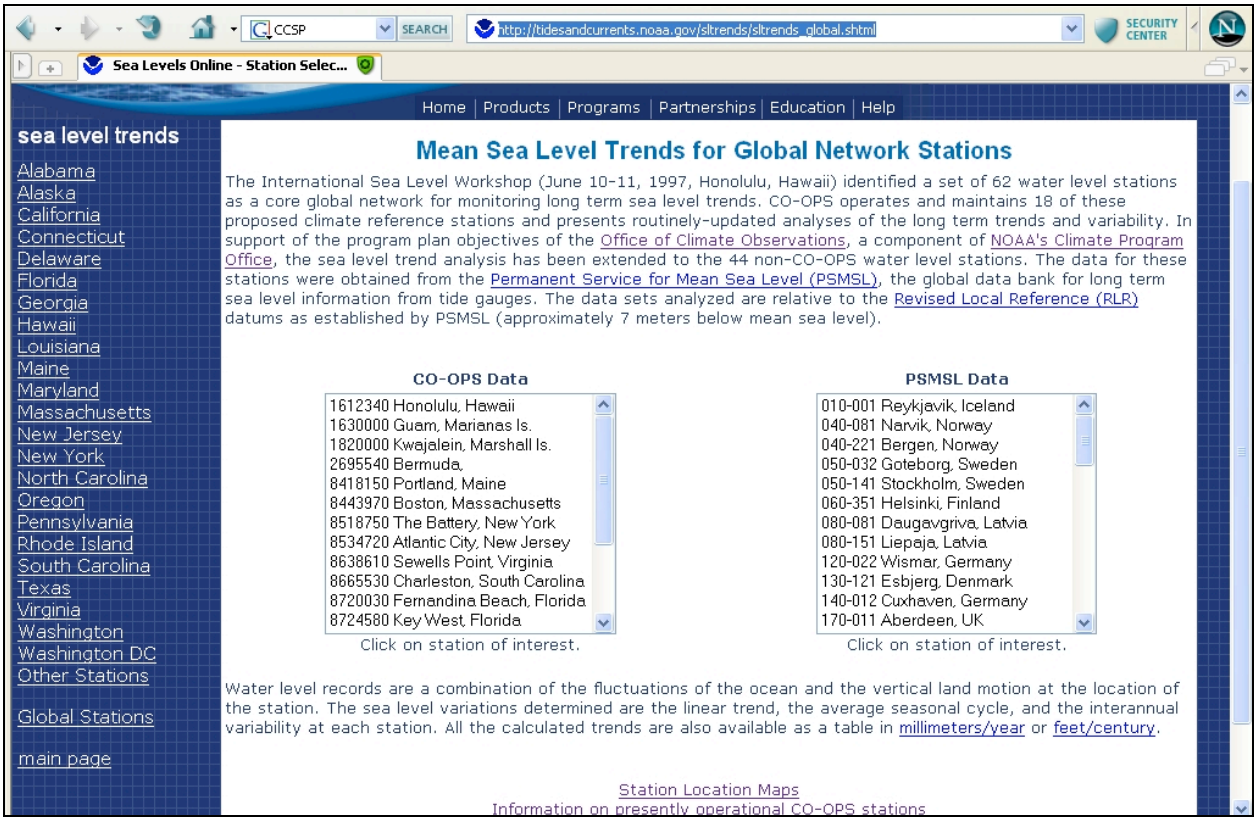


Figure 1. The new NOAA web-site for viewing information on sea level trends and monthly mean sea level anomalies at global tide stations.

The 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

The following figures illustrate the types of analyses being prepared for Honolulu:

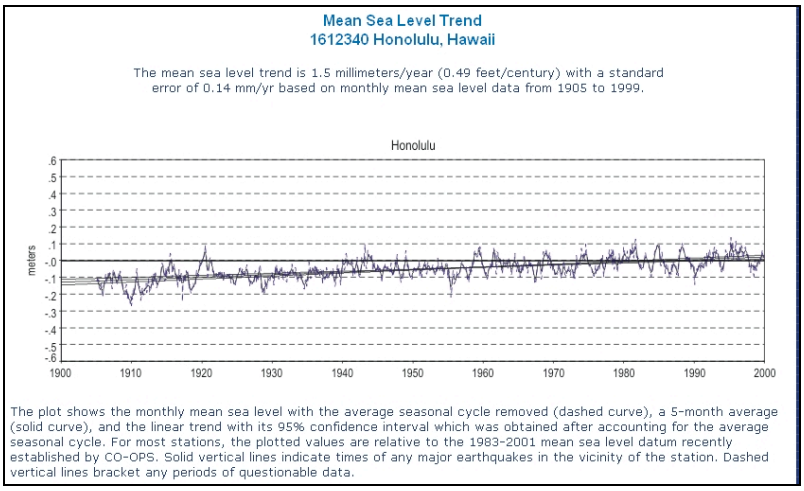


Figure 2. Sea level Trends Analyses are routinely updated.

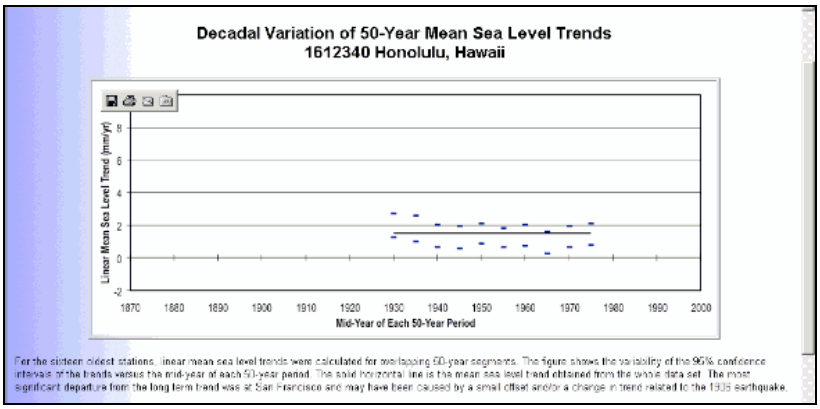


Figure 3. Long-term Variation in Trends are routinely updated.

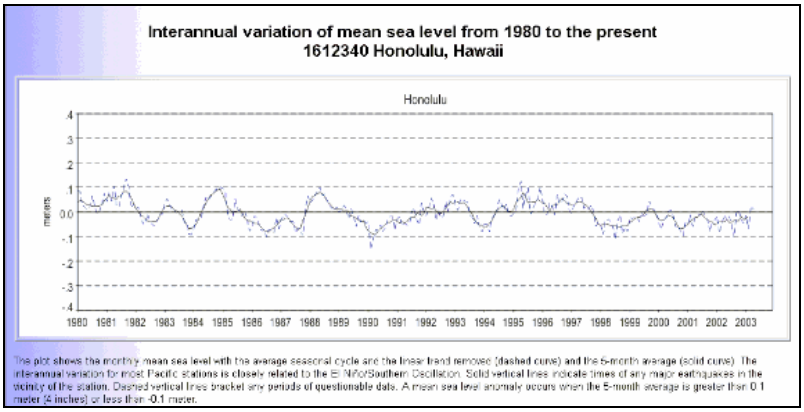


Figure 4. The Monthly Mean Sea Level anomalies are updated annually.

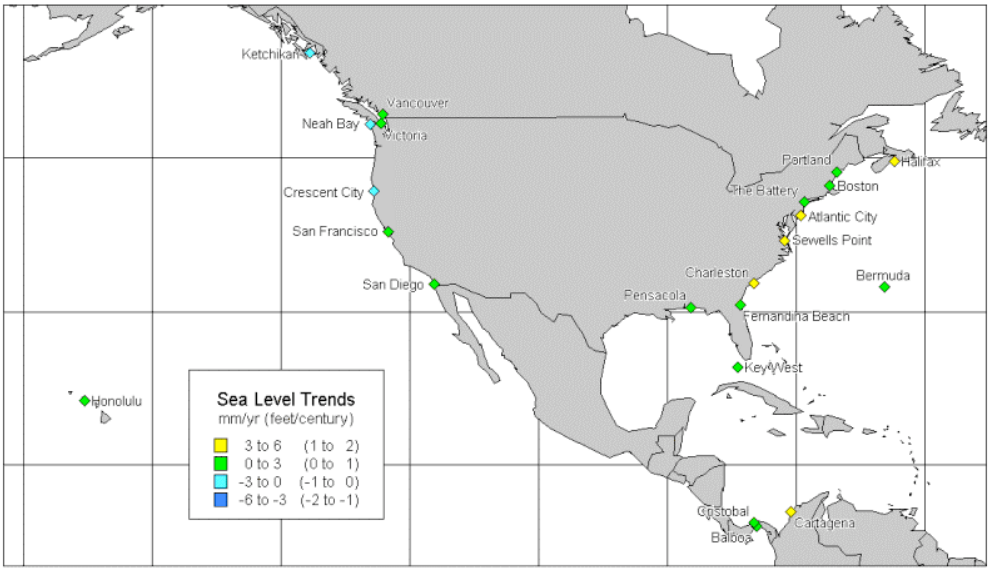


Figure 5. North America Relative Sea Level Trends

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:

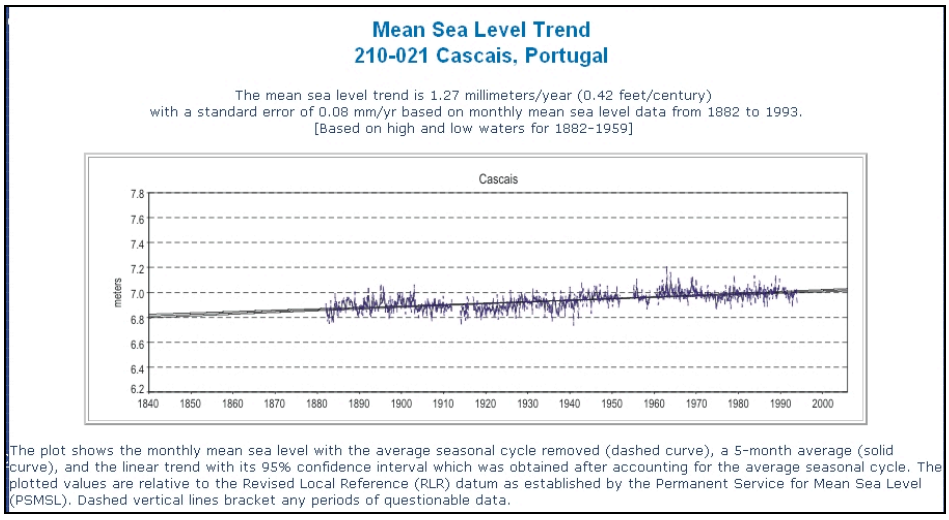


Figure 6. The Sea Level Trend Analysis

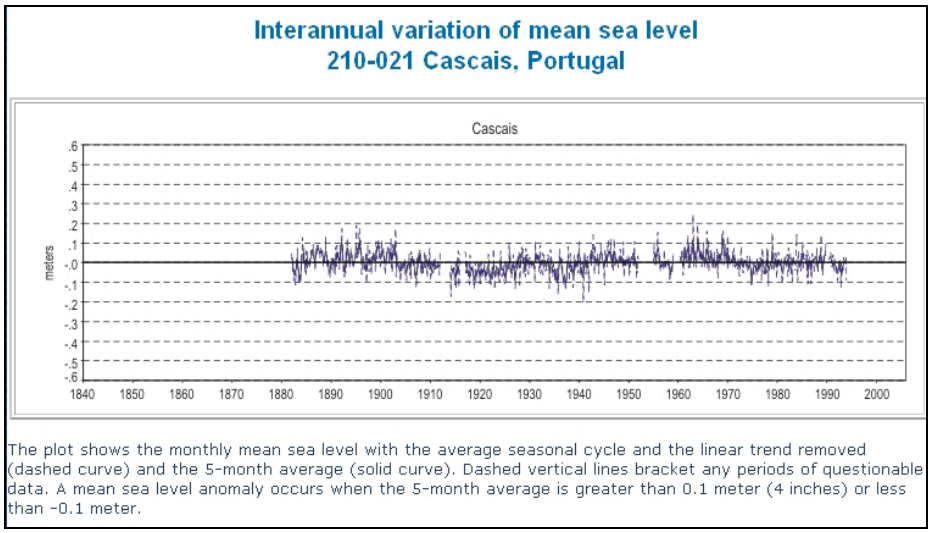


Figure 7. The interannual variation analysis.

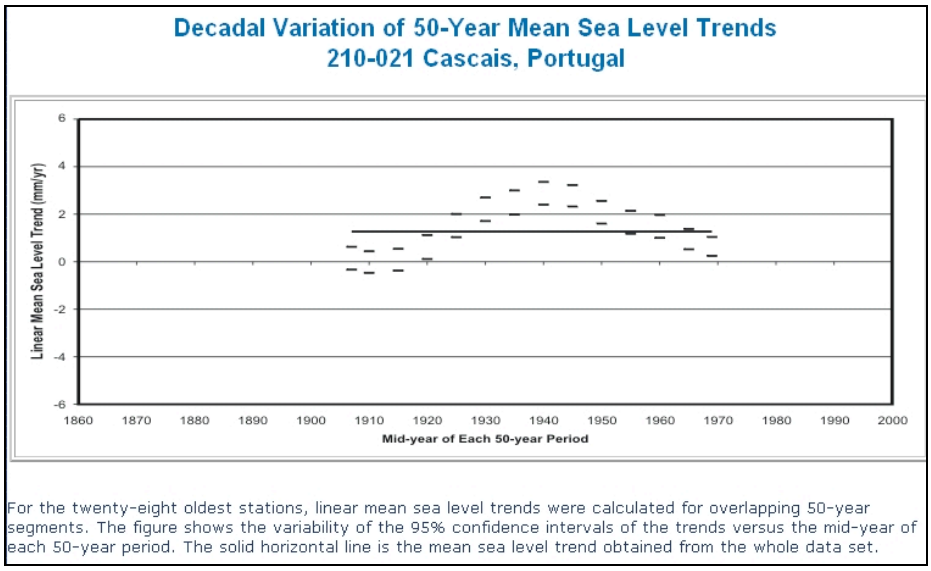


Figure 8. The decadal variation analysis.

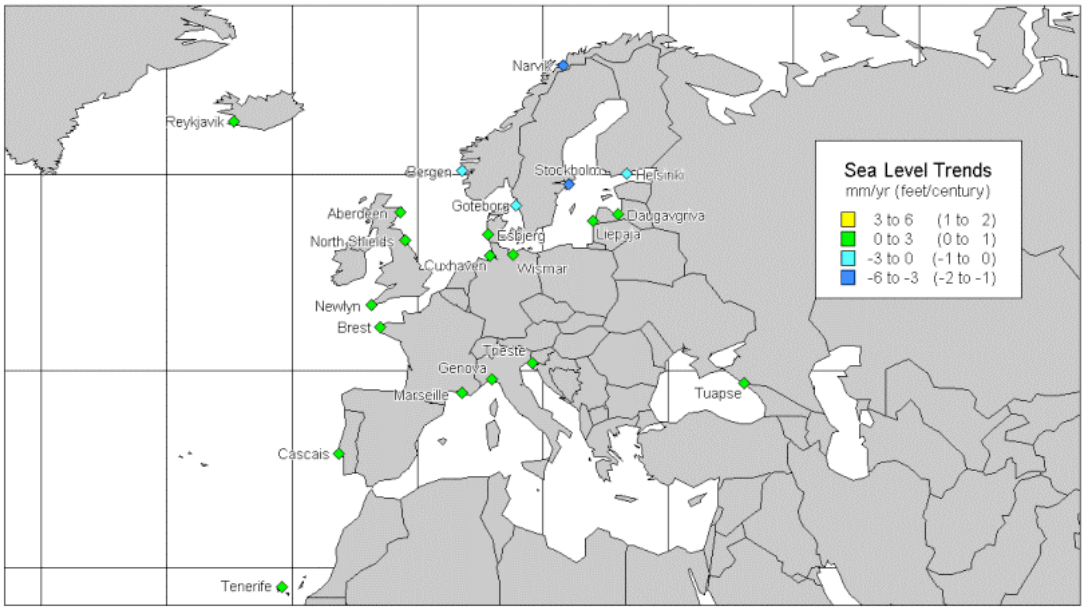


Figure 9. European Relative Sea Level Trends

In addition, production of Exceedance Probability Analysis for NWLON stations and work on development of a web-interface continued in FY2007.

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

Laury Miller
NOAA NESDIS Laboratory for Satellite Altimetry, Silver Spring, MD

Project Summary

The launch of the Jason-2/Ocea Surface Topography Mission (OSTM) on June 15, 2008, will mark the beginning of a major transition for NOAA. NOAA and it's partner operational agency, EUMETSAT, will begin assuming responsibility for continuing the record of global sea level rise established by NASA and CNES with the Topex and Jason-1 satellite altimeter missions. The NOAA Laboratory for Satellite Altimetry (LSA) will play an important role in this transition, helping insure that Jason-2 observations satisfy the stringent requirements of a climate data record and providing scientific leadership, both inside and outside of NOAA. This responsibility is expected to grow with the proposed FY10 start of a Jason-3 mission to be launched in 2013.

In order to best take advantage of these changing roles and responsibilities, we propose to substantially redirect the OCO Satellite Altimetry Program in FY08 and onward as follows:

- The design and maintenance of (1) the NOAA Radar Altimeter Database (Scharroo/Altimetrics) and (2) the Altimeter/Tide Gauge Calibration System (Mitchum/USF & Soreide/PMEL) will continue but with NOAA Jason-2 Program funds rather than OCO funds

- The routine computation of precise Geosat Follow-On orbits (Lemoine/NASA) will continue with OCO funds.

- The research on connecting the Geosat and Topex global mean sea level time series (Miller/LSA) will be completed with OCO funds in FY08.

- The reconstruction of past sea level change from altimeter and tide gauge observations (Nerem/UC) will be replaced with a new OCO supported activity, research into the discrepancy between observed and model predicted sea level rise (Miller/CICS).

Background

Sea level rise is widely recognized as possibly one of the most devastating consequences of global warming. Nearly all shoreline areas around the world will eventually be affected by rising levels, either from erosion or inundation. The impact on hundreds of millions of coastal inhabitants, especially those in underdeveloped countries, may be severe.

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 rate was about 1 mm/yr, while during the second half of the 20th century the rate increased to 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.

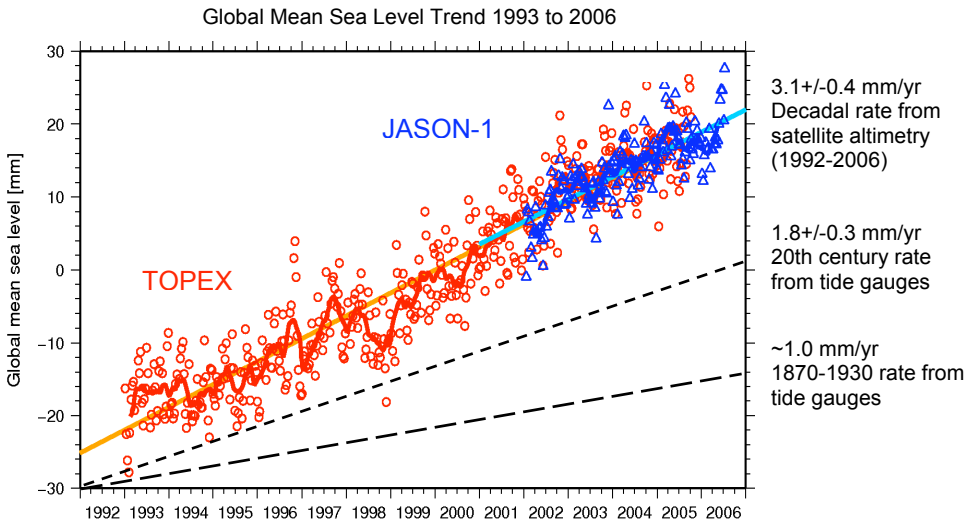


Figure 1. Global mean sea level trend from 1993 to 2006 based on TOPEX and JASON-1 altimeter observations. The trend over the past 14 years is roughly 2 times greater than the trend over the last half century and 3 times greater than the trend over the late 1800's – early 1900's. The latter two trends are based on tide gauge observations that only produce useful global estimates on intervals greater than 50 years, due to their limited geographical coverage.

To put the current observations into perspective, it is important to note that the altimeter measured rate of sea level rise is 50% greater than the "best-estimate" predicted by the IPCC Third Assessment Report (TAR) climate models (Rahmstorf et al., 2007) and the Four Assessment Report (FAR) predictions are probably not much better (Leuliette, 2006). The shaded area in Figure 2 represents the range of the TAR sea level predictions from 1990 onward. (The models are initialized with actual ocean and atmosphere observations prior to 1990, then allowed to run forward in coupled mode, without data assimilation, from 1990 onward). The model estimates diverge immediately from the observed sea level rise shown in the upper blue and red curves. Whereas the observed rate was 3.3 ± 0.4 mm/yr from 1993-2006, the best-estimate TAR projection is less than 2 mm/yr. The cause for this large discrepancy is unknown, and while it could represent short-term natural variability not captured by the models, failure to project even near-term sea level rise serves as a warning. The IPCC long-range projections presently being used to develop climate adaptation strategies could have similar problems.

Determining the cause of the observation/model-projection discrepancy is another principle goal of the OCO Satellite Altimetry Program.

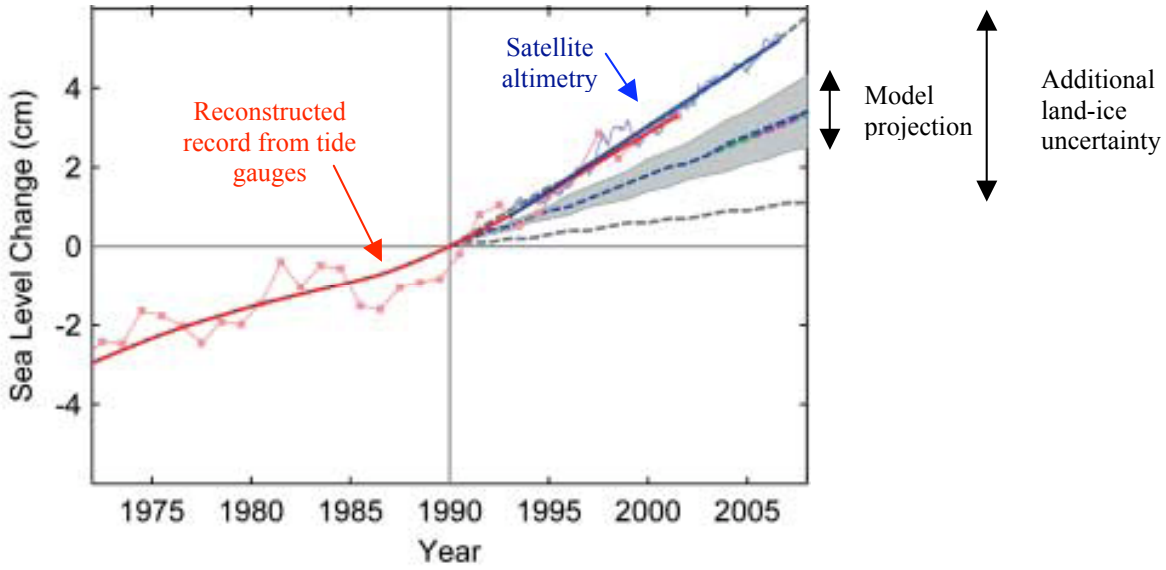


Figure 2. Sea-level data based primarily on tide gauges (annual, red) and from satellite altimeter (3-month data spacing, blue, up to mid-2006) and their trends. All trends are nonlinear trend lines and are computed with an embedding period of 11 years and a minimum roughness criterion at the end (*6*), except for the satellite altimeter where a linear trend was used because of the shortness of the series. Sea level, data are shown as deviations from the trend line value in 1990, the base year of the IPCC scenarios. (Figure extracted from Rahmstorf, S., A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker, and R.C.J. Somerville, Science, 316, 709, 2007.)

Over the past several years we have developed several program elements that contribute toward these goals. 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.
- The reconstruction of past sea level change from a combination of satellite altimeter and tide gauge measurements.
- Research into new methods of calibrating altimeter observations with tide gauge measurements.
- The design and maintenance of a web-based, public source of altimeter/tide gauge calibration information for all current and past satellite missions.

Satellite altimetry is a unique type of ocean remote sensing observation because it provides much more than a surface measurement. Spatial and temporal variations in sea surface height are driven by temperature and salinity changes throughout the water column as well as changes in the total mass of the water column When combined with in-situ density observations, like those obtained from the Argo profiler array, satellite altimetry provides an ideal tool for monitoring changes in the Earth's heat budget and hydrologic cycle.

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) beginning in 2013. 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.

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.

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/

FY07 Accomplishments

a.) Operational Support of the NOAA Radar Altimeter Database System (RADS): Altimetrics, LLC

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 that purpose, as well as providing a tool for studying important ocean "weather" problems such as hurricane intensity forecasting. Over the past year, data from the three currently functioning altimeters (Jason-1, Envisat, GFO) was added to RADS. Many significant improvements were made to the Geosat data set (1985-1988), including the development and implementation of a new ionosphere correction model and the incorporation of new, more precise orbits computed separately on this grant (**Activity (b) GFO & Geosat Precise Orbit Determination).** The impact of all of these changes is evident in the improved Geosat global sea level trend estimate (**Activity (d) Altimeter/Tide Gauge Calibration Research).**

b.) GFO and Geosat Precise Orbit Determination.

The U.S. Navy's Geosat Follow-On (GFO) altimeter mission has been operational since 2000. During 2007, 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 6 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 a recent *EOS* articles on Katrina, published by members of the LSA (Scharroo, R., W. H. F. Smith, and J. L. Lillibridge ,2005, 2006).

OCO funds were also used to pay for the computation of new, more precise orbits for the final 2 years of Geosat, the 17-day Exact Repeat Mission (November 1986 to December 1988). (The orbits for the first 1.5 years of Geosat, the no-repeating Geodetic Mission, were upgraded in fy07). The new ERM orbits were computed using an improved gravity field based on GRACE observations, greatly reducing the random errors from 14 to 7 cm rms, with some larger values late in the mission due to high solar activity. This work is part of an effort by the LSA to upgrade the quality of the Geosat data set (see **(a),** above and (**d**) below) and thus make it possible to determine more precisely the bias between the Geosat and TOPEX global mean sea level time series

c.) Predictions of Regional Sea Level Change Patterns by 2100; R.S. Nerem and S. Dorsi, Univ. of Colorado

The following reflects a change in the UC component of our FY07 Work Plan, previously aimed at reconstructing past sea level change from a combination of altimeter and tide data. The new project, "Predicting Regional Sea Level Change Patterns by 2100", fits more closely with our second principle objective: determining the cause of the observation/model-projection discrepancy.

Global mean sea level varies mainly in response to two factors: 1) the warming of the oceans, which causes thermal expansion or thermosteric sea level change, and 2) the exchange water between the continents and the oceans. The latter has been thought to cause sea level to rise uniformly around the globe, hence it has often been termed "eustatic" sea level rise. However, *Mitrovica et al.* [2001] showed that the regional patterns of sea level change associated with melting ice in Greenland, Antarctica, and mountain glaciers outside of the polar ice sheets are not uniform. In fact, sea level may change very little in some locations in the proximity of the melting ice. This is due to the gravitational attraction of the ice on the ocean water surrounding the ice. For example, sea level rise caused by melting ice in Greenland is almost entirely offset along the coast of Greenland as sea level falls due to the removal of the ice (and the gravitational attraction on the ocean water).

Patterns of sea level change due to thermal expansion have also been shown to be regionally variable due to regional variations in the ocean warming. This is clearly seen in satellite altimeter measurements from TOPEX and Jason over the last 15 years when compared

to ocean temperature measurements. Figure 1 shows the 15 year trends of sea level change from 1993-2007 compared to the same for thermosteric sea level change computed from ocean temperature measurements [*Willis et al*., 2004]. Clearly, much of the regional variability of sea level rise observed over the last 15 years is due to variations in ocean heat content.

The observed regional variations in sea level rise raise an important question: what will the regional patterns of sea level change be in the future? Variations in the regional rate of sea level change will have important implications for the socio-economic impact of sea level change, and in addition those patterns could be used as "fingerprints" of the various contributions to sea level change. We therefore set out to construct a crude estimate of the regional variations in sea level rise by 2100. For the thermosteric contribution to sea level change, we examined the predictions of nine different global climate models used in the most recent IPCC AR4 assessment [*Solomon et al*., 2007]. As shown in Figure 2, the differences between each of the regional model predictions is large, reflecting uncertainty in the model predictions of the regional variations in ocean heat content. Computing the ensemble mean of these model predictions (Figure 3) probably reduces the errors in the predictions, but also reduces the signal. Therefore, we chose one of the models (MIROC) to use in our predictions of regional change.

Next, we chose a value for the total value of sea level rise by 2100, and added in contributions from mountain glaciers and the ice sheets to reach this total. *Rahmstorf* [2007], as well as a number of other investigators, has suggested that sea level change by 2100 could be in excess of 1 meter. Based on this, we chose the following sea level contributions (Figure 4): 1) thermosteric – 20 cm, mountain glaciers – 25 cm, Greenland – 30 cm, and Antarctica – 25 cm, for a total of 1 meter. The ice contributions were used to scale the sea level patterns predicted by *Mitrovica et al*., [2001], assuming uniform melting across Greenland and Antarctica (highly unlikely). The sum of each of the individual contributions (Figure 4) is shown in Figure 5. While the average change is 1 meter, this varies between near zero sea level change around Greenland and the Gulf of Alaska, to nearly 1.4 meters of sea level change in the western Pacific and the Indian ocean. Sea level rise along the coast of Antarctica is roughly 0.5 meters. The coast of the U.S. would experience a sea level rise of 80 – 90 cm.

While the uncertainties associated with the map in Figure 5 are quite large, the map does demonstrate an important aspect of sea level change: the regional impact of future sea level rise will be quite variable. When combined with the effects of vertical land motion in certain regions (e.g. subsidence along the U.S. Gulf coast), the problem becomes even more complex. Therefore, studies assuming a uniform rise in sea level with no land motion will be of limited use for predicting the impacts of sea level change.

d.) Altimeter/Tide Gauge Calibration Research: Laury Miller, LSA

In addition to focusing on the problem operational altimeter/tide gauge calibration, the LSA is also interested in exploring methods for connecting non-overlapping altimetry missions, like the 4-year gap between Geosat and TOPEX. If a procedure could be developed for doing this, it would be possible to lengthen the altimetric record of global sea level rise by nearly 40%. A University of Maryland undergraduate student, Caroline Harbitz, was hired through CICS to work with the LSA on this problem. Caroline worked full-time last summer (2007) and over the winter semester break (January, 08), preparing tide gauge data sets used in analysis of the Geosat/TOPEX gap. A paper describing some preliminary results was presented at the Jason-1/OSTM Science Working Team meeting in Hobart, Tasmania, and also at the AMS Satellite

Meterology & Oceanography Conference, in Amsterdam. The plan is to finish this project this Summer (2008), with a paper submitted for publication. (*In part, as result of her work with the LSA, Caroline is planning on applying to WHOI, URI/GSO, and LDO graduate programs next Fall).*

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. The work is being done at PMEL, under the direction of Nancy Soreide, with science guidance from Dr. Gary Mitchum, University of South Florida. A preliminary version of the public Tide Gauge Altimeter website has been installed in the Seattle Web Farm environment. The URL is http://www.altcal.noaa.gov/. The Overview, Methods and Links sections of the website provide background information that describes and explains the data on the website.

On the Products section of the website, at http://www.altcal.noaa.gov/products.html, the user can: 1. See Tide Gauge station locations on a map; 2. Click links to view single time series plot; 3. Check the box to select plot and click "Display Plots" to display multiple plots; 4. Click on to download netCDF file; 5. On the web page presenting the results, (called the "result" page), the user can also "enlarge plot" and "download data".

PHP scripts have been developed that dynamically create the product results graphics and data download pages and perform these functions. The next step is an automated system to retrieve data/plot files from USF's ftp server to PMEL's web server on a routine and regular basis. Once the files have been properly prepared on the USF server and the automated retrieval procedure has been activated, the PHP scripts will be used to present the data/plots to the user through a web interface.

Publications and Reports:

Miller, L., and B.C. Douglas, "Gyre-scale Atmospheric Pressure Variations and their Relationship to 19th and 20th Century Sea Level Rise", *Geophys. Res. Lett.,* **34**, L16602, doi:10.1029/2007GL030862.

Ohring, G., J. Tansock, W. Emery, J. Butler, L, Flynn, F. Weng, K. St. Germain, B. Wielicki, C. Cao, M. Goldberg, J. Xiong, G. Fraser, D. Kunkee, D. Winker, **L. Miller**, S. Ungar, D. Tobin, J. G. Anderson, D. Pollock, S. Shipley, A. Thurgood, G. Kopp, P. Ardanuy, and T. Stone (2007), ASIC3 Report in EOS, "Achieving Satellite Instrument Calibration for Climate Change," Eos Trans. AGU, 88(11), 136.

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.

Leuliette, E. W., (2008) Interpreting the sea level rise record from satellite altimetry, Ocean Sciences Meeting, Orlando, Florida, 2-7 March 2008.

Leuliette, E. W. and W. H. F. Smith (2008), Interpreting the ocean mass contribution to sea level change, Eos Trans. AGU, 89(23), Jt. Assem. Suppl., Abstract G31B-07.

Nerem, S., D. P. Chambers, J. Famiglietti, and **E. Leuliette**, (2007) Hydrologic contributions to global mean sea level, IUGG XXIV General Assembly, Perugia, Italy, July 2-13, 2007.

Nerem, R. S., D. Chambers, G. Mitchum, and **E. Leuliette** (2007), Building a Climate Record of Sea Level Change, Eos Trans. AGU, 88(52), Fall Meet. Suppl., Abstract G33B-1244.

Appendix A. Predictions of Regional Sea Level Change Patterns by 2100: Figures & References

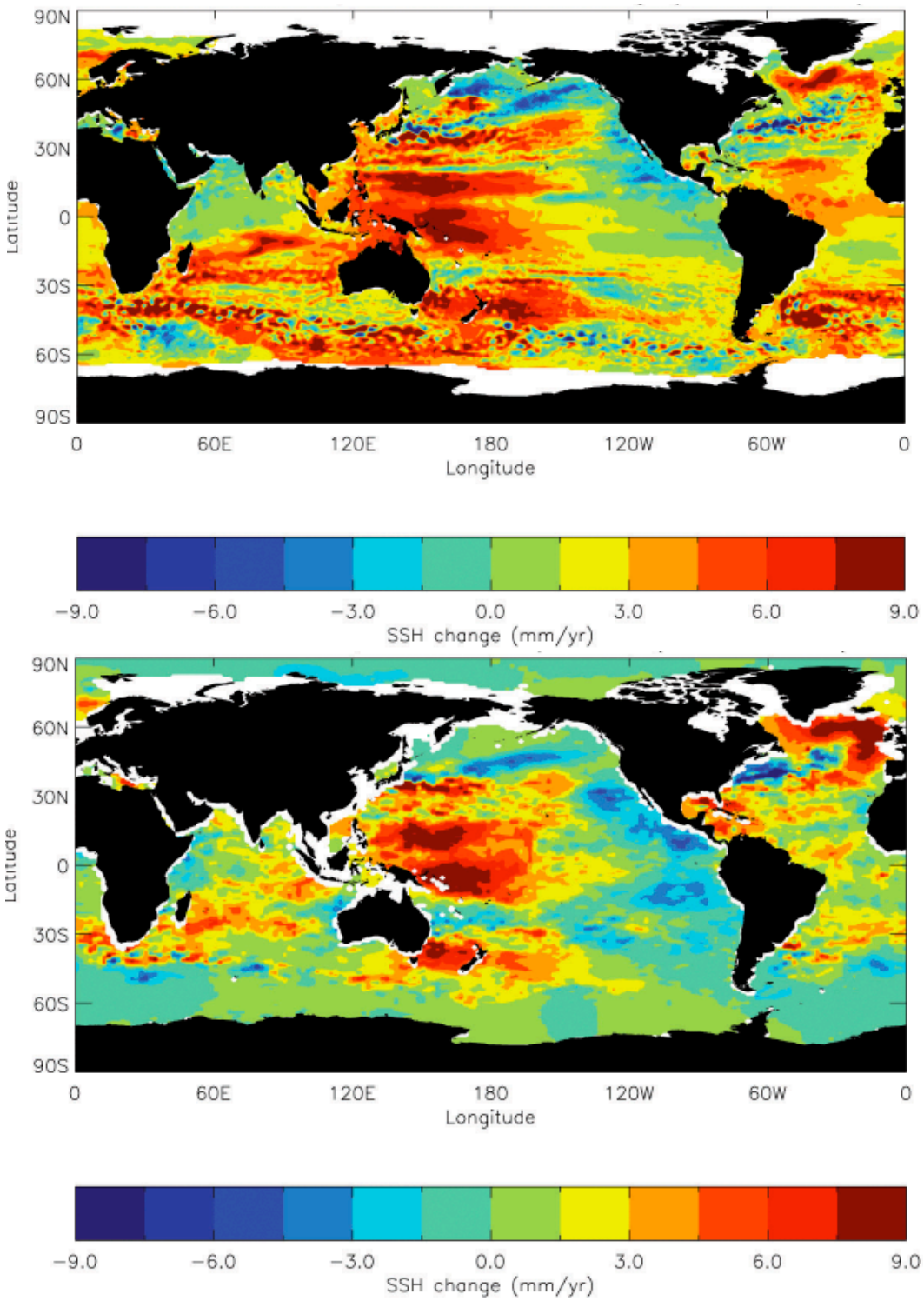


Figure 1. Regional variations in the trend in total sea level change over 1993-2007 as observed by TOPEX and Jason (top) and the trend in thermosteric sea level change over the same time period as observed by ocean temperature measurements (bottom) [*Nerem et al*., 2007].

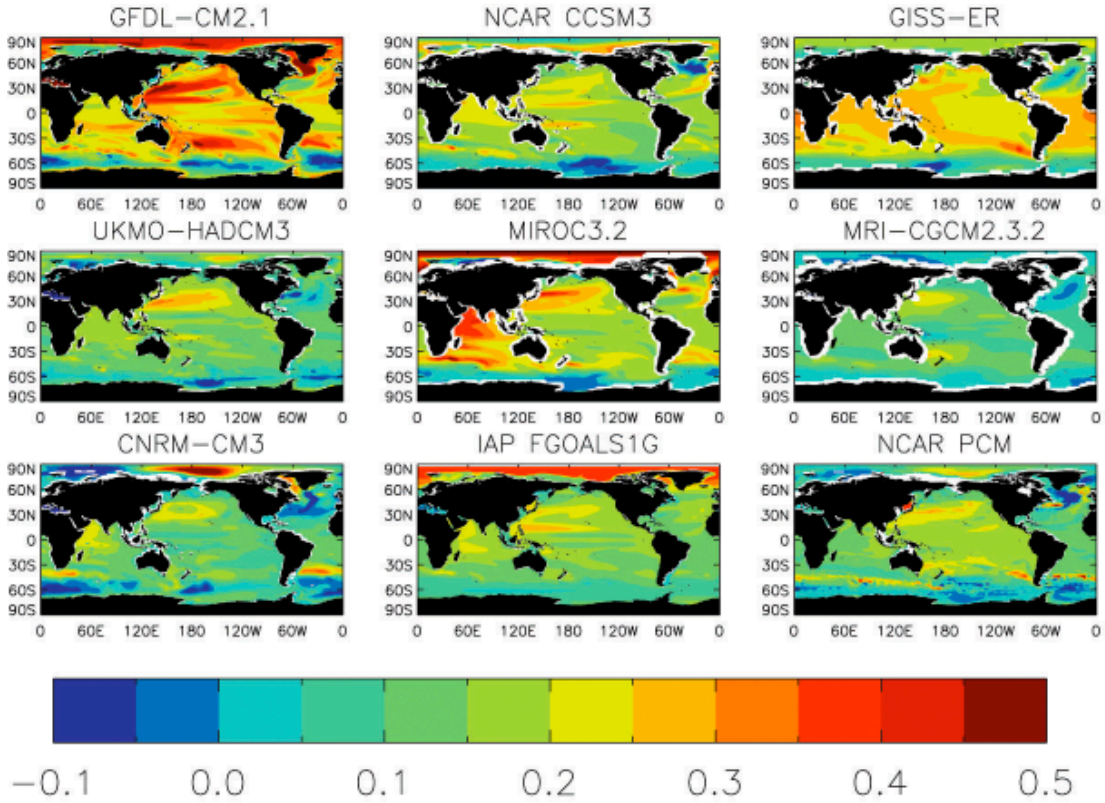


Figure 2. Predictions of regional thermosteric sea level change predicted by 9 different models from the IPCC AR4 assessment.

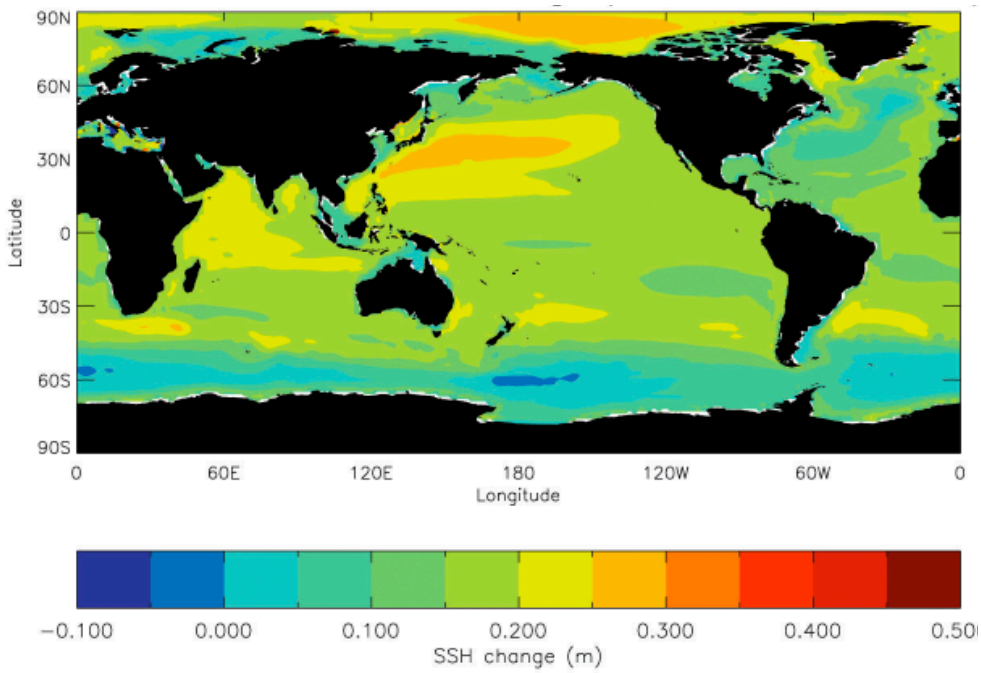


Figure 3. Ensemble mean of the predictions of thermosteric sea level change shown in Figure 2.

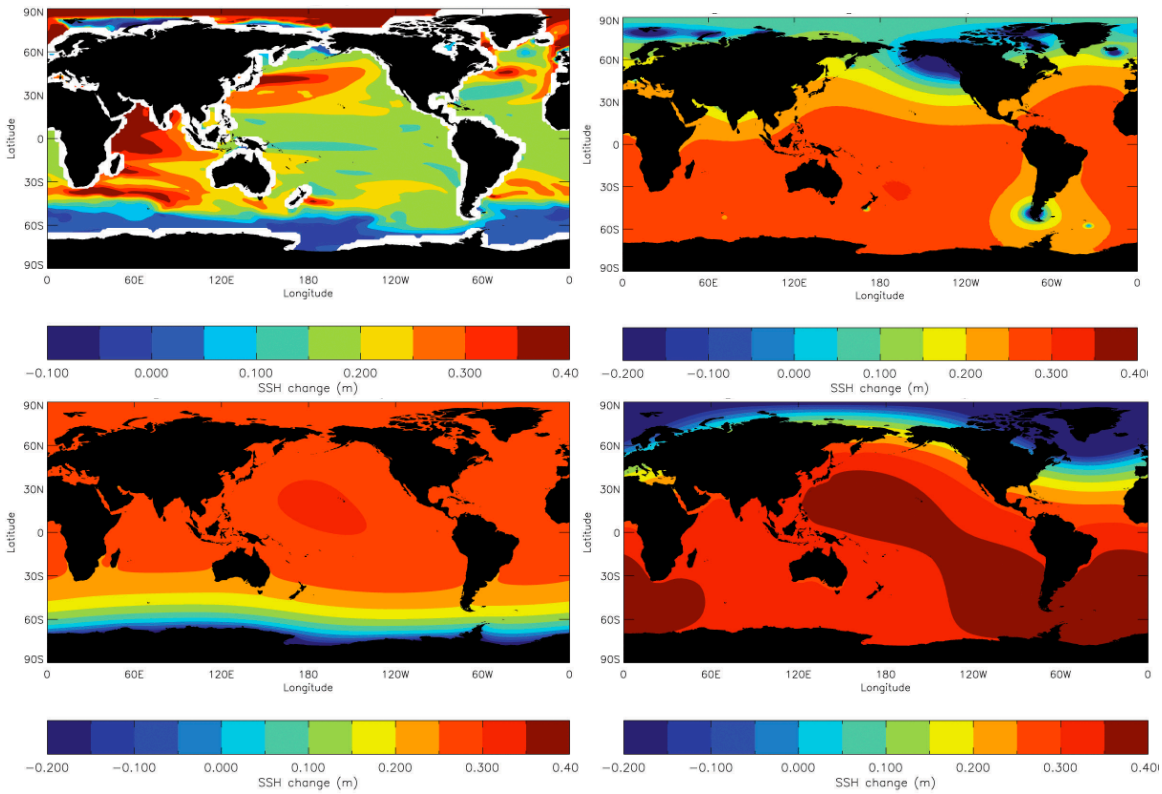


Figure 4. Patterns of sea level change expected from thermosteric change (top left), melting of mountain glaciers (top right), melting of Antarctic ice (bottom left), and melting of Greenland ice (bottom right).

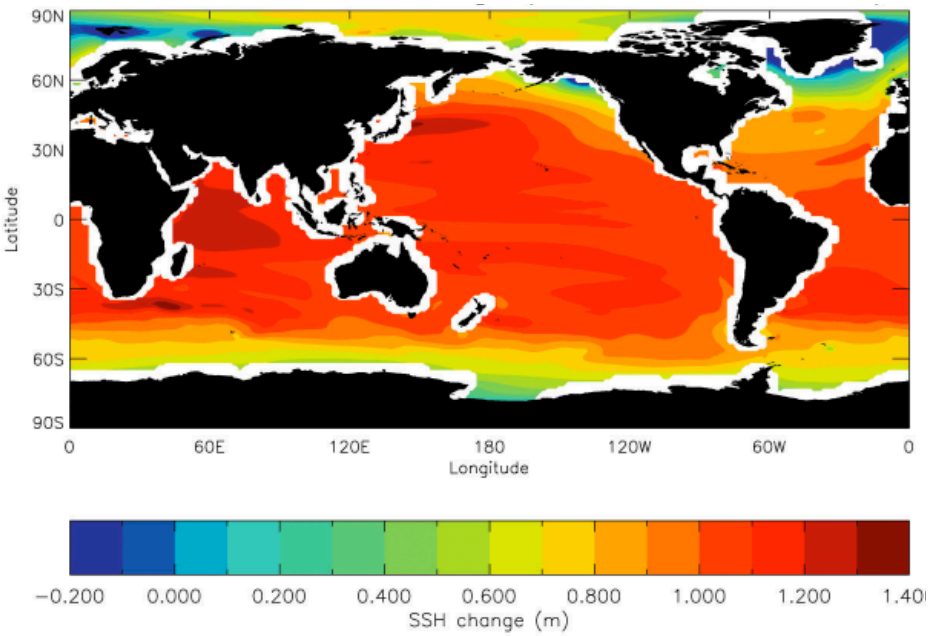


Figure 5. A prediction of regional patterns of sea level change by 2100 assuming the following globally averaged contributions: steric (20 cm) from the MIROC model, mountain glaciers (25 cm), Greenland (30 cm), and Antarctica (25 cm), for 1 m of global average sea level change by 2100.

References:

Mitrovica, J. X., et al. (2001), Recent mass balance of polar ice sheets inferred from patterns of global sea level change, Nature, 409, 1026-1029.

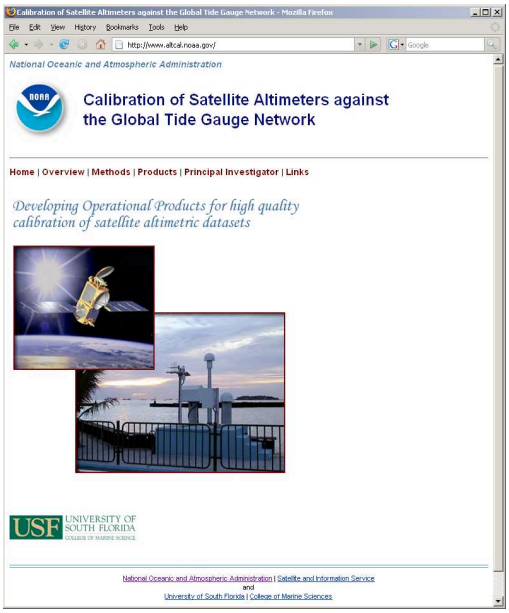
Nerem, R. S., S. Doris, J. K. Willis, D. P. Chambers, and G. T. Mitchum, Satellite and In Situ Observations of Regional Sea Level Change: What can they tell us about future changes?, *Eos Trans. AGU*, 88(52), Fall Meeting Suppl., Abstract G44A-01, 2007

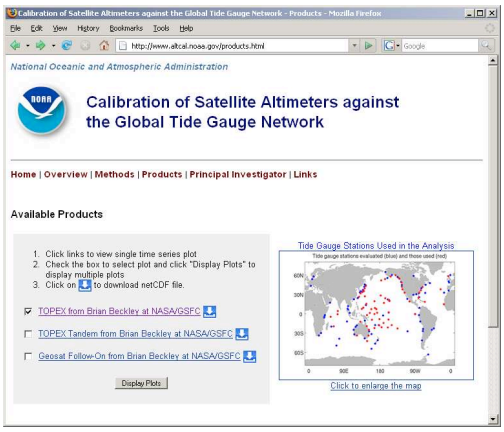
Rahmstorf, S. (2007), A Semi-Empirical Approach to Projecting Future Sea-Level Rise, Science, 315, 368-370.

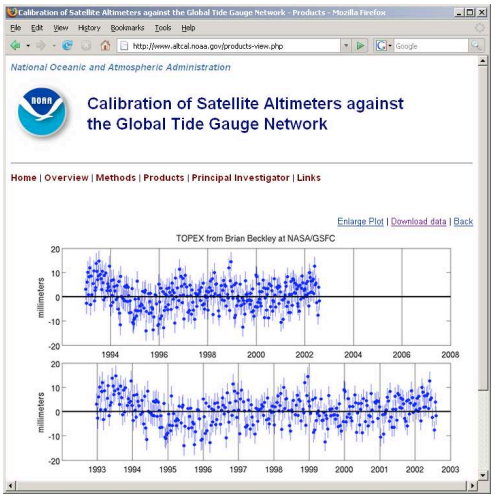
Solomon, S., et al. (Eds.) (2007), Climate Change 2007: The Physical Science Basis, Cambridge University Press.

Willis, J. K., et al. (2004), Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales, J. Geophys. Res., 109, doi:10.1029/2003JC002260

Appendix B. Altimeter/Tide Gauge Calibration Web Site: Example pages.







Global Carbon Data Management and Synthesis Project

Christopher L. Sabine[1], Richard A. Feely[1], Steve Hankin[1], Rik Wanninkhof [2], Tsung-Hung Peng[2], Alex Kozyr[3], Robert Key[4], Frank Millero[5], Andrew Dickson[6]
[1] NOAA Pacific Marine Environmental Laboratory, Seattle, WA
[2] NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami FL
[3] Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN
[4] Princeton University, Princeton, NJ
[5] University of Miami, RSMAS, Miami, FL
[6] Univ. of California San Diego, Scripps Institution of Oceanography, La Jolla, CA

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 are added to the data set. Each of these three steps is related and often requires iterative refinements of the previous steps to develop the final products leading to improved estimates of ocean uptake and storage.

The OCO ocean carbon network makes two basic types of observations: surface CO_2 observations with ships of opportunity and moorings and water column carbon observations with repeat hydrography cruises. The Global Carbon Data Management and Synthesis Project addresses both

observation types. Because surface observations are collected in a different manner and have different requirements for developing the final product than the repeat hydrography data, the data management for these two data types is discussed separately. The activities and accomplishments for both data types in FY07 are discussed below.

ACCOMPLISHMENTS

The funds received for Global Carbon Data Management and Synthesis Project were instrumental in providing data to the scientific community at large; for promoting and allowing the global synthesis and interpretation of national and international surface and water column carbon data; and integration of the carbon program elements within the NOAA Climate Observation Program.

Measurement Coordination and Initial Quality Control

The first NOAA carbon principal investigator meeting was hosted by AOML in Miami in February 2007. This meeting was attended by most investigators involved in the four Climate Observation Program carbon projects: repeat hydrography, CO_2 measurements from ships, CO_2 measurements from buoys, and synthesis and data management. The meeting also included program managers from the Climate Observation Program and Global Carbon Cycle Program and worked to improve coordination of the NOAA carbon projects and develop consensus on "best practices" for measurements and data management. In addition, members of the Global Carbon Data Management and Synthesis Project participated in a variety of national and international workshops to improve coordination between the NOAA carbon program and the national and international carbon community:

- Sustained Indian Ocean Biogeochemistry and Ecological Research (SIBER) Workshop, Goa, India, October 1-8, 2006
- CLIVAR Global Synthesis and Observations Panel SSG meeting, La Jolla, CA, Dec. 8-9
- North American Carbon Project PI meeting, Colorado Springs, CO, January 22-24, 2007
- Joint Canada-US-Mexico NACP meeting, Colorado Springs, CO, January 25-26, 2007
- Atlantic Ocean Carbon Synthesis Meeting, Kiel Germany, March 21-23, 2007
- Ocean Surface pCO_2 and Vulnerabilities Workshop, Paris, France, April 11-13, 2007
- Anthropogenic Stresses on Ocean Ecosystems Workshop, Seattle, WA, April 23-24, 2007
- Ocean Carbon and Biogeochemistry annual workshop, Woods Hole, MA, July 23-26, 2007
- NOAA GCC program PI meeting, Silver Spring MD, September 10-11, 2007

Repeat Hydrography

DIC data from all new repeat hydrography cruises up through 2007 as well as the hydrographic, nutrient and CFC data from all NOAA led cruises have gone through post cruise calibration and corrections. The responsible PIs have completed the first level of quality control and submitted finalized data to the Carbon Dioxide Information Analysis Center (CDIAC) and the Clivar Carbon and Hydrographic Data Office (CCHDO). The data and the flags are double checked by both CDIAC (Kozyr) and Princeton (Key). Any discrepancies are resolved, though that is seldom necessary. Both the early data submission and the extremely high quality of the CLIVAR carbon measurements have greatly simplified this procedure. At CDIAC, Kozyr has refined the CLIVAR web presentation so that it is simple for a user to access CLIVAR data as well as data from previous cruises along the same sampling

line. This web organization makes it easy for any end user to see which sections have been repeat-sampled and to download the appropriate data for subsequent investigation.

CDIAC has processed all new Repeat Hydrography sections: P16S_2005, P16N_2006, I8S_2007, I9N_2007. CDIAC also works closely with the CCHDO to merge the final carbon data with the final hydrographic data and ensure that the latest results are available to the community in a variety of formats. All of the latest repeat hydrography data have also been added to the CDIAC Mercury and WAVES (http://cdiac3.ornl.gov/waves/) data management tools. CDIAC numeric data packages (NDPs) for the A20, P02 and P16S cruises have not been published yet because the alkalinity data on these cruises have not been finalized.

All future cruise plans are coordinated with the international community through the International Ocean Carbon Coordination Project (IOCCP) and the international CLIVAR office.

Surface CO_2

CDIAC received and processed new data from the following VOS lines: Nuka Arctica 2005 lines (Norway), Skaugran 1995 -1999, Alligator Hope 1999-2001, Pyxis 2001-2006, Ryofu Maru 1989-2007, Keifu Maru 2001-2007, and Kofu Maru 1998-2002 (all Japan), Aurora Australis 1993 – 2002 cruises (Australia), Explorer of the Seas 2004-2006 (USA). Data from the OCO moored CO_2 observations have also been received and processed. All data were quality controlled, evaluated and made available to public through CDIAC VOS web page: http://cdiac.esd.ornl.gov/oceans/global_pco2.html. The metadata for these data were added to Mercury: http://mercury.ornl.gov/ocean/.

Based on meetings with the international ocean carbon community and from our PI meeting, AOML and PMEL have reprocessed all of our current and historical underway pCO_2 data into a common internationally agreed upon format. Meta-data was updated in the format advocated by the International Ocean Carbon Coordination Panel (IOCCP) and data have been forwarded to the national repository at CDIAC. The moored CO_2 data and meta-data have also been put into the same formats to encourage a better integration of these data streams. The latest surface CO_2 data were also sent to Dr. Takahashi for inclusion in his updated climatology. This marks the first time that the Takahashi climatology will include both underway and moored data. The full Takahashi dataset has been published by CDIAC as a numeric data package NDP-088 (CDIAC-152): *Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed During 1968–2006 (Version 1.0)*.

During the last fiscal year, new software was written at PMEL to quickly process data files that are transmitted daily via Iridium satellite from the NOAA ships *Ka'imimoana* and *Albert Rickmers*. This software processes the daily data and creates diagnostic plots of pCO_2, temperature, salinity, barometric pressure, water flow and gas flow. The plots are posted on a newly created internal website and are used as a diagnostic tool for data processing and quality control of the underway pCO_2 data. All current and previous VOS data files are quality controlled using the data submission protocol for ships under the NOAA Office of Climate Observations (OCO) workplan "pCO_2 measurements from ships". After installation of real-time data transmission on the AOML VOS ships, a new download and near-real time display program was produced at AOML to accommodate different origins of the data streams. Data and error reports are transmitted from the ships via Iridium or FTP every morning and checked for instrumental issues.

Data Management and Contextual Quality Control

Repeat Hydrography

In collaboration with European partners in the Carboocean effort we are engaged in a major synthesis of data sets in the Atlantic, Arctic and Southern oceans. The focus is on older data (pre-2003) in the Atlantic Ocean and is being collated by Dr. Key of Princeton. Last year Key reported a total collection of 85 cruises and the expectation that "several more" would be obtained by the Carboocean data submission deadline of 12/31/06. Carboocean is a European Union program and European scientists have been the source for virtually all these previously unavailable data. In reality the number of submitted cruises exploded to a total of 169. This incredible increase was largely influenced by the deadline, but also by the fact that the study region was expanded during a meeting late last year in Iceland, to include the entire Arctic Ocean and the Southern Ocean rather than just the North Atlantic and Nordic Seas. The workload implied by this growth combined with the very tight Carboocean time schedule very significantly exceeded what was possible with the support from this grant. Consequently, additional funding was requested from NOAA-OGP via a separate grant. Upon hearing that this proposal would be funded, part time technical help (Xiaohua Lin) was hired at Princeton specifically for data formatting and similar database chores. This new data collection will be known as CARINA after the defunct European project of the same name. Figure 1 shows the CARINA station locations for the cruise data distributed to the working teams in October.

The data from the CLIVAR CO_2 repeat hydrography cruises will be used as a standard against which the CARINA cruises will be compared. As part of this effort, Wanninkhof and Key attended a synthesis meeting at Kiel, Germany in March 2007. At the Kiel meeting it became obvious that the manual secondary QC techniques used during GLODAP would be impossible for this volume of data and time frame. The plan to semi-automate the process was assigned to a software team that included input from Wanninkhof and Key. This software is still evolving and will continue to develop, but sufficiently sophisticated versions are now available on-line and being used by each group. Thus far, the software will automatically identify those stations in a merged dataset which are within given distance of each other and then carry out a routine deep water "crossover" analysis similar to those used in GLODAP. The maximum station separation distance and the list of tested parameters are chosen by the operator. Next, the crossover results are passed to an objective minimizing routine similar to that used by (Johnson et al., 2001). Some CARINA cruises data are now available through the open CDIAC CARINA web site (http://cdiac.ornl.gov/oceans/CARINA/Carina_inv.html). A password protected CARINA web site has been established at CDIAC for secondary QC and synthesis work. AOML leads the effort of secondary quality control of the post-1997 WOCE cruises and CLIVAR/CO_2 cruises in the Atlantic. PMEL is leading the secondary quality control for the Pacific sector of the Southern Ocean. The Carboocean synthesis subgroups are in the process of examining over 800 crossovers for DIC, O_2, NO_3, T, S, SiO_2, and PO_4.

A similar effort is beginning in the Pacific as part of the North Pacific Marine Science Organization (PICES) section on Carbon and Climate. PMEL investigators (Feely and Sabine) have been PICES members for years. Approximately a year ago PICES PIs decided to construct a data set of historic cruises from their countries similar to CARINA. At the annual meeting, which was held in Victoria, B.C. during October, Japanese scientists presented a list of approximately 200 cruises on which carbon measurements had been made during recent times. The data from about 60 of these cruises had actually been obtained and converted to similar format. Korean attendees (primarily K. Lee) volunteered additional Korean cruises for the collection and communication channels were opened between scientists who are actively trying to recover decades of data from C.-S. Wong's Canadian laboratory.

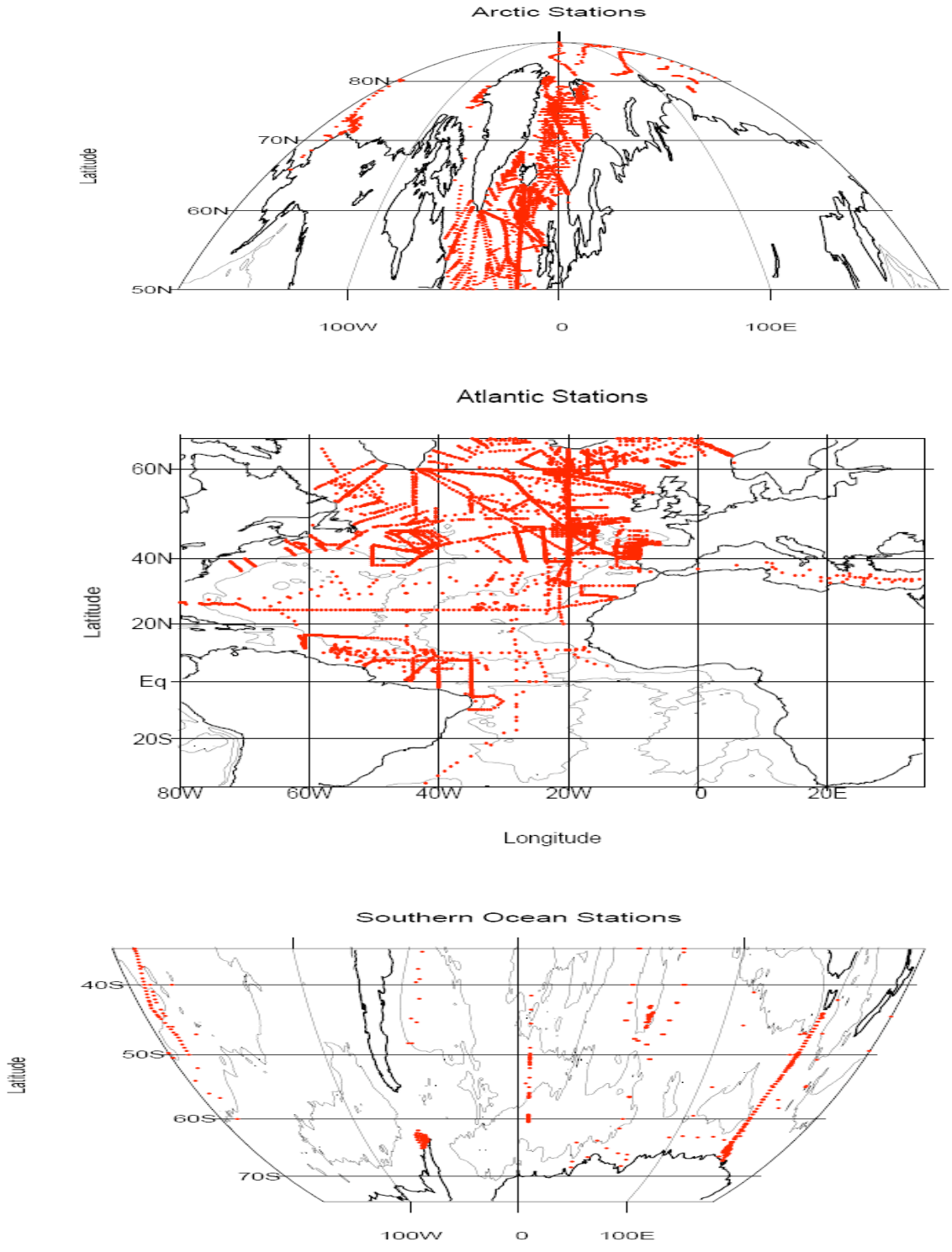


Figure 1. Maps of new stations (beyond GLODAP) compiled for CARINA dataset and international data synthesis efforts.

At the meeting various rules for data sharing, etc. were discussed and agreed. In most respects the operating procedures will be quite similar to those used for Carboocean/CLIVAR. With collaborations from Toru Suzuki, MIRC (Japan), CDIAC has started to compile the PICES database for the secondary quality control effort (http://cdiac.ornl.gov/oceans/PICES/PICES_table.html). Initial quality control and additional formatting will be done at Princeton and work groups will eventually be formed to carry out secondary QC and subsequent science.

One major difference between the PICES and CARINA efforts is that the PICES work will not be funded by a central organization. That is, PICES does not fund science it only covers travel expenses for PICES members to the annual meeting. This funding arrangement is identical to that of the original CARINA collaboration of the 1990s and in that case the project was a failure. We are hopeful that this result can be reversed. That optimism is based on three key factors: (1) a few Japanese scientists with secure funding have a strong vested interest in the project (2) the existence and full cooperation of CDIAC from the outset and (3) the experience provided by the U.S. participants. In the worst case scenario, secondary QC tasks could be carried out primarily by the funded Japanese and U.S. participants. This would be far from ideal and would significantly extend the required analytical time, but should eventually produce a valuable data product for the North Pacific.

Surface CO_2

Working though the IOCCP and EU Carboocean project, Global Carbon Data Management and Synthesis Project members helped promote and establish a standard global surface CO_2 data set for the international community. This effort builds on the work started in 2001 as part of the EU ORFOIS project by Dorothee Bakker (UEA) and now continues as part of the Carboocean project. Benjamin Pfeil and Are Olsen (Bjerknes Centre for Climate Research) have compiled more than 1250 cruises from 1972 - 2007, with approximately 4.5 million measurements, into a dataset with a common format that has undergone standard 1st level Quality Control procedures. These data will be submitted to CDIAC by the end of calendar year 2007. Project members will continue to work with the international community to develop regional teams to conduct the second level quality control in a manner similar to the CARINA data discussed in the previous section.

In FY07 PMEL continued development of the Ocean Carbon Data Management System (OCDMS) with a focus on underway data as the primary area for data management work. The LDEO (Takahashi) consolidated collection was the target of much of these efforts guided by the strategy that, through addressing this dataset -- the largest assembled collection of underway cruises -- the techniques and tools needed to handle individual OCO-sponsored carbon measurement cruises would advance as well. Indeed, we also applied these tools to individual cruise data from PMEL and AOML. The work involved developing a new database schema; tools and procedures for ingesting the data; quality control filters; tools and techniques for high speed retrieval of selected subsets from the collection; and an LAS-based system (user interface and products) for visualization of the data and interaction with it. A version of the work was presented by Jon Callahan to the Carbon Science Team meeting in Miami in February, 2007. A more recent update was presented by Steve Hankin at the NOAA Global Carbon Cycle PI meeting in September.

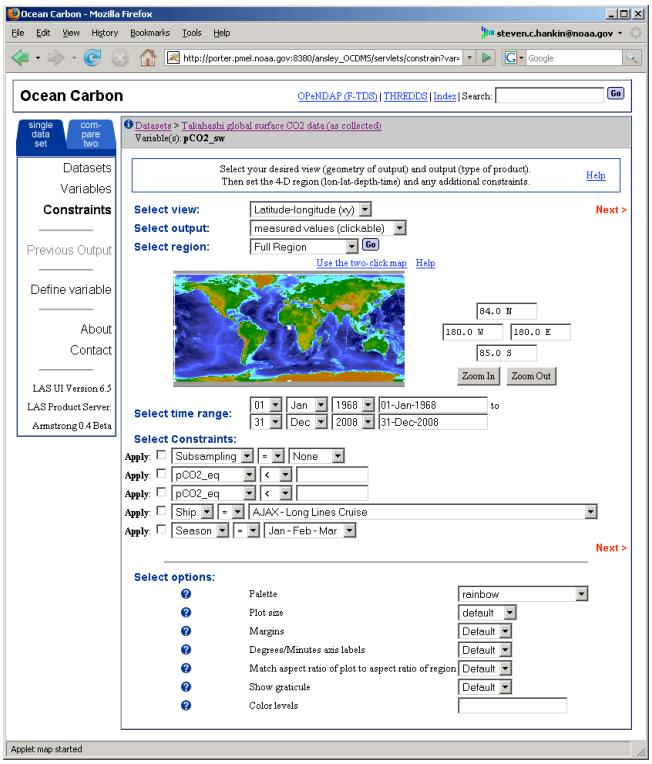


Figure 2. OCDMS User Interface snapshot

The process of ingesting data as a collection into a database provides a final filter on several aspects of quality control. The filters that were developed for the OCDMS and utilized on the LDEO collection ingested over 3.2 million records from which they flagged 34,485 (1.1%) as invalid due to out-of-range (not plausible) values and 14379 (0.4%) as duplicates. (Duplicate records can cause mis-weighting during analyses.) These errors were reported back to LDEO, and have been incorporated into the recently released update of the LDEO database.

To achieve adequate interactive performance it was necessary to derive hourly, 4x daily and daily subsets of the data in the database as well as the full resolution tracks. Typically the system determines which subsampled level of data to access based upon the scope of the request, though the user can override this. In the screen snapshot of the user interface (Figure 2) this control is visible as the Subsampling constraint. An example illustrating the importance of the subsampled database tables is found in Figure 3 (left), where we see a global snapshot of pCO_2 seawater for 1968 through the present. The LAS system delivers such a figure in a matter of seconds, although the full resolution data contain millions of observations.

Exploratory styles of interacting with the data are also provided. For example, zooming into a localized view of data (Figure 3 right) and viewing the relationships between properties. The ability to constrain data queries based upon essential metadata is an important requirement of the system. In Figure 2 above we see controls to constrain searches based upon ship ID and seasonality. Seasonality is of particular importance in interpreting the data. Further constraint options may be added in the future as requested by carbon scientists.

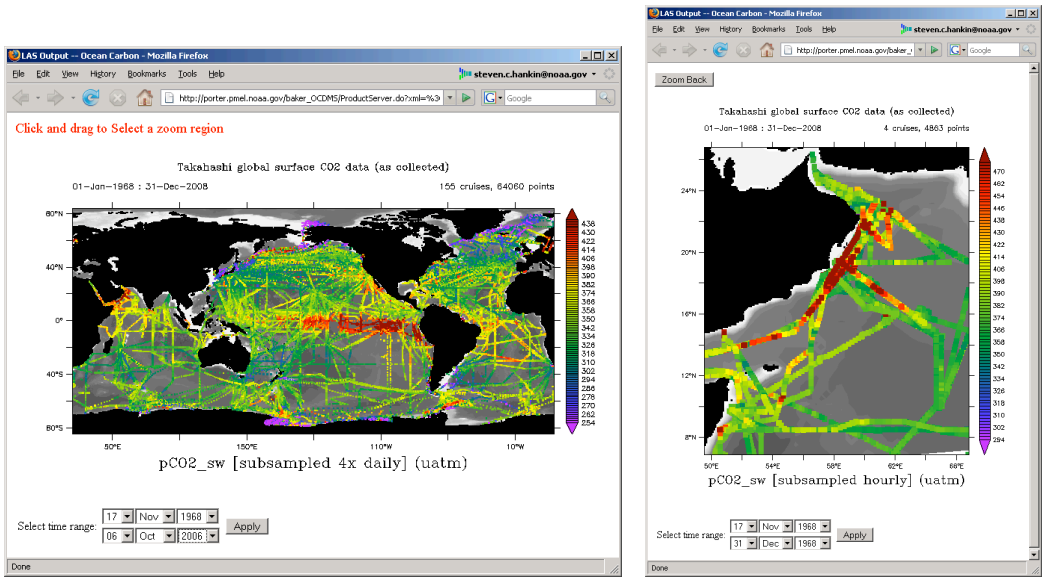


Figure 3. pCO_2 seawater from LDEO 1968 to present globally (left) and zoomed (right)

Figure 4 illustrates the display of ocean carbon maps onto the Google Earth® application. While not a specifically pressing need of the carbon science community, tools such as Google Earth® provide outreach to other communities and demonstrate the interoperability of the OCDMS with other applications.

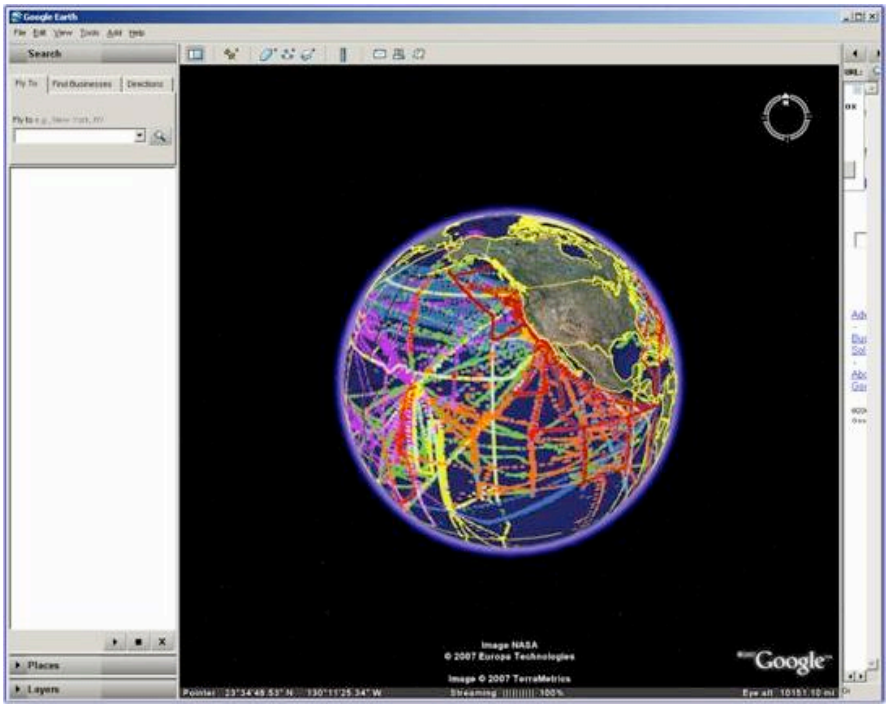


Figure 4. Carbon map displayed on Google Earth®

Synthesis and Interpretation

Repeat Hydrography

Global Carbon Data Management and Synthesis Project members have continued to investigate ocean carbon system variability using both the existing GLODAP dataset as well as new Repeat Hydrography cruises. This work has focused primarily on understanding the natural variability in the ocean carbon system and how these changes can be distinguished from the expected secular trends from rising atmospheric CO_2.

Three publications on the changes in the Atlantic have been written with PI's of this program as co-author (Chanson et al., 2007; Levine et al., 2007; Wanninkhof et al., 2007). The work shows that the anthropogenic CO_2 increase is unequivocal but that quantification is very dependent on approach with estimates for the Atlantic ranging from 0.4 to 0.8 mol/m^2/yr with most converging at 0.6 mol/m^2/yr. On a basin-scale several approaches yield similar estimates but regional differences and biases are very apparent. Comparisons of the basin-wide patterns of decadal anthropogenic CO_2 uptake based on several different permutations of the multi-linear regression approach are provided in Figure 5. Modeling efforts using the NCAR community model confirm the magnitude and general location of decadal variability in the sub-polar gyres that can be primarily attributed to changes in ventilation (Levine et al., 2007).

Ever since GLODAP produced the first global estimates of the oceanic anthropogenic CO_2 distribution, one very curious result has remained: the fact that the near surface anthropogenic CO_2 concentrations were so much higher in the Atlantic than in the Indo-Pacific. When first noted, C. Sabine and K. Lee rechecked the GLODAP Atlantic methods and results. Their efforts indicated that methodology variations might explain some of the difference, but the major portion appeared to be real. Since then R. Toggweiler (GFDL) along with J. Sarmiento and R. Key (Princeton) have been trying to understand the discrepancy. Over the years several theories have been proposed, however, in each case testing eventually killed all previous ideas. Very recently Toggweiler proposed a new theory. As with some of the previous ideas, this one hinges on the fact that most of the global river input is into the Atlantic and that riverine chemistry (concentrations) is significantly different than the ocean for both DIC and alkalinity. This chapter of the investigation is just starting, however, it differs from previous ones both in simplicity and the fact that longer time scale processes are included. If successful, a report of this research will be included in the 2008 annual report.

The Pacific has been examined by the group using a couple of different approaches. For example, isopycnal analyses have been used to investigate the temporal changes in DIC between the 1991 and 2006 occupations of P16N. Comparisons of DIC along isopycnal surfaces with sigma-theta of 26.0, 26.2, 26.4, 26.6, 26.8, 27.0, and 27.2 for P16N. The DIC increases vary on each isopycnal, with 2.4 μmol/kg along 27.2, and 18.0 μmol/kg along 26.4. Using the estimated thickness of isopycnal horizons between 15°N and 45°N, we obtained a mean DIC inventory change of 0.58 μmol/kg/yr in the North Pacific between 1991 and 2006. For the South Pacific, the DIC increase is apparently much faster. We have seen significant DIC increases along each isopycnal horizons, on the order of 20 μmol/kg from 26.0 to 27.2. Based on the estimated thickness of isopycnal layers between 15°S and 40°S, the mean DIC inventory change is estimated to be 1.61 μmol/kg/yr for the period from 1991 to 2005.

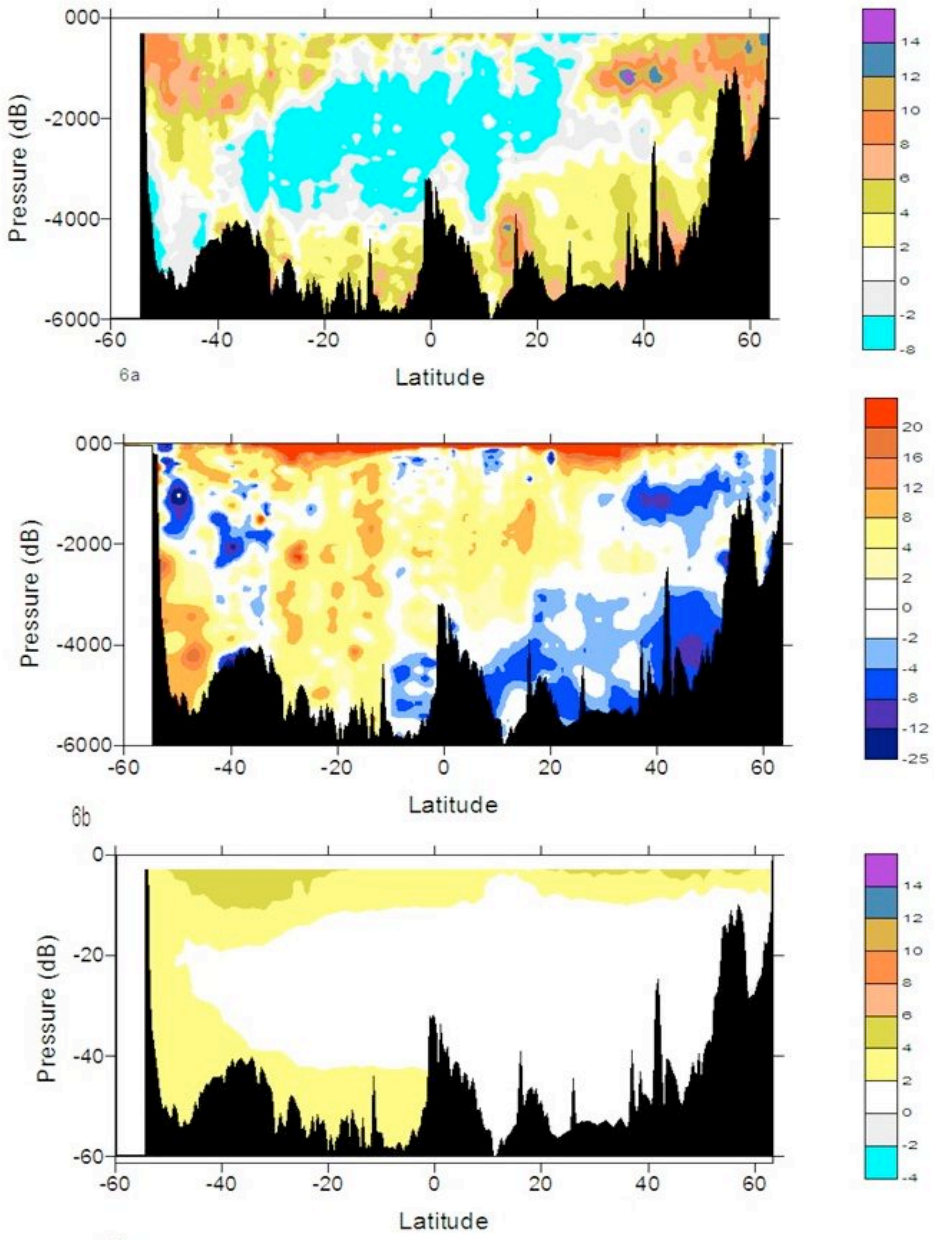


Figure 5: Different multi linear regression (MLR) approaches to estimate the anthropogenic CO_2 increase over the last decade for the full water column along line A16 through the middle of the Atlantic Ocean utilizing S,T, AOU, NO_3, and SiO_4 as input parameters. (a) MLR determined from 1989/1993 data subtracted from 2003/2005 DIC data. (b) 1989/1993 DIC data subtracted from a MLR created 2003/2005 DIC data. (c) MLR determined from 1989/1993 data subtracted from the MLR determined with the 2003/2005 data using S, T, AOU, NO_3, and SiO_4 from 2003/2005. The approach is referred to as the extended multi-linear regression (e-MLR). Note the differences in scale.

We have also used the extended multiple linear regression (eMLR) technique to investigate changes over the last decade in DIC inventories on a meridional line (P16 along 152ºW) up the central Pacific and on a zonal line (P02 along 30ºN) across the North Pacific (Sabine et al., 2007). Maximum changes in the total DIC concentrations along P02 are 15-20 µmol kg^{-1} over 10 years, somewhat higher than the ~1 µmol/kg/yr increase in DIC expected based on the rate of atmospheric CO_2 increase. The

maximum changes of 15-20 µmol/kg along the P16 line over the 14/15 year time frame fit with the expected magnitude of the anthropogenic signal, but there is a deeper than expected penetration of the signal in the North Pacific compared to the South Pacific. The effect of varying circulation on the total DIC change based on decadal alterations of the apparent oxygen utilization rate is estimated to be greater than 10 µmol/kg in the North Pacific, accounting for as much as 80% of the total DIC change in that region (Figure 6). The average anthropogenic CO_2 inventory increase along 30ºN between 1994 and 2004 was 0.43 mol/m^2/yr, with much higher inventories in the western Pacific. Along P16, the average Northern Hemisphere increase was 0.25 mol/m^2/yr between 1991/1992 and 2006 compared to an average Southern Hemisphere anthropogenic CO_2 inventory increase between 1991 and 2005 of 0.41 mol/m^2/yr.

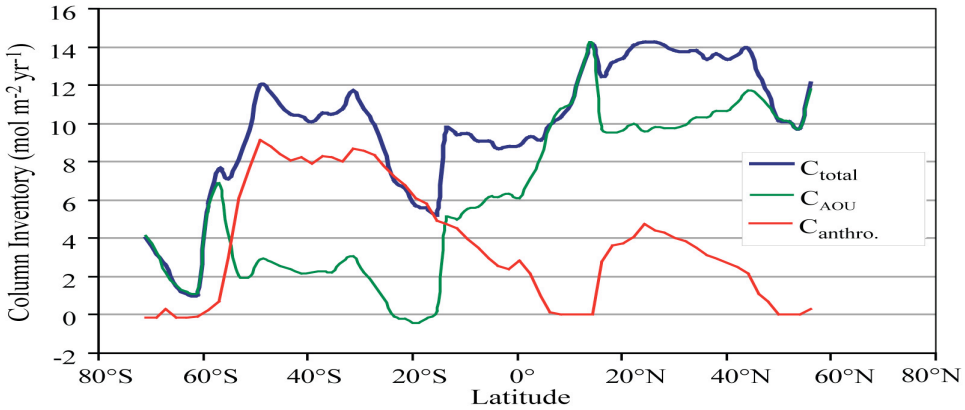


Figure 6. Plot of column inventories along P16N (150°W) showing the total inventory, the inventory attributed to circulation changes as estimated from AOU and the anthropogenic CO_2 inventory.

The Repeat Hydrography program began surveying the Indian Ocean with the I8S/I9N line, nominally along 95°E, in February to March 2007. The DIC data have been finalized and submitted to CDIAC, but we are just starting to look at the data in terms of secondary quality control and decadal changes. Comparison of deep data with the previous WOCE cruises shows that both cruises have very high quality data. Figure 7 shows the initial comparison of measured values along the section. This figure clearly indicates large changes in DIC over the time period, but additional analyses must be made to evaluate whether these changes directly result from anthropogenic CO_2 uptake or not.

The Princeton group has been examining model and data derived results comparing data from reoccupations separated by 6 months up to 2 years. With these short time intervals, differences in DIC along a section should be totally dominated by processes other than invasion of anthropogenic CO_2 from the atmosphere. This research is still in progress, but the model results confirm the findings from the Pacific that physical changes alone can generate DIC changes along a section that are as large as the expected decadal anthropogenic CO_2 invasion signal. On shorter time scales, the physical changes along a section can be very significant in the upper water column. The model suggests that some but not all of the resulting DIC change is reflected in oxygen change. Over the next few months we will be using model output to help understand what is causing these differences. We are hopeful that this work will eventually lead to improved methods for quantifying both natural variability and anthropogenic CO_2 uptake.

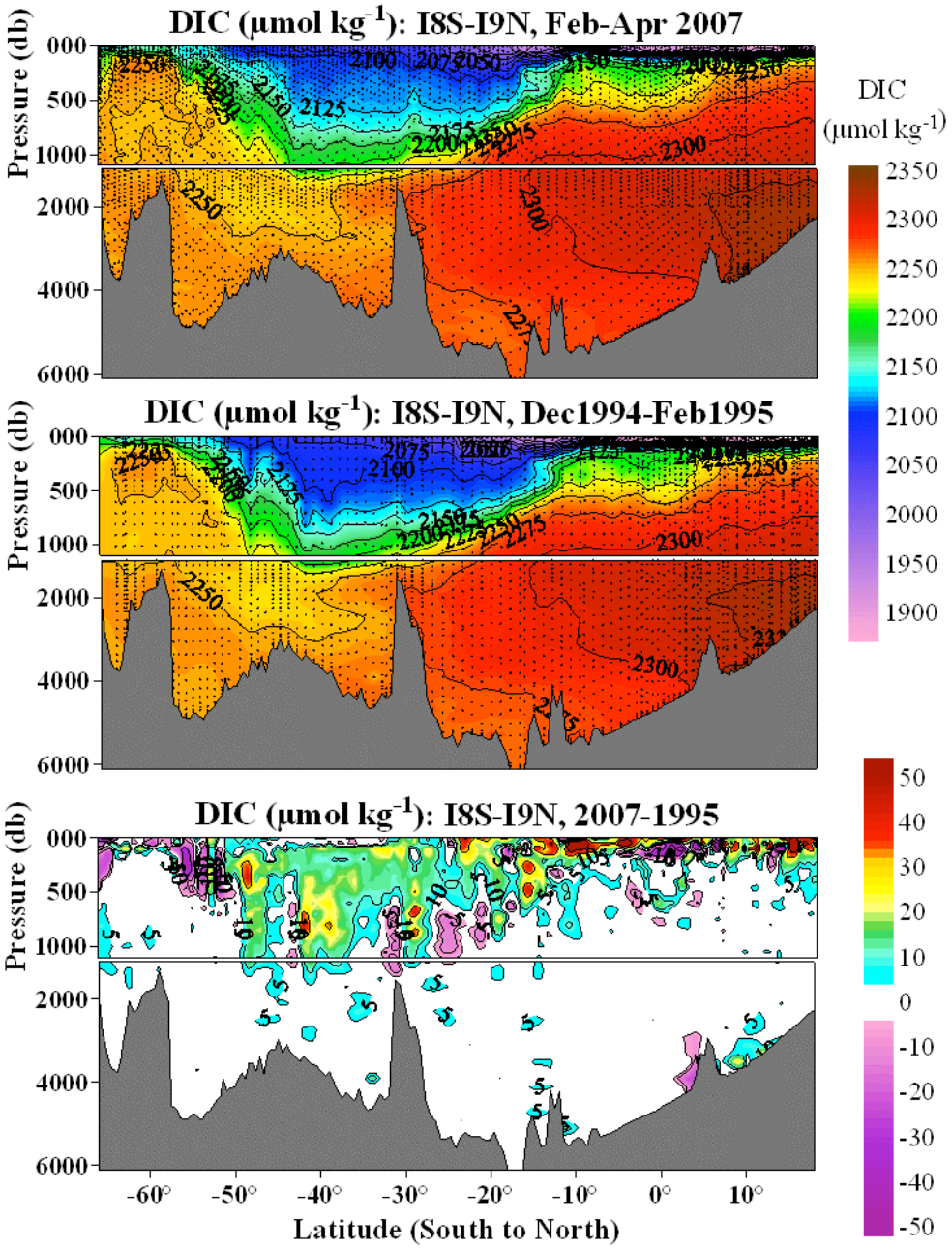


Figure 7. Meridional sections of DIC in the eastern Indian Ocean from the 1995 WOCE survey, from the 2007 repeat hydrography cruise, and a plot of the difference between the measured values.

Surface CO_2

Global Carbon Data Management and Synthesis Project members are also investigating ocean carbon system variability in the surface ocean using both the existing GLODAP data set as well as new data. This work has focused primarily on understanding the time and space scales of variability of CO_2 in the global ocean.

In McNeil et al. (2007), we produced an empirical estimate of the CO_2 flux in the Southern Ocean based on near surface DIC and alkalinity data from GLODAPv1.1 (Key et al., 2004) plus additional data provided by N. Metzl. The empirical relationships were multiple linear regressions in

form, but limited to hydrographic parameters and nutrients for fitting. The equations were able to reproduce surface DIC and alkalinity (normalized to constant salinity) values to within 8 µmol/kg. The equations were used with global climatologies of the fitting parameters to investigate seasonal variations in the surface concentrations of DIC and alkalinity. The procedure was also used to approximate surface pCO_2 concentrations and to subsequently calculate air-sea CO_2 fluxes. In general the flux estimates were similar to those reported by (Takahashi et al., 2002), and somewhat higher than inversion based estimates.

In Sweeney et al. (2007) we used the GLODAPv1.1 radiocarbon data, augmented in the far North Atlantic using an approximation technique, to re-estimate the global mean air-sea gas exchange rate based on the bomb-produced radiocarbon inventory. The method was a natural extension of that originally used by (Broecker and Peng, 1982) and (Broecker et al., 1985). The derived gas exchange rates were lower than Broecker's estimates and Wanninkhof (1992) estimate. The total inventory of bomb-produced radiocarbon in the ocean (from this work) is now in agreement with global budgets based on radiocarbon measurements made in the stratosphere and troposphere.

In Takahashi et al. (2007) a climatological mean distribution for the surface water pCO_2 over the global oceans in non-El Nino conditions was constructed with spatial resolution of 4° (latitude) x 5° (longitude) for a reference year 2000 based upon about 3 million measurements of surface water pCO_2 obtained from 1970 to 2006. Seasonal changes in the surface water pCO_2 and the sea-air pCO_2 difference over four climatic zones in the Atlantic, Pacific, Indian and Southern Oceans are presented. The annual mean for the net sea-air CO_2 flux over the global oceans is estimated to be 1.4 ± 0.7 Pg-C/yr. Taking the pre-industrial steady state ocean source of 0.4 ± 0.2 Pg-C/yr into account, the total ocean uptake flux including the anthropogenic CO_2 is estimated to be 1.8 ± 0.7 Pg-C/yr in 2000.

Using the approach described in (Lee et al., 1998), and (Park et al., 2006) we have estimated the interannual variability in air-sea CO_2 fluxes from 1989-2006 using the new climatology of Takahashi et al. (2007). The effect of this new climatology on the past estimate of variability from 1990-2006 is shown in figure 8. The newer results show a 30 % increase in interannual variability as determined by the difference in standard deviation.

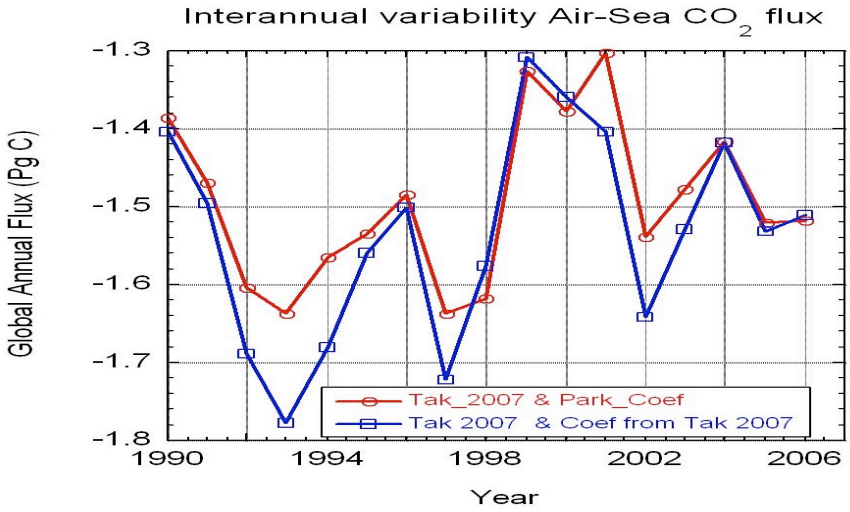


Figure 8: Comparison of estimated interannual variability using monthly sea surface temperature anomalies and the updated global pCO_2 climatology of Takahashi et al., (submitted). The red line are the results using the SST-pCO_2 relationship derived by Park et al. (2006) while the blue line gives the SST-pCO_2 relationships derived from the new climatology by Trinanes (pers. comm.) as part of this effort.

Ocean Acidification

Recent laboratory and field studies have provided evidence for deterioration of many species of marine organisms that produce calcium carbonate shells due to increasing carbon dioxide levels in seawater and the resulting decline in pH. For example, increasing seawater acidification has been shown in controlled studies to significantly reduce the ability of reef-building corals to produce their skeletons, affecting growth of individual corals and making the reef more vulnerable to erosion. Some estimates indicate that, by the middle of this century, coral reefs may erode faster than they can be rebuilt potentially making them less resilient to other environmental stresses (e.g., disease, bleaching, storms). The Global Carbon Data Management and Synthesis Project has been providing information directly related to better understanding the effects of ocean acidification and Dr. Richard Feely (PMEL), along with other project PIs, has been actively involved in developing the NOAA strategy for investigating and monitoring ocean acidification and its consequences. We have organized and participated in several national and international conferences on the subject. This is an emerging topic in the ocean community and will likely play a much more prominent role in our interpretation of ocean carbon data in FY08 and beyond.

REFERENCES

Broecker, W. and Peng, T.H., 1982. Tracers in the Sea. Eldigio Press, Columbia University, Palisades, NY, 690 pp.

Broecker, W.S., Peng, T.H., Ostlund, G. and Stuiver, M., 1985. The distribution of bomb radiocarbon in the ocean. J. Geophys. Res., 90(6953-6970).

Chanson, M. and F.J. Millero, Effect of filtration on the total alkalinity of open-ocean seawater, Limnol. Oceanogr.: Methods, 5, 293-295, 2007.

Johnson, G.C., Robbins, P.E. and Hufford, G.E., 2001. Systematic adjustments of hydrographic sections for internal consistency. J. Atmos. and Ocean. Tech., 18: 1234-1244.

Key, R.M. et al., 2004. A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP). Global Biogeochemical Cycles, 18(4).

Lee, K.R., Wanninkhof, R., Takahashi, T., Doney, S. and Feely, R.A., 1998. Low interannual variability in recent oceanic uptake of atmospheric carbon dioxide. Nature (396): 155-159.

Levine, N.M., Doney, S.C., Wanninkhof, R., Lindsay, K. and Fung, I.Y., 2007. The impact of ocean carbon system variability on the detection of temporal increases in anthropogenic CO_2. J. Geophys. Res. , in press.

McNeil, B.I., N. Metzl, R.M. Key, R.J. Matear and A. Corbiere(2007) An empirical estimate of the Southern Ocean air-sea CO_2 flux, Global Biogeochem. Cycles, 21(3), GB3011, doi:10.1029/2007GB002991.

Park, G.-H., Lee, K., Wanninkhof, R. and Feely, R.A., 2006. Empirical ocean temperature-based estimates of variability of oceanic uptake of CO_2 over the last two decades. Journal of Geophysical Research, C07S07(111): doi:10.1029/2005JC003090.

Prentice, I.C. et al., 2001. The carbon cycle and atmospheric CO_2. In: J.T. Houghton and D. Yihui (Editors), Climate Change: The Scientific Basis, Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 183-287.

Sabine, C.L., R.A. Feely, F.J. Millero, A.G. Dickson, C. Langdon, S. Mecking, J. Swift, and D. Greeley, 2007. Decadal changes in Pacific carbon. J. Geophys. Res., submitted.

Sweeney, C., E. Gloor, A. R. Jacobson, R. M. Key, G. McKinley, J. L. Sarmiento, and R. Wanninkhof, 2007. Constraining global air-sea gas exchange for CO_2 with recent bomb C-14 measurements, Global Biogeochemical Cycles, 21, doi:10.1029/2006GB002784.

Takahashi, T. et al., 2002. Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects. Deep-Sea Research Part Ii-Topical Studies In Oceanography, 49(9-10): 1601-1622.

Takahashi, T., et al., 2007. Climatological Mean and Decadal Change in Surface Ocean pCO_2, and Net Sea-air CO_2 Flux over the Global Oceans, Deep -Sea Res., submitted.

Wallace, D.W.R., 2001. Storage and transport of excess CO2 in the oceans: The JGOFS/WOCE Global CO_2 Survey. In: G. Siedler, J. Church and J. Gould (Editors), Ocean Circulation and Cliamte: Observing and Modeling the Global Ocean. Academic Press, San Diego, CA, pp. 489-521.

Wanninkhof, R., 1992. Relationship between wind-speed and gas-exchange over the ocean. J. Geophys. Res., 97: 7373-7382.

Wanninkhof, R. et al., 2007. Decadal changes of carbon and related parameters along meridional section A16 in the Atlantic Ocean. In preparation.

FY07 PUBLICATIONS AND REPORTS FROM THIS PROJECT

Berelson, W.M., W.M. Balch, R. Najjar, R.A. Feely, C. Sabine, and K. Lee (2007) Relating estimates of $CaCO_3$ production, export, and dissolution in the water column to measurements of $CaCO_3$ rain into sediment traps and dissolution on the sea floor: A revised global carbonate budget. Global Biogeochem. Cy., 21, GB1024, doi: 10.1029/2006GB002803.

Birdsey, R.A., R. Cook, S. Denning, P. Griffith, B.E. Law, J. Masek, A.M. Michalak, S. Ogle, D. Ojima, Y. Pan, C.L. Sabine, E. Sheffner, and E.T. Sundquist (2007) Investigators share improved understanding of the North American Carbon Cycle. Eos Trans. AGU, 88(24), doi: 10.1029/2007EO240004.

Caldeira, K., D. Archer, J.P. Barry, R.G.J. Bellerby, P.G. Brewer, L. Cao, A.G. Dickson, S.C. Doney, H. Elderfield, V.J. Fabry, R.A. Feely, J.-P. Gattuso, P.M. Haugan, O. Hoegh-Guldberg, A.K. Jain, J.A. Kleypas, C. Langdon, J.C. Orr, A. Ridgwell, C.L. Sabine, B.A. Seibel, Y. Shirayama, C. Turley, A.J. Watson, and R.E. Zeebe (2007) Comment on "Modern-age buildup of CO_2 and its effects on seawater acidity and salinity" by Hugo A. Loáiciga. Geophys. Res. Lett., 34, L18608, doi: 10.1029/2006GL027288.

Chanson, M. and F.J. Millero (2007) Effect of filtration on the total alkalinity of open-ocean seawater, Limnol. Oceanogr.: Methods, 5, 293-295.

Doney, S.C., N. Mahowald, I. Lima, R.A. Feely, F.T. Mackenzie, J.-F. Lamarque, and P.J. Rasch (2007) Impact of anthropogenic atmospheric nitrogen and sulfur deposition on ocean acidification and the inorganic carbon system. Proc. Nat. Acad. Sci., 104(37), 14,580–14,585.

Dugdale, R.C., F.P. Wilkerson, F. Chai, and R.A. Feely (2007) Size-fractionated nitrogen uptake measurements in the equatorial Pacific and confirmation of the low Si–high-nitrate low-chlorophyll condition. Global Biogeochem. Cy., 21, GB2005, doi: 10.1029/2006GB002722.

Inoue, H.Y., R.A. Feely, M. Ishii, T. Kawano, A. Murata, and R. Wanninkhof (2006) Long-term trend of the partial pressure of CO_2 in surface waters and sea-air CO_2 flux in the equatorial Pacific. Chapter 1 in Global Climate Change and Response of Carbon Cycle in the Equatorial Pacific and Indian Oceans and Adjacent Landmasses, H. Kawahata and Y. Awaya (eds.), Elsevier Oceanography Series, Vol. 73, Elsevier, Amsterdam.

Lee, K., L.T. Tong, F.J. Millero, C.L. Sabine, A.G. Dickson, C. Goyet, G.-H. Park, R. Wanninkhof, R.A. Feely, and R.M. Key (2006) Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans. Geophys. Res. Lett., 33, L19605, doi: 10.1029/2006GL027207.

Levine, N., M, S. C. Doney, R. Wanninkhof, K. Lindsay, and I. Y. Fung (2007) The impact of ocean carbon system variability on the detection of temporal increases in anthropogenic CO_2, J Geophys. Res., in press.

McGillis (chair and ed.), W., R. Duce, D. Erickson, C. Fairall, D. Farmer, R. Feely, B. Huebert, W. Jenkins, W. Keene, R. Kiene, P. Matrai, K. Melville, W. Miller, R. Najjar, E. Saltzman, P. Schlosser, D. Siegel, W.-J. Cai, D. Ho, S. Doney, K. Johnson, C. McNeil, M.J. Perry, J. Prospero, O. Schofield, P. Shepson, D. Turk, and R. Wanninkhof (2006) The United States Surface Ocean—Lower Atmospheric Study (SOLAS), Science Implementation Strategy. Published in collaboration with the U.S. Ocean Carbon and Biogeochemistry (OCB) program and the International integrated Marine Biogeochemistry Ecosystem Research (IMBER) and SOLAS programs, 123 pp.

McNeil, B.I., N. Metzl, R.M. Key, R.J. Matear and A. Corbiere (2007) An empirical estimate of the Southern Ocean air-sea CO_2 flux, Global Biogeochem. Cycles, 21(3), GB3011, doi:10.1029/2007GB002991.

Metzl, N., B. Tilbrook, D. Bakker, C. Le Quéré, S. Doney, R. Feely, M. Hood, and R. Dargaville (2007) Global changes in ocean carbon: Variability and vulnerability. *Surface Ocean CO_2 Variability and Vulnerability Workshop, Paris, France, 11–14 April 2007*. Eos Trans. AGU, 88(28), 287.

Millero, F.J., T. B. Graham, F. Huang, H. Bustos-Serrano, D. Pierrot (2006) Dissociation constants of carbonic acid in seawater as a function of salinity and temperature, Mar. Chem. *100*, 80-94.

Millero, F.J., The marine inorganic carbon cycle (2007) Chem. Rev., 107, 308-341.

Millero, F.J., F. Huang, T. Graham, D. Pierrot (2007) The dissociation of carbonic acid in NaCl solutions as a function of concentration and temperature, Geochim. Cosmochim. Acta, 71, 46-55, doi:10.1016/j.gca.2006.08.04.

Reay, D.S., C.L. Sabine, P. Smith, and G. Hymus (2007) Spring-time for sinks. Nature, 446(7137), doi: 10.1038/446727a, 727–728.

Reay, D.S., P. Smith, G. Hymus, and C. Sabine (2007) New Directions: The changing role of the terrestrial carbon sink in determining atmospheric CO_2 concentrations. Atmos. Environ., 41(27), 5813–5815.

Sabine, C.L., and R.A. Feely (2007) The oceanic sink for carbon dioxide. In Greenhouse Gas Sinks, D. Reay, N. Hewitt, J. Grace, and K. Smith (eds.), CABI Publishing, Oxfordshire, UK.

Sabine, C.L., R.A. Feely, and R. Wanninkhof (2007) 3. Global Oceans; f. Global ocean carbon cycle — in *State of the Climate in 2006*, A. Arguez (ed.). Bull. Am. Meteorol. Soc., 88 (suppl.)(6), S40–S43.

Sabine, C.L., R.A. Feely, F.J. Millero, A.G. Dickson, C. Langdon, S. Mecking, J. Swift, and D. Greeley (2007) Decadal changes in Pacific carbon. J. Geophys. Res., submitted.

Sonnerup, R.E., A.P. McNichol, P.D. Quay, R.H. Gammon, J.L. Bullister, C.L. Sabine, and R.D. Slater (2007) Anthropogenic delta^{13}C changes in the North Pacific Ocean reconstructed using a multiparameter mixing approach (MIX). Tellus, 59B, 303–317.

Sweeney, C., E. Gloor, A.J. Jacobson, R.M. Key, G. McKinley, J.L. Sarmiento, R. Wanninkhof (2007) Constraining global air-sea gas exchange for CO_2 with recent bomb ^{14}C measurements, Global Biogeochem. Cycles, 21, GB2015, doi:10.1029/2006GB002784, 2007.

Takahashi, T., S.C. Sutherland, and A. Kozyr (2007) Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed During 1968 - 2006 (Version 1.0). ORNL/CDIAC-152, NDP-088. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, 20 pp.

Takahashi, T., S. C. Sutherland, R. Wanninkhof, C. Sweeney, R. A. Feely, D. W. Chipman, B. Hales, G. Friederich, F. Chavez, A. Watson, D. C. E. Bakker, U. Schuster, N. Metzl, H. Yoshikawa-Inoue, M. Ishii, T. Midorikawa, C. Sabine, M. Hopemma, J. Olafsson, T. S. Arnarson, B. Tilbrook, T. Johannessen, A. Olsen, R. Bellerby, H. J. W. d. Baar, Y. Nojiri, C. S. Wong, and B. Delille (2007), Climatological Mean and Decadal Change in Surface Ocean pCO_2, and Net Sea-air CO_2 Flux over the Global Oceans, Deep -Sea Res., submitted.

Determination of the Information Content in Long-Occupied Voluntary Observing Ship (VOS) Expendable Bathythermograph (XBT) Transects.

Robert L. Molinari[1] and Gustavo Goni[2]
[1] Cooperative Institute of Marine and Atmospheric Studies, University of Miami, Miami, FL
[2] NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL

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 Low Density (LD) VOS XBT network as the Argo program coupled with satellite imagery were viewed as suitable replacements for mapping of upper layer temperature structure. 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 LD VOS XBT 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 are available from World War II to the mid-1960s and provide profiles to 200-250 m. Initially XBT's, introduced to oceanography in the mid-1960s, sampled to 450 m and in the early 1970's, 750 m XBT's 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 1960's and 1970's. New sampling strategies that employed VOS, 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 VOS transects. The resulting transition from research cruise coverage in the 1960's and 1970's to repeat transect coverage in the 1990's

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 proposed two-year project has two-components. During the first year, data collected along lines that have been occupied for more than 30-years 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 1940's for the upper 200 m 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. The climatic signatures extracted with the simple statistical 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 will be determined. 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 in developing and applying the generic software that can be used to perform analyses on all the selected lines.

Applying software:

(1) The software to compute simple statistical properties such as the mean section, standard deviation, amplitude and phase of the annual and semi-annual harmonics, etc. has been completed and has begun to be applied to Atlantic sections. An unexpected finding, was that many of the numbered lines in the Atlantic were not occupied by individual ships but exist only because several other lines cross the nominal line. Since these latter lines are not likely to be occupied in the future (i.e., regular shipping is probably not available), analysis will not be applied to the "imaginary" transects.

(2) To date high density lines in the Atlantic have been reviewed. A7, 8, and 10 all include decadal signals related to the subtropical gyre (A7 and 10), the Gulf Stream (A10) and the tropical Atlantic (A10) justifying continuation. However, it should be determined if the high density resolution of these lines is capable of resolving the signals found in the low density sampling.

(3) At present, there are no lines in the subpolar Atlantic. Lines A1 and A2 have been discontinued because of lack of funding. The importance of the subpolar gyre to the meridional overturning circulation argues for resumption of a line in the subpolar Atlantic.

(4) A website has been developed and will serve to display all the products generated from this project.

Additional software developed:

(1) Software to compare sea level anomalies generated from altimetric observations to upper ocean heat content has been developed. The comparisons will be applied to the long-occupied low density lines to determine which portions of the global ocean require in situ observations to study surface variability and to identify areas where model and altimetric measurements of sea level require particular care.

(2) Considerable decadal variability has been observed in upper ocean characteristics. An important question is what causes this variability, in particular switching from one phase of the signal to another. Band pass filtering of the upper layer temperature data has been used to identify switching in the North Atlantic. However, questions exist relative to the results of this analysis (i.e., different latitudes were used, in regions where different variability might be active). Band pass filtering subroutines isolating the decadal period have been developed and will be applied to sections that exhibit decadal signals (e.g., subtropical and subpolar Atlantic and Pacific). The results of this analysis will be applied to model results in an attempt to identify switching dynamics.

(3) Programs that correlate time series from different will be developed to study the scales of upper layer temperature variability.

Deliverables: One year from receipt of funding, 31 May 2008

(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.

(4) Identification of regions where satellite altimetry observations do not provide an

adequate measure subsurface structure.

(5) Explanation of the switching mechanism in decadal signals

(6) Website illustrating all the products generated during the period of this proposal.

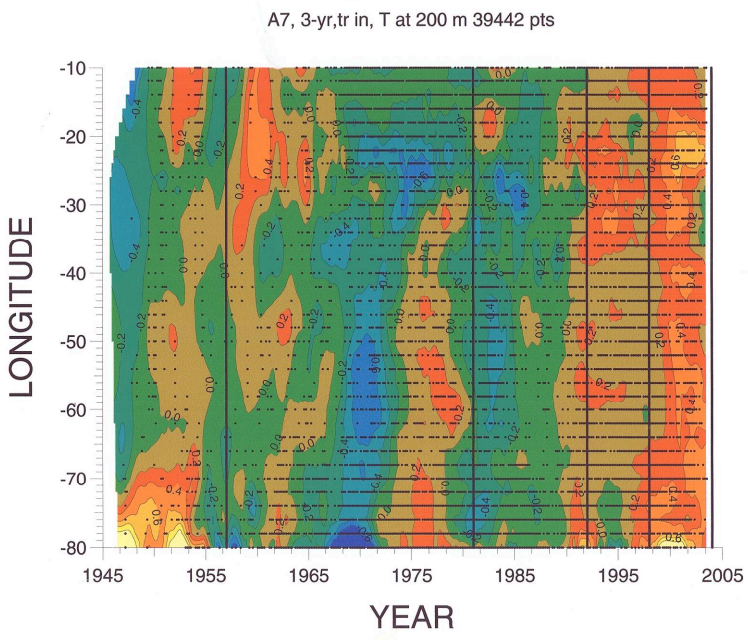


Figure legend: Time (in years) versus longitude along low and high-density line A7 (which extends from Miami to the Mediterranean) plot of temperature anomaly at 200 m. The record pre-1967 was developed from mechanical bathythermograph data and post-1967, expendable bathythermograph data. Units are degrees C. The vertical lines represent years considered by Bryden to develop his hypothesis of declining meridional overturning circulation, MOC, (i.e., positive anomalies indicate a deeper thermocline and more intense subtropical gyre). Bryden hypothesized that the weaker subtropical gyre increased northward heat flux. The contours relative to the years of data indicate that a stronger MOC would have been observed earlier in the record if a shift of a few years in sampling occurred (i.e., higher frequency variability brings into question the finding of a weakened MOC).

References

1. Davis et al. (1992) The autonomous Lagrangian circulation explorer (PALACE). *Journal of atmospheric and Oceanic Technology, 9,* 264-285.
2. Molinari, R.L. (2004) Annual and decadal variability in the western subtropical North Atlantic: Signal characteristics and sampling methodologies. *PROGRESS IN OCEANOGRAPHY, 62,* 33-66.
3. Roemmich et al. (1999) Argo: The global array of profiling floats. In: Oceanobs 99, Saint-Raphael, France, Smith and Koblinsky, editors.
4. Smith et al. (1999) The role of XBT sampling in the ocean thermal network. In: Oceanobs 99, Saint-Raphael, France, Smith and Koblinsky, editors.
5. Watanabe, M., M. Kimoto, T. Nitta, and M. Kachi (1999) A comparison of decadal

climate oscillations in the North Atlantic detected in observations and a coupled GCM. JOURNAL OF CLIMATE, 12,2920-2940.

Arctic Ice Thickness: State of the Arctic Report

Jacqueline A. Richter-Menge[1], Jim Overland[2], Andrey Proshutinsky[3] and Vladimir Romanovsky[4]

[1] US Army Engineer Research Development Center, Cold Regions Research and Engineering Laboratory, Hanover, NH

[2] NOAA Pacific Marine Environmental Laboratory, Seattle, WA

[3] Woods Hole Oceanographic Institution, Woods Hole, MA

[4] University of Alaska Fairbanks, Fairbanks, AK

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.

Fy2007 Accomplishments

- Completion, publication and dissemination of State of the Arctic Report

On November 16, 2006, NOAA's Public Affairs Office held a press release for the NOAA State of the Arctic Report (http://www.pmel.noaa.gov/pubs/PDF/rich2952/rich2952.pdf). 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.

NOAA printed 400 copies of the report. All of these were distributed.

- Contributed to the 2006 BAMS State of the Climate Report, providing the atmosphere, ocean, sea ice and land summary for the Arctic section.

- Completion and public release of the web-based Arctic Report Card

A NOAA press release on October 17, 2007 announced the availability of the web-based 2007 Arctic Report Card (http://www.arctic.noaa.gov/reportcard/). The purpose of this publication is to present clear, reliable and concise information on recent observations of environmental conditions in the Arctic, relative to historical time series records. It provides a method of updating and expanding the content of the *State of the Arctic Report*, published in fall 2006, to reflect current conditions. Material presented in the Report Card is prepared by an international team of scientists and is peer-reviewed by topical experts nominated by the US Polar Research Board. The audience for the Arctic Report Card is wide, including scientists, students, teachers, decision makers and the general public interested in Arctic environment and science. The web-based format will facilitate future timely updates and expansions of the content.

- 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 FY2007, 11 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

Observing System Research Studies

D.E.Harrison
NOAA Pacific Marine Environmental Laboratory, Seattle, WA

Project Summary

This project supports the design, evaluation and development of the global ocean observing system for climate through a variety of research activities. These activities include data set preparation/dissemination, data analysis and modeling studies. The goal is to expand our knowledge of what we know and can rationalize, and what we cannot know or rationalize, from the observing system as deployed at present and from the historical data set that has been produced over past decades. It also supports the evolution of the observing system through evaluation of alternative observing strategies and evaluation of the differences between available ocean analysis products (taken as one measure of the uncertainty in the analysis products).

Finally it supports the goals of the Office of Climate Observations and NOAA's Climate Goal through the PI's activities as Chair of the Ocean Observations Panel for Climate (co-sponsored by the GOOS, GCOS and WCRP) and other national and international leadership activities involved with sustained ocean observing. The PI is also a member of the JCOMM Management Committee and works with its Program Areas to progress the development and delivery of global ocean services.

No data are collected through this project; the Ten Climate Monitoring Principles are not relevant to the activities undertaken.

Initial focus has been on SST variability since it is agreed to be the most important variable for climate impacts. Work has been done with all of the variables of the global ocean observing system, and shall continue in FY08 as described below.

No Add Task support is requested for FY08.

Accomplishments FY 2007

We have shown, through examination of the ocean historical data set, that there is very strong space and time variation in decadal trends of upper ocean temperature. The variation on this time scale is of sufficient magnitude to dominate the 50year trend in many regions. This means that, to the extent that upper ocean temperature trends are important to future SST anomaly evolution we may expect ocean decadal variability to contribute more to climate variability over the next decades than the contribution from global warming.

Our work also questions whether recently published estimates of long term trends of world ocean heat content are accurate enough to be useful useful, because so much of the

world ocean has not been observed adequately to permit a meaningful trend estimate to be made. We showed that differences in the interpolation techniques used to produce a global "data set" have very substantial effects on the inferred global 50year trend. This works makes once again the case that obtaining and maintaining global coverage of in situ observations is critical for accuracy of long term world ocean trends.

We showed that the seasonal climate influence of ocean surface conditions are more substantial over the NW Americas and particularly Alaska than had been reported, but that it is necessary to consider jointly the state of the Arctic Oscillation and ENSO; considering either separately leads to the appearance of less weather impact. The joint impact is not the sum of the separate impacts. Better understanding of the predictability of the Arctic Oscillation is important; predictability may be better than has been thought based on our autocorrelation statistics, but the mechanisms responsible for this remain to be elucidated. This work argues for the importance of observations to understand better the Arctic Oscillation.

We showed that knowledge of meridional surface wind anomalies is as important as knowledge of surface zonal wind anomalies in the creation of Indian ocean SST anomalies that are thought to affect southern Africa weather. The surface heat flux contribution of meridional advection of surface humidity can dominate zonal advection in the regions of interest, contrary to previous suggestions. The latent heat flux anomaly is a key element of the evolution of SST anomalies on the basin scale.
We showed that it is possible to understand the differences in tropical North Atlantic SST anomalies in the 'hurricane alley' formation regions between 2005 (lots of hurricanes) and 2006 (few hurricanes) by considering differences in the large scale atmospheric circulation over the region, and the resulting changes in air-sea heat fluxes. It is not necessary to invoke changes in the atmospheric loading of aerosols off of west Africa to rationalize the observed SSTA patterns. These latter papers show once again how important accurate knowledge of air-sea fluxes is for understanding (and predicting) SST anomalies of climate relevance; the observing system activities that serve to help us evaluate operational air-sea flux estimates are very important.

Finally we showed that there has been a change in the wind patterns associated with westerly wind events over the tropical Pacific since the major 1997-98 El Nino event, and that these seem sufficient to explain why we have been having more 'Dateline El Nino' than 'conventional El Nino' events since then. We used numerical ocean model experiments to obtain the latter conclusion. This work suggests a new index might be developed for tracking the likelihood of an El Nino appearing in any given year; investigation of this will be a priority for FY08.

International and national ocean observing system leadership work, primarily as Chair of the Ocean Observations Panel for Climate (co-sponsored by the Global Ocean Observing System program, the Global Climate Observing System program and the World Climate Research Program) and as Chair of the Climate Observing System Council, continued during FY07.

It was primarily a year of consolidation and follow-through for global ocean observing system activities. After several years of developing and agreeing international plans and pilot projects, several years of hard work like FY07 lie ahead as these continue to be taken forward. Implementation of the observing system itself continued, but at a reduced pace; development of ocean services and ocean analysis and reanalysis continues; development of the real time ocean metadata system is progressing. A major new effort is underway to engage better the ocean biogeochemistry and living resource communities in the next phase of planning for the ocean observing system.

Observing System Meetings/Workshops led or attended FY07

Oct JCOMM Mgmt Committee-V GVA
Oct Global Climate Observing System SC GVA
Nov JCOMM Services Coord Gp Exeter
Nov Global Ocean Observing System Regional Forum III CapeTown
Nov Autumn COSC DC
Dec SCOR Coordination Mtg London
Jan Partnership for Observations of the Global Ocean-8 Qingdao
Mar GOO Science Steering Committee Seoul
March WCRP Joint Scientific Committee Zanzibar Tanzania
April Atmospheric Observation Panel for Climate GVA
April OOPC-XII Paris
May Bonn German Climate modeling review panel
Jun Office Climate Observations annual review and Spring COSC
Jun IGOOS -8 Paris
July Ocean09 planning Paris
Aug IGODAE Steering Team St John's Newfoundland
Aug ClimateTest Bed SAB DC
Sept CLIVAR SSG Geneva
Sept 2nd ocean reanalysis MIT

Publications

Bond, N.A. and D.E. Harrison (2006) ENSO's Effect on Alaska during Opposite Phases of the Arctic Oscillation.U.S. International Journal of Climatology 26, 1821-1841.

Harrison, D.E. and M. Carson (2007) Is the World Ocean warming? Upper Ocean Temperature Trends, 1950-2000 JPO 37(2), 174-187.

Chiodi, A.M. and D.E. Harrison (2007), Mechanisms of summertime subtropical southern Indian Ocean sea surface temperature variability: on the importance of humidity anomalies and the meridional advection of water vapor. J. Climate 20(19), 4835-4852

Harrison, D. E. and M. Carson (2008). Is the upper ocean warming? Comparison of 50yr trends from different approaches. To appear (Journal of Climate)

Chiodi, A.M. and D.E. Harrison (2008), Hurricane alley SST variability in 2005 and 2006. Submitted to J Climate

Harrison, D.E. and A.M. Chiodi (2008) Pre and Post 97/98 westerly wind events and equatorial Pacific cold tongue warming. Submitted to J. Climate.

Appendix of Acronyms

CEOF	Complex Empirical Orthogonal Function
CLIVAR	Climate Variability program (WCRP)
COOP	Coastal Ocean Observations Panel (GOOS)
DOE	Dept of Energy
ECMWF	European Centre for Medium-Range Weather Forecasting
EOF	Empirical Orthogonal Function
FAO	Food and Agriculture Organization (UN)
GCOS	Global Climate Observing System (WMO/IOC/FAO)
GLOS	Global Sea Level Observing System (JCOMM)
GODAE	Global Ocean Data Assimilation Experiment of OOPC
GOOS	Global Ocean Observing System of IOC
IOC	Intergovernmental Oceanographic Commission
IOOS	Integrated Ocean Observing System (US)
JCOMM	Joint Commission on Oceanography and Marine Meteorology
LLNL	Lawrence Livermore National Laboratory
LAS	Live Access Server
MAN	Management Committee (JCOMM)
MJO	Madden-Julien Oscillation
NCEP	National Centers for Environmental Prediction
NODC	National Oceanographic Data Centre
NRC	National Research Council
OOPC	Ocean Observations Panel for Climate (GOOS/GCOS/WCRP)
OpenDAP	Data protocol
POGO	Partnership for Global Oceanography
SCOR	Scientific Committee for Ocean Research
SLP	Sea Level Pressure (also MSLP)
SST	Sea Surface Temperature
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measurement Mission
WCRP	World Climate Research Program
WWE	Westerly Wind Event

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 2007 was to quantify the effects of oceanic advection on the expected performance of the ARGO system. During the FY 2007 we completed the analysis with the coarse-resolution model and focused our efforts on the eddy-resolving simulations.

Coarse-resolution studies

The global ocean model used in this study has 2° resolution in both latitude and longitude; see Kamenkovich (2005) for the model description. The atmospheric forcing used to drive the model is derived from observation-based estimates. Daily values for the 2-meter air temperature and humidity, 10-meter wind speed, and zonal and meridional components of the wind stress are taken from years 1979-2001 of the NCEP-NCAR reanalysis. Climatological monthly values are used for all other atmospheric variables and freshwater fluxes. The simulated ocean state is as realistic as can be expected in a coarse-resolution model. However, because of the coarse resolution, the intensity of the boundary currents is underestimated and the mesoscale eddies are not resolved. The effects of the oceanic advection on the ARGO system in reality are expected to be even stronger than in this model.

In these simulations, 3,000 ARGO floats are advected with the GCM-simulated velocities at 1500m depth during most of the time. Every 10th day, a simulated float surfaces, while taking the temperature and salinity (T/S) profile; it then spends 8 hours at the surface, where the float is advected by the surface currents. A float becomes "lost" if it enters a shallow region. Resulting data are used to reconstruct temperature and salinity of the ocean, using objective analysis.

This year activities were mainly focused on the expected accuracy of reconstruction of the upper-ocean stratification. In particular, we analyzed the mixed-layer depth (MLD), thermocline depth, and upper ocean heat content. In this report, we present the results for MLD; our conclusions for other variables are qualitatively similar.

Figure 1 shows the differences between the reconstructed and original GCM-simulated MLD for March; hereafter, we refer to these differences as "errors" in reconstruction. The reconstructed March MLDs exhibit significant errors in the Northern North Atlantic where the MLD is extremely deep due to the formation of the North Atlantic Deep Water (Fig.1a). The mixed layer is also deep (Fig.1a) and the reconstruction errors are large (100-150m, Fir.1b) in the regions immediately north of the Gulf Stream and Kuroshio (Fig.1a). These regions are characterized by large errors in all analyzed fields, including temperature, salinity, heat content and thermocline depth.

In October, the deepest mixed layer, in nature and in this GCM, is found in the Antarctic Circumpolar Current (ACC), south of Australia (Fig.2a). This is the region of the winter-time formation of the Subantarctic Mode Water. The errors in reconstructed MLD are, however, surprisingly small here (Fig.2b). In contrast, the errors are significantly larger at the locations of concentrated ACC currents, where the mixed layer is not necessarily the deepest.

We conclude that the vicinities of concentrated ocean currents correspond to the largest errors in the reconstructed fields. In these regions, the gradients in the mapped fields are sharp and the corresponding spatial variation scale is much shorter than in the rest of the World Ocean. The standard density of the ARGO array is not sufficient to resolve the fronts associated with these currents.

Eddy-resolving simulations of the North Atlantic

To investigate the effects of mesoscale variability on the accuracy of the ARGO system, we carried our analysis in a high-resolution regional model of the North Atlantic. High horizontal resolution ($1/8^o$ resolution in latitude/longitude) permits realistic simulation of 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 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. For the analysis, we used 9 years of high-resolution data from the model.

We begin by analyzing the effects of advection by the intense but steady currents. In our first experiment, the floats are advected by the time-mean velocities, and all mesoscale variability is effectively filtered out. In agreement with our previous coarse-resolution experiments, the regions of the fast advection correspond to the largest systematic biases in the reconstructed fields. In particular, in the vicinity of the North Atlantic Current, the reconstructed MLD is shallower than in the original GCM data.

Next we analyze the effects of the mesoscale variability on the performance of the ARGO system. In our second experiment, the ARGO floats are advected by the full velocities, which include mesoscale eddies simulated by our model. In Figure 3b, we show the difference in the absolute values (magnitudes) of errors between the standard run with full advection and the run with the mean advection only. The mesoscale variability results in the noticeable increase in the error magnitudes throughout the entire domain. The vicinity of the North Atlantic Current is characterized by the particularly large increase in the error magnitude (20-50m).

To further quantify effects of advection, we conduct the third experiment, in which the magnitude of mesoscale variability is amplified by a factor of 2.5. This amplification factor was chosen to bring the variance in the simulated sea-surface height closer to the observed one. As a result of the amplification, the biases in the simulated fields increase everywhere in the domain (Fig.3c). The largest change is seen within the Labrador Current, and near the Cape Hatteras.

More frequent sampling results in the increase in the error magnitudes in the vicinity of the North Atlantic Current (Fig.3d). Vecchi and Harrison (2006), in their study of the Indian Ocean, observe a similar effect of more frequent sampling and attribute it to the increased convergence/divergence of the floats when they are brought to the surface more frequently. In the rest of the domain, the effects of the more frequent sampling are small.

Significance of results

The results clearly demonstrate the importance of oceanic advection in affecting the expected performance of the ARGO observing system. In the vicinity of sharp oceanic fronts, the coarse spatial resolution of the ARGO data results in significant errors in the reconstructed fields. 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. More frequent sampling, on the other hand, is unlikely to improve performance of the ARGO system within these regions. Mesoscale variability has a noticeable degrading effect on the ability of the ARGO system to reproduce the oceanic state.

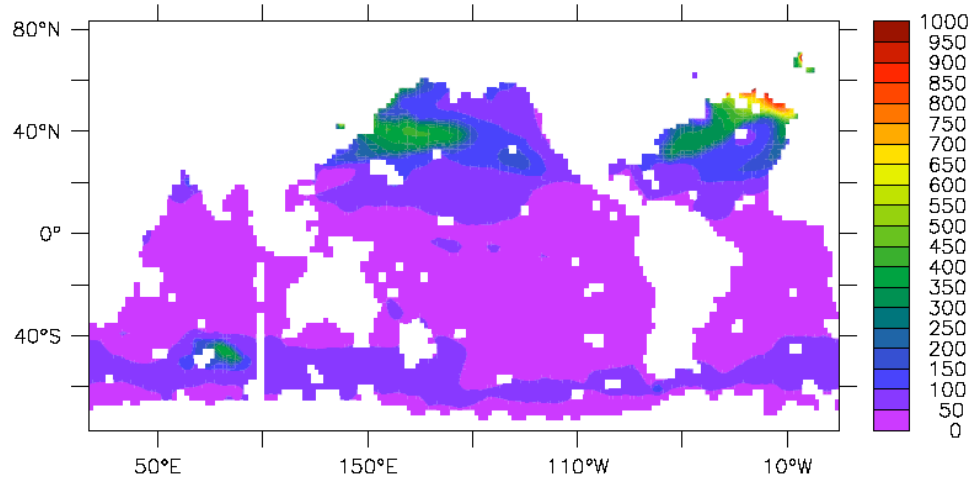
References:

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.

Figures

(a)



(b)

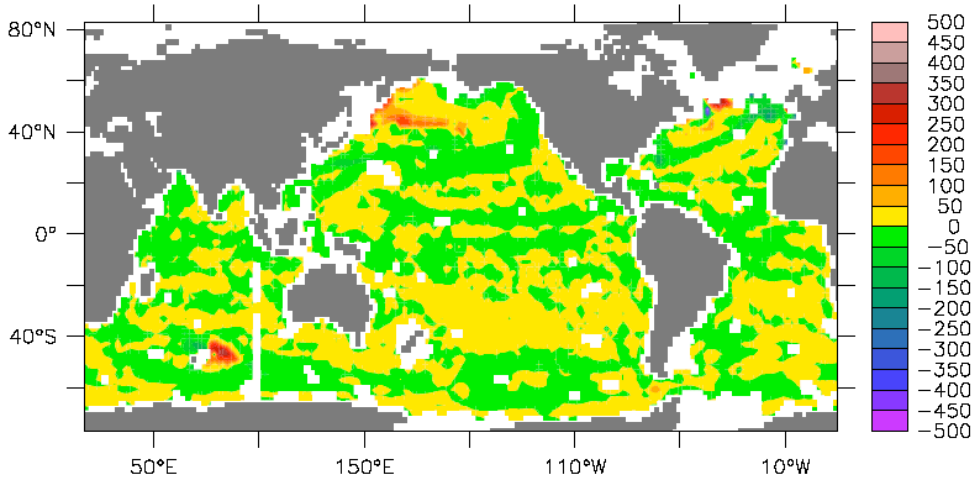
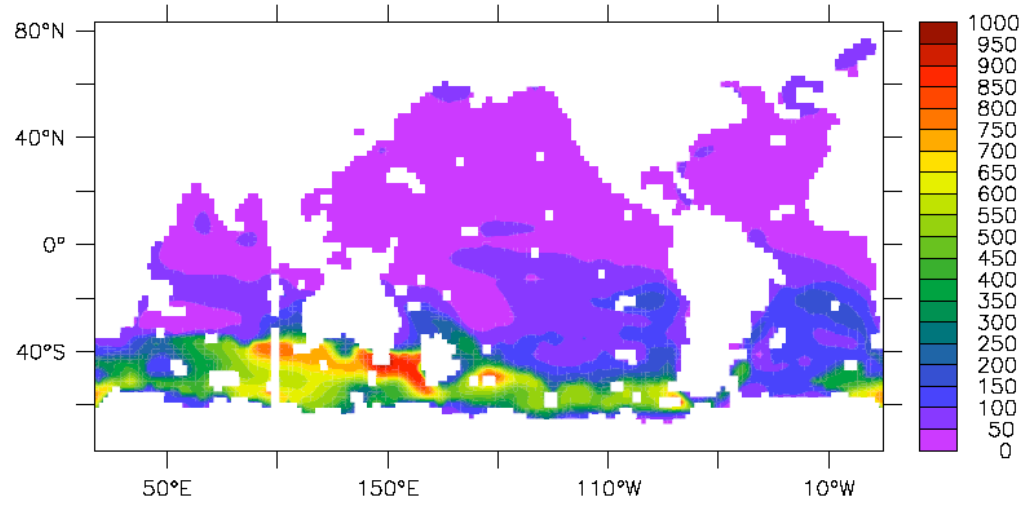


Figure 1: (a) The reconstructed mixed-layer depth (MLD) in March. **(b)** Difference between the reconstructed and original GCM-simulated MLD. The white areas indicate grid points rejected due to the large formal errors of the objective mapping routine.

(a)



(b)

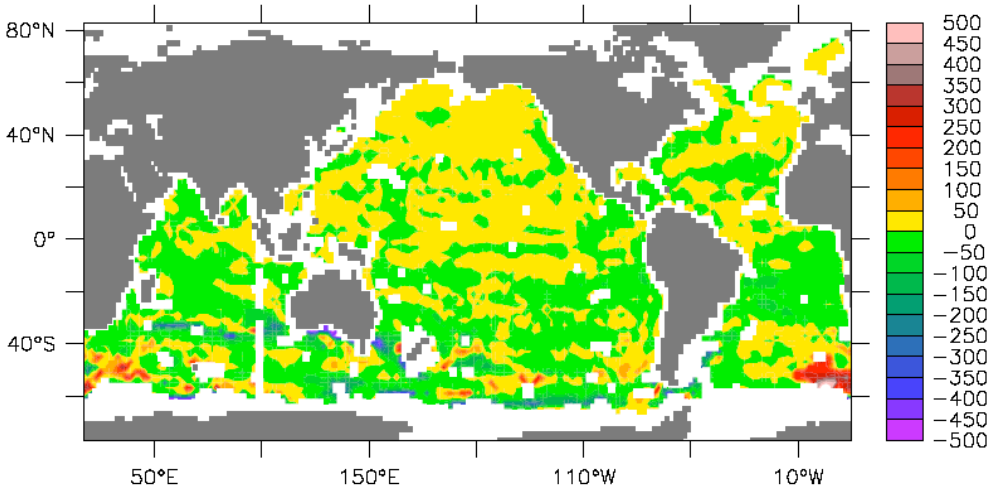


Figure 2: (a) The reconstructed mixed-layer depth (MLD) in October. **(b)** Difference between the reconstructed and original GCM-simulated MLD. The white areas indicate grid points rejected due to the large formal errors of the objective mapping routine.

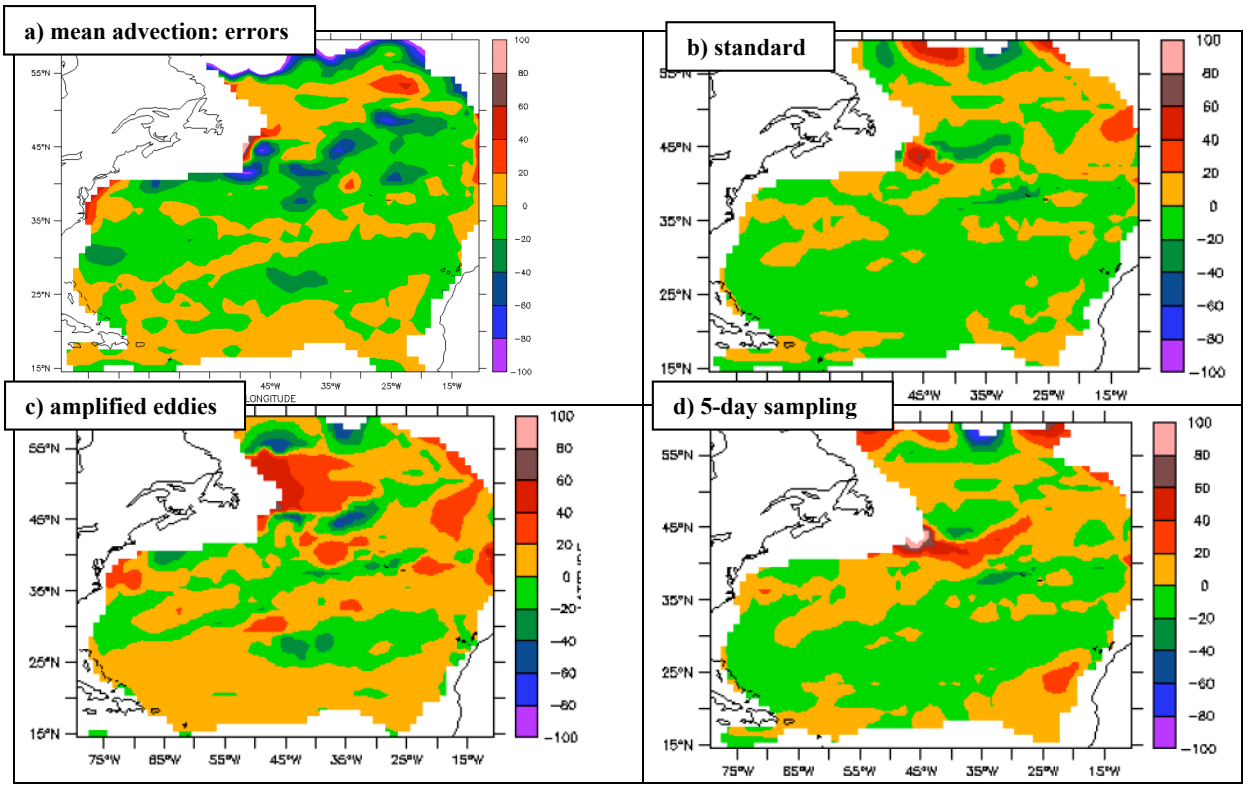
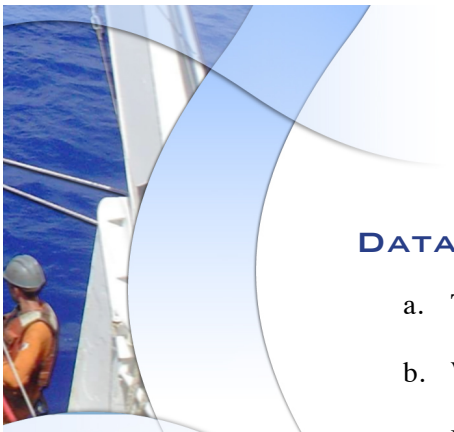


Figure 3: Effects of eddies on the errors in the reconstructed MLD in the eddy-resolving model. **(a)** The difference between the reconstructed and original GCM-simulated fields; the run with the mean advection (no eddies). **(b)-(d)**: The difference in the magnitude of errors (see text) between the runs with the full (eddy+mean) advection and the run with the mean advection only. (a) standard run; (c) run with the eddy variability amplified by a factor of 2.5; (d) run with sampling every 5 days.



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.

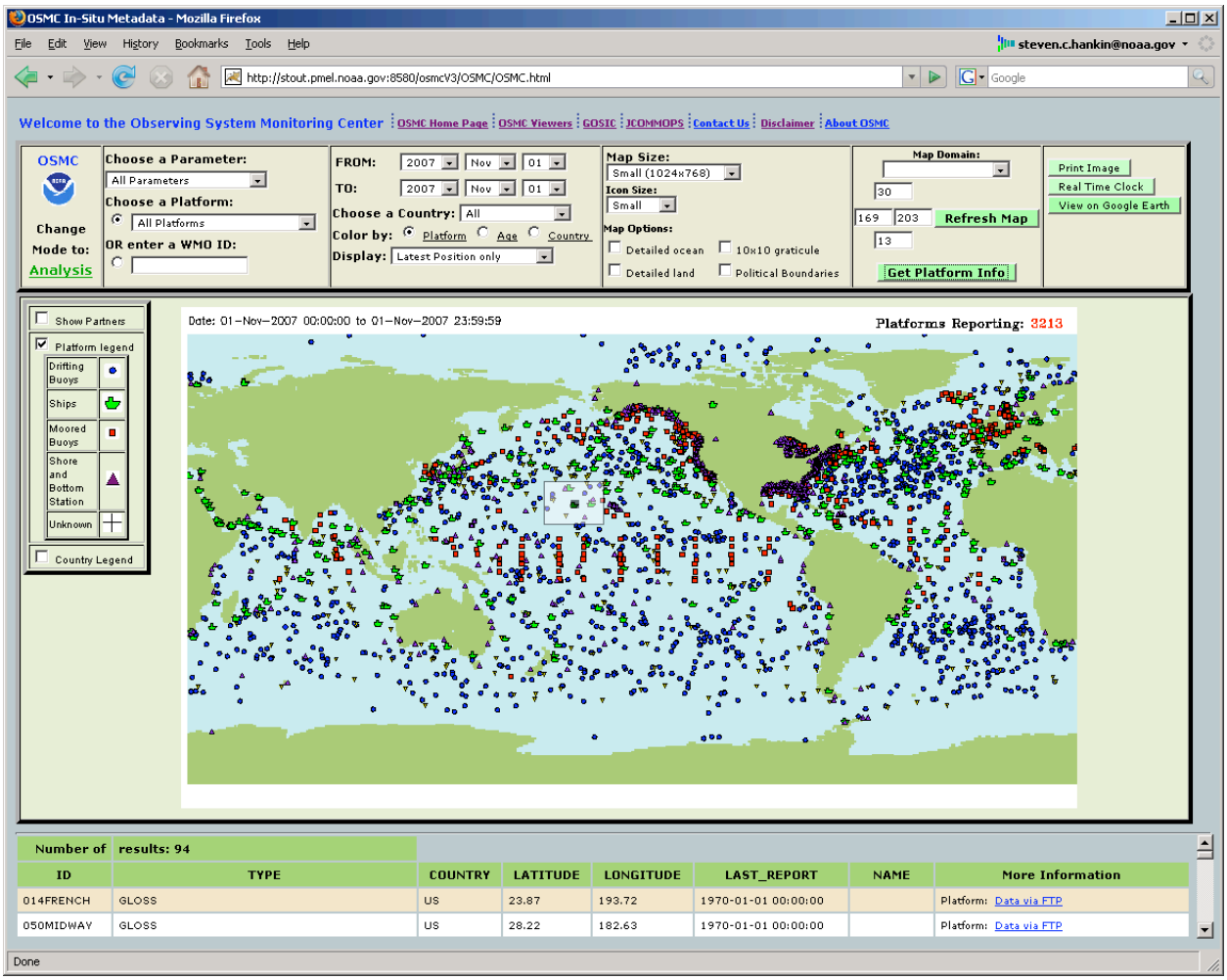


Figure 1. Screen snapshot of OSMC interface

The OSMC system displays the current and historical status of the global observing system for *in situ* ocean surface meteorological and oceanographic measurements (Figures 1, 2). It provides dynamically generated maps to visualize the coverage of observations. 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.

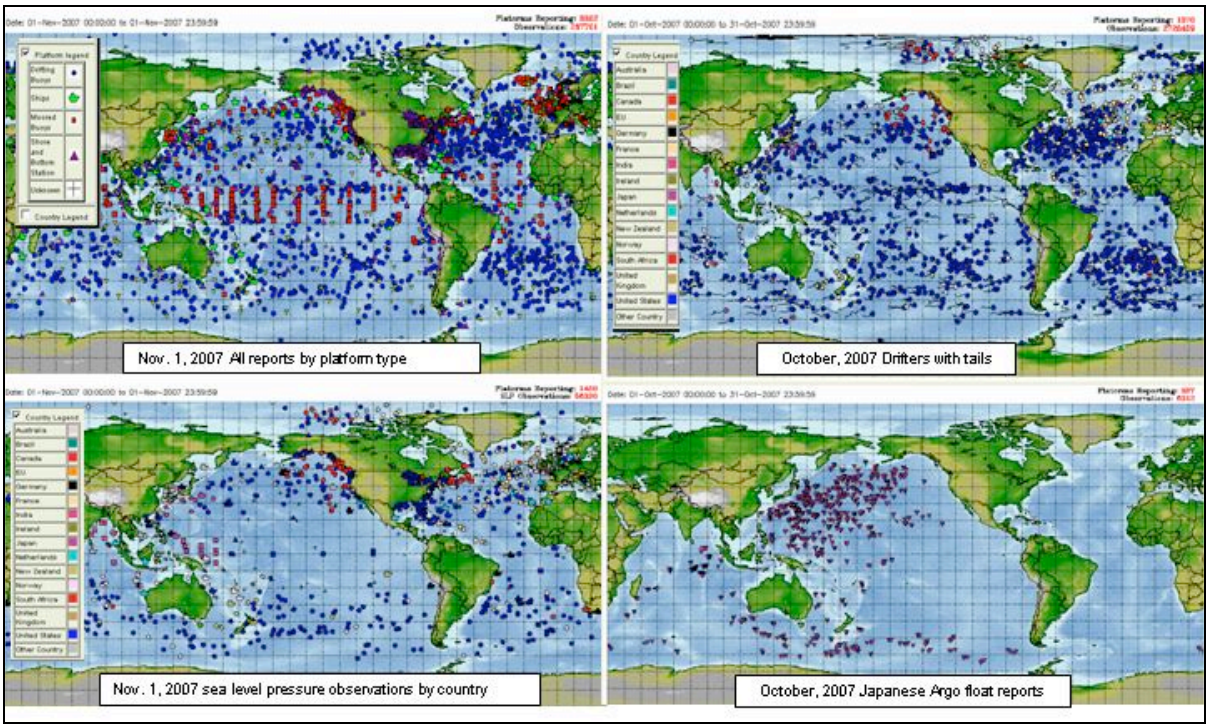


Figure 2. Sample OSMC maps

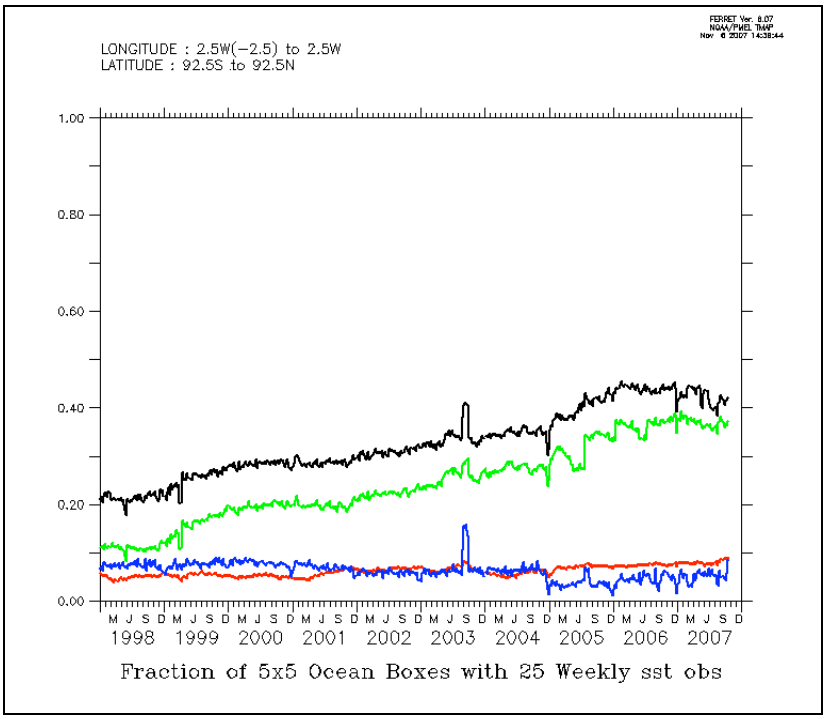


Figure 3. Progress in implementation of the ocean observing system

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

	Argo Floats	CMAN	Drifting Buoys	Moored Buoys	Ships	Unknown	Undefined	Sum
11-08-2007	3	295	1253	358	0	0	0	1909
11-07-2007	124	339	1271	406	0	0	0	2140
11-06-2007	161	337	1268	405	596	47	225	3039
11-05-2007	170	337	1260	410	722	55	271	3225
11-04-2007	144	296	1262	406	717	53	266	3144
11-03-2007	150	298	1262	405	709	53	257	3134

*A count is defined as a platform reporting any type of observation on a particular day.

Figure 4. One of many OSMC table-based summaries

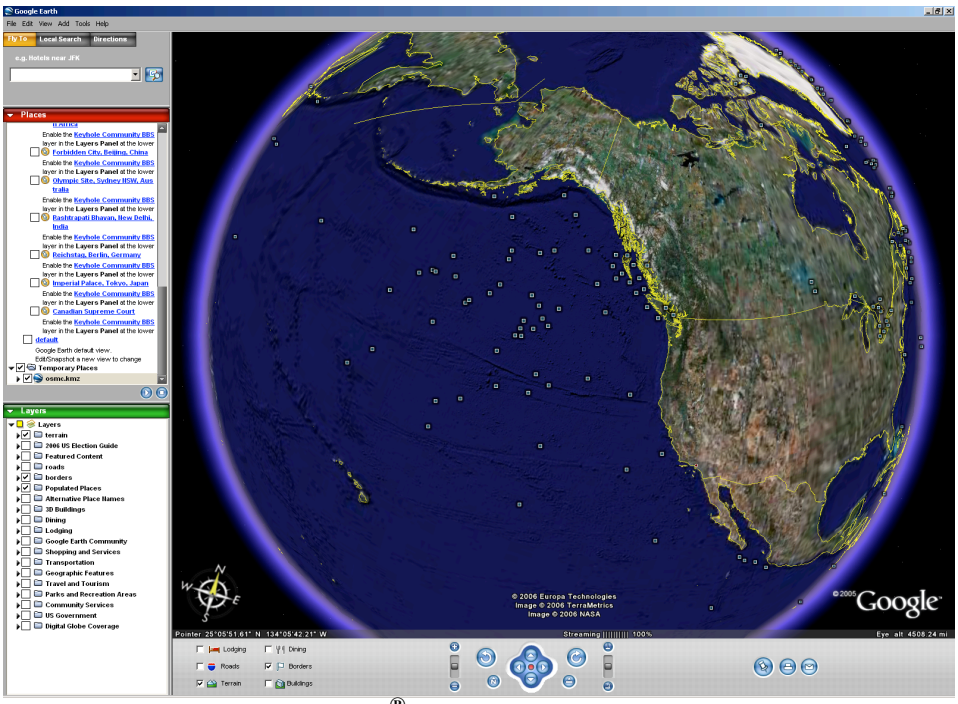


Figure 5. Google Earth® viewer showing ocean observations

The OSMC also offers analysis capabilities, developed through collaborative interaction with the Climate Observing System Council (COSC) and NOAA observing system scientists. These analysis capabilities help managers to assess the adequacy of the observations to compute critical ocean state fields, such as sea surface temperature. Figure 7 shows a 5x5 degree gridded analysis of a simple metric for the adequacy of the sampling of SST – the percentage of weeks in which at least 25 observations are made in a grid box.

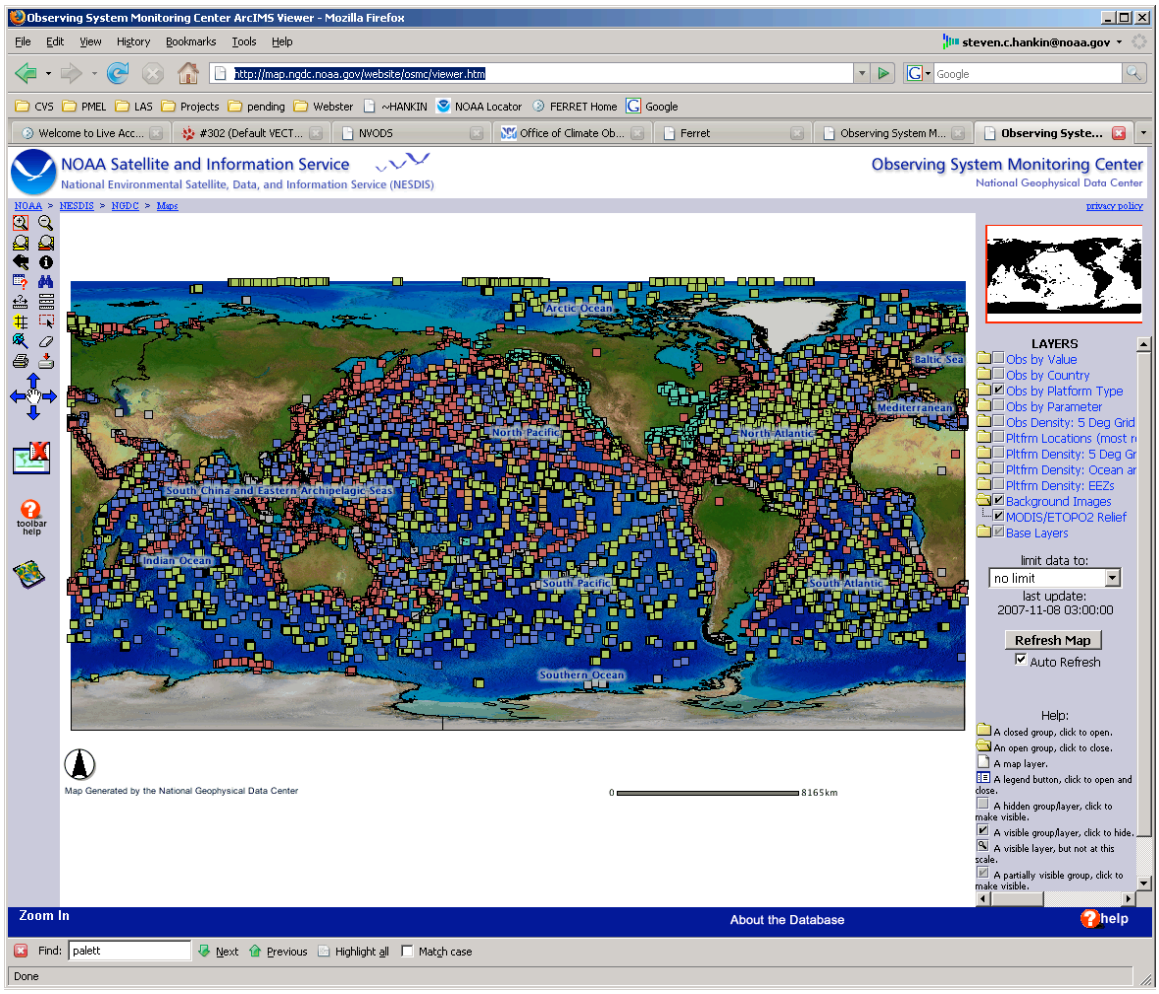


Figure 6. ArcIMS® viewer with observations of the last 10 days colored by platform type

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.

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.

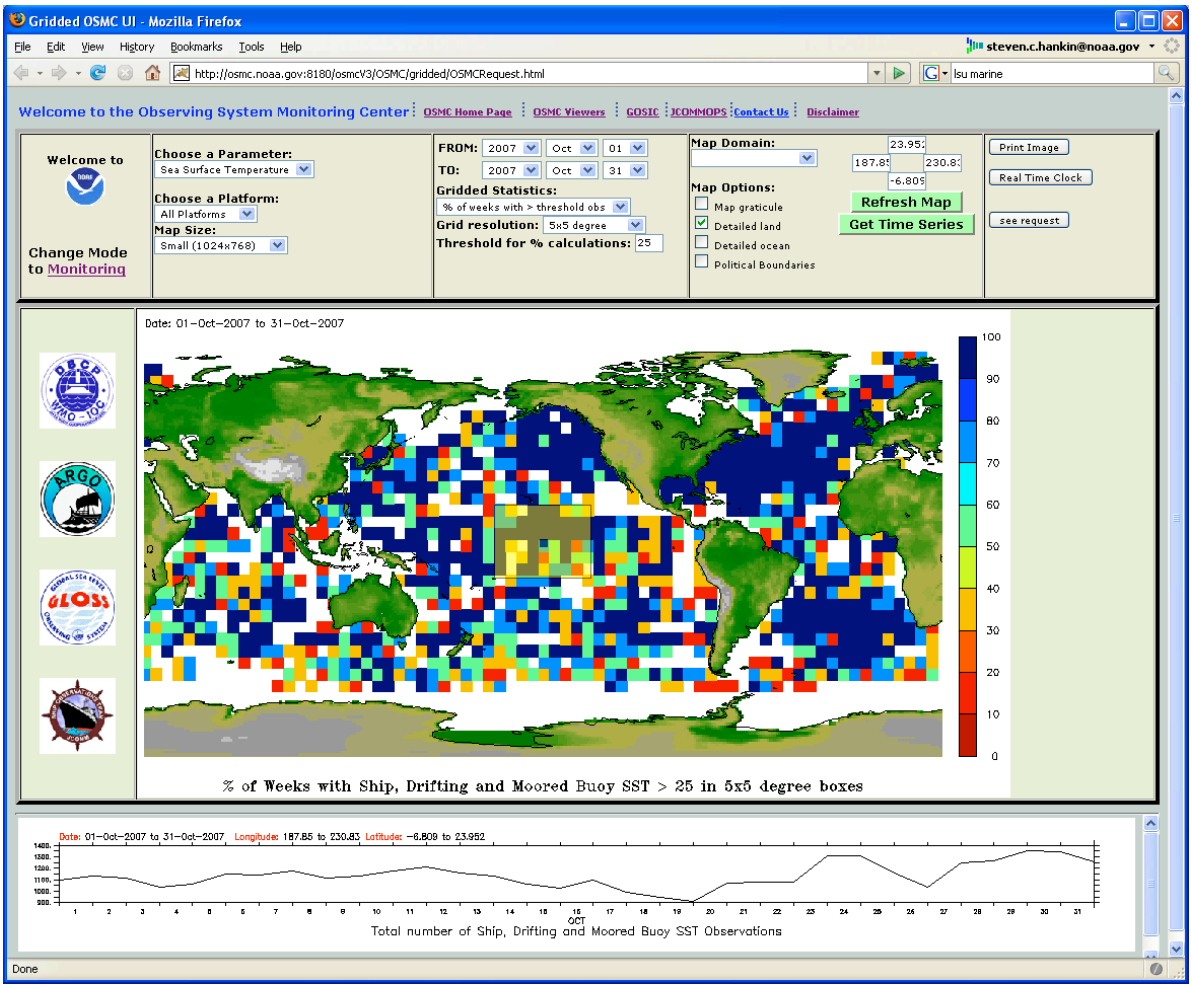


Figure 7. Analysis interface of the OSMC

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.

FY2007 Progress

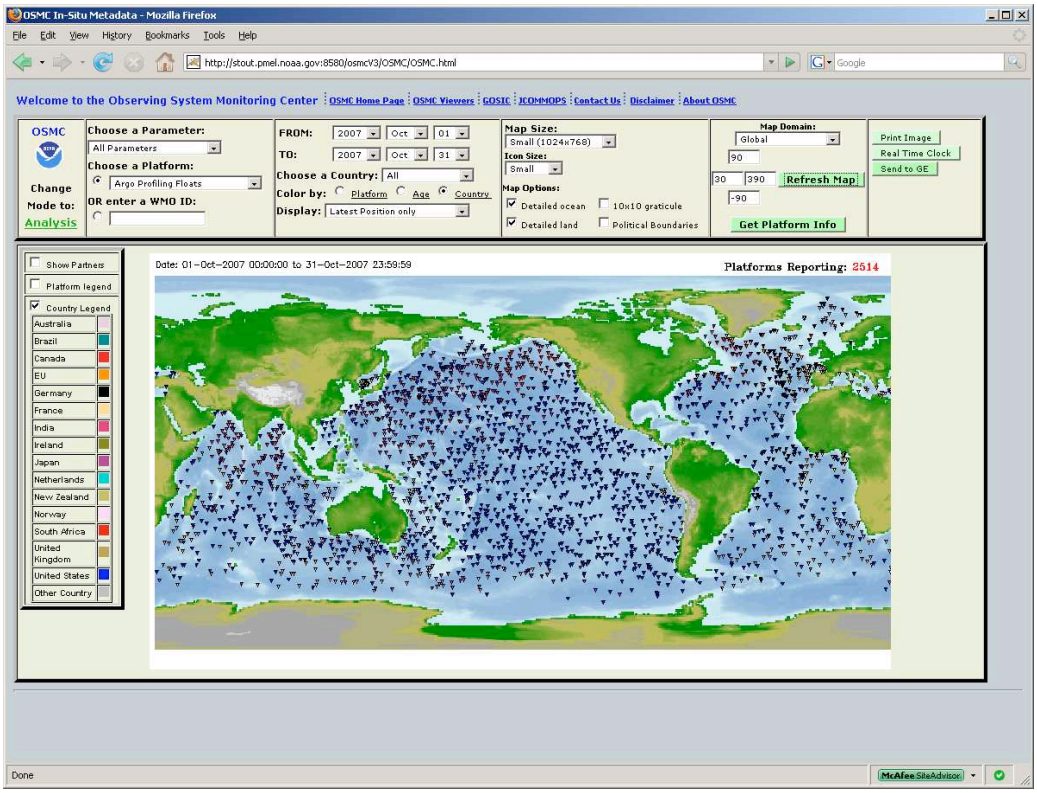
The following milestones track the progress made on OSMC during fiscal year 2007. "Group" lists only those accomplishments or events that involved the entire collaborative group.

Group Accomplishments (PMEL, NDBC, NGDC)

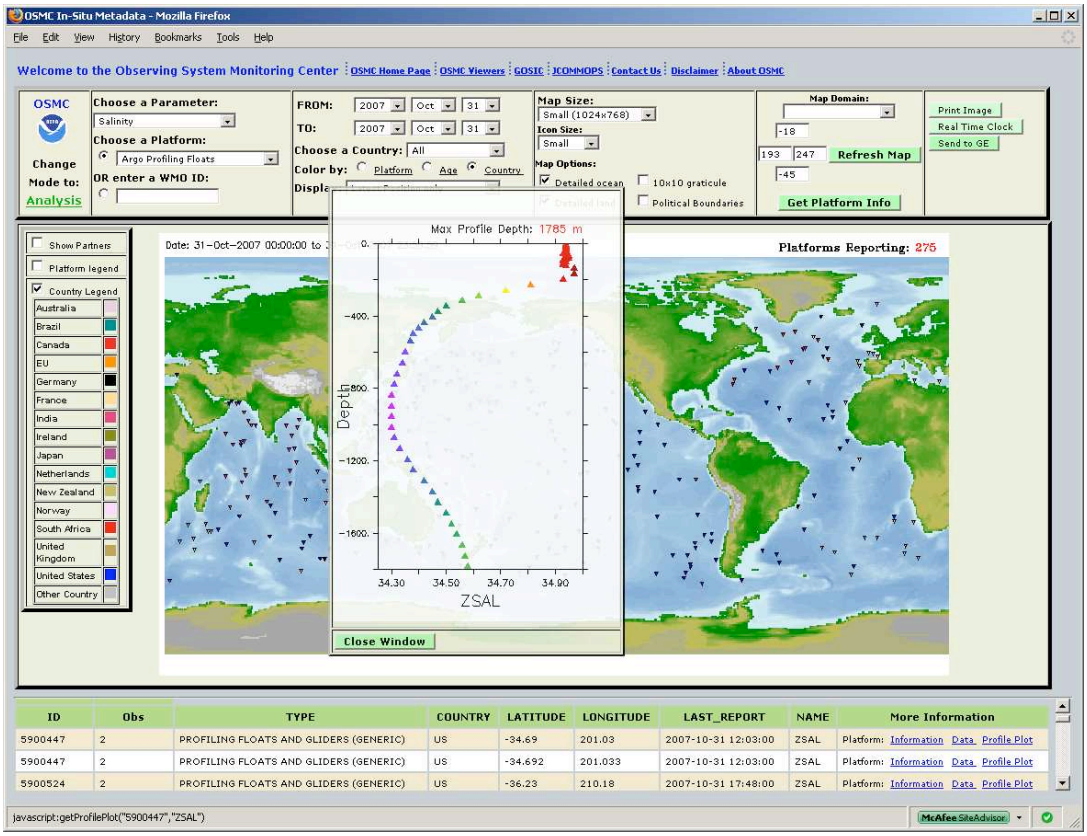
- The OSMC collaboration released the OSMC system through the publicly accessible OCO Web site. The OSMC site was advertised to the Climate Observing System Council (COSC), JCOMMOPS and OCO partners nationally and internationally.
- The group continued to support OCO needs for materials and information needed for initiatives, briefings, presentations, and ad-hoc requirements.
- The group met for an OSMC all-hands meeting July 17-18, Seattle in which progress was assessed, strategic plans and priorities were decided upon, and technical issues that had been identified through weekly telcons were addressed.
- During the July 2007 meeting at PMEL decisions were taken to advance the OSMC system towards "version 3". Version 3 will incorporate a new primary "feed" for the OSMC data and metadata (an important step toward making the OSMC the "gold standard" for ocean observing system metadata); new database design; and major enhancements to the OSMC products and LAS user interface to support visualization and analysis of the observing system. A functioning "beta" of version 3 was hosted at NDBC and made available to the OCO (though not linked to the OSMC home page) on Oct. 11. Most new features in this server represent the shared contributions of the entire collaboration – database structure and queries from NGDC; database content from NDBC; and delivery of that information through the LAS OSMC user interface by PMEL.

PMEL Accomplishments

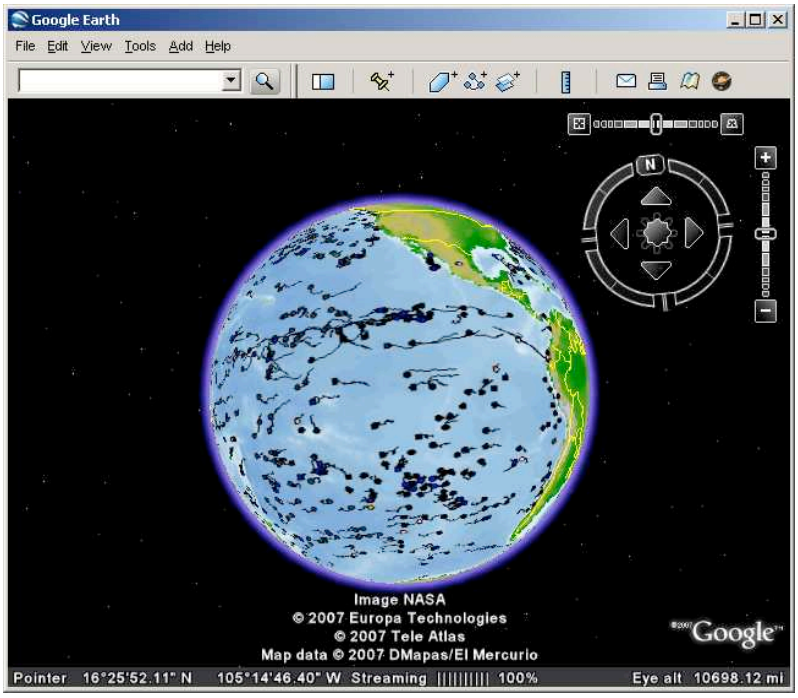
- PMEL met its on-going project leadership responsibilities for the OSMC collaboration: organizing meetings and telcons; overseeing the tracking of bug fixes, milestones, and deliverables; coordinating plans of high level strategy; helping to ensure that group-wide communications continue to flow smoothly. PMEL also continued to provide the primary (though by no means sole) point for coordination of OSMC developments and outreach with projects such the Integrated Ocean Observing System (IOOS); the NOAA Data Management Committee (DMC); the NOAA "GEO-IDE" data integration framework; and NOAA science programs.
- In the Oct. 11 "beta" release of OSMC version 3 the new features that were added by PMEL include
    - Maps of "Latest position" such as this example, which shows the last reporting position of all Argo floats that reported during the month of October, 2007.



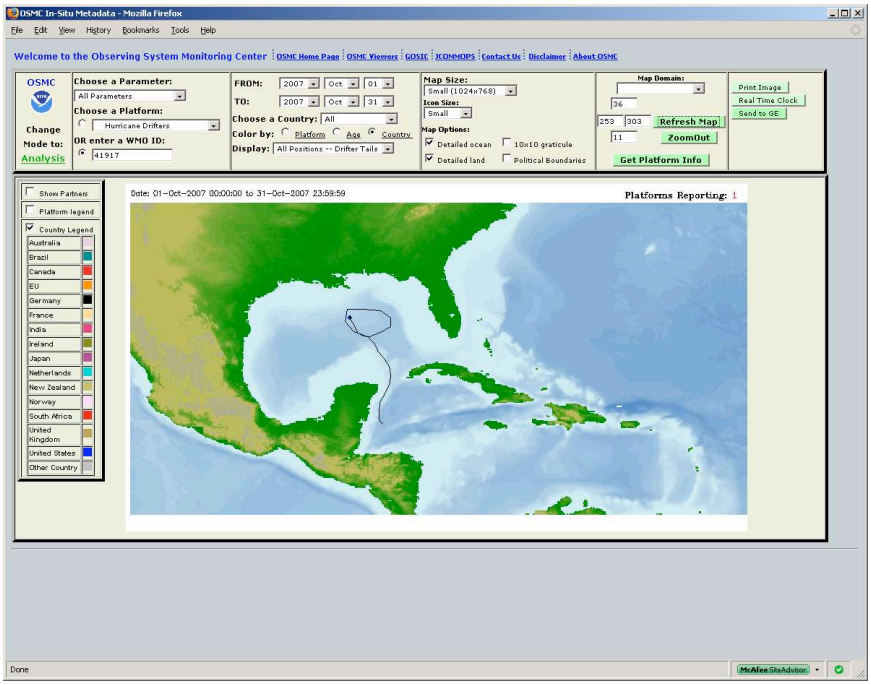
- Beta release of the visualization style for profile observations



- Drifter-tail style of visualizations made to OCO specifications (the two images following are examples)
- Maps generated for the OSMC may be mapped to Google Earth®.

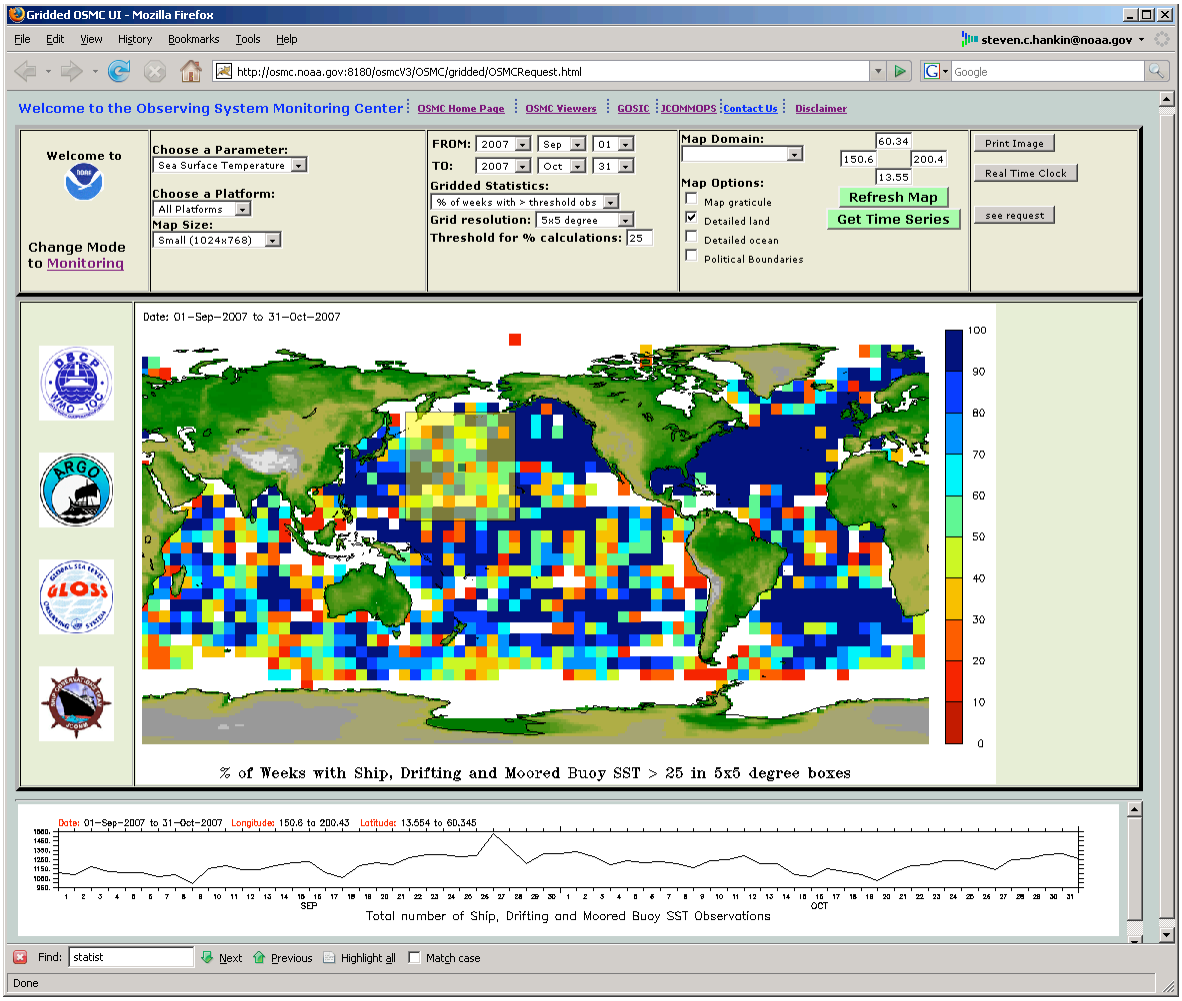


- Ability to track a particular platform by its WMO ID. In this example we see the path of WMO ID 41917 for the month of October, 2007.



- Recoding of all SQL queries from LAS to address the new database schema design of the OSMC
- "Clickable" text in the OSMC drill-down queries links to platform management sites
- Arbitrary zooming via "rubber band" into custom regions
- Numerous look and feel changes -- icons for organizations contributing to OSMC, progress bar, layout, response when query contains no data, etc.

- The OSMC was upgraded to use version 7 of LAS – a complete redesign of the system internals. Version 7 is approximately 6 times faster than the previous version (this performance measure excludes database access and rendering) and is much more flexible. It builds the foundation required for DMAC-style live access to remote data sources that will become available through web services.
- The Analysis subsystem for the OSMC LAS was fully integrated into the system in May, 2007 and improved upon in several increments since then. In the example here we see a map that provides a quantitative measure of the adequacy of sampling of in-situ SST, based upon a simple threshold of requiring 25 obs/week/5x5 degree cell. In the bottom frame of the figure we see a time series of the number of observations in the indicated region of the Pacific.



- The following platform types were added to the LAS viewer
    - tide gauges
        - includes NWLON, Real Time Reporting, GLOSS subtypes
    - dart buoys
    - ocean reference stations (not all ocean reference stations have been identified)
    - tropical moored buoys
    - weather buoys
    - unknown platforms (marked with a simple "+")
- The following parameters were added to the LAS viewer
    - wave height
    - water temperature (profiles)
    - salinity (profiles)
    - wind speed
    - wind direction
- PMEL installed and set up a bug and issues tracking system for the OSMC project that has proven very helpful for group communications and tracking of progress.
- PMEL has assumed web primary responsibility for creating and editing the OSMC home page. The home page was made public during 2007 and advertised at several venues. A number of minor improvements were made subsequent to the initial release of the home page.

NDBC Accomplishments

- Continued to update the OSMC Oracle database and NetCDF files with data from the following sources:
    - GODAE T-File
    - GTS feed from NWSTG
    - WMO Allocation table (Country info)
    - WMO Pub 47 data (meta-data)
    - JCOMOPS WMO Platform Cross-Reference (meta-data)
    - NDBC Website (meta-data)

- New data sources added
    - Migrated the existing data feeds (GODAE, WMO, JCOMMOPS, etc) to the new database schema
    - Migrated existing data to the new schema.
    - Started decoding XBT profile data
    - Added the GLOSS Tide Gauge data
    - Added wave height parameter and started populating field from the GTS data
    - Identified Tropical Moored Buoy and Weather Buoy assets

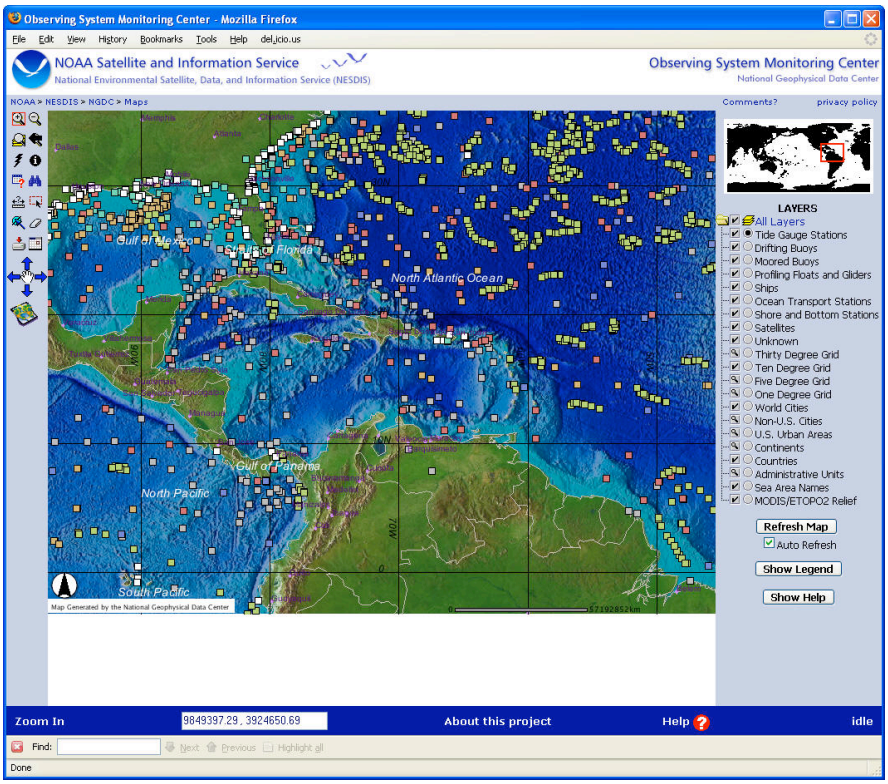
- Database technical enhancements

- Implemented the new database schema which was a joint design between NDBC, NGDC and PMEL.
- Added the Daily Summary table to the database
- Spatially enabled the database
- Added last report date in platform table
- Implemented time partitions
- Implemented materialized views
- Performed OSMC server upgrades and security patches as required

NGDC Accomplishments

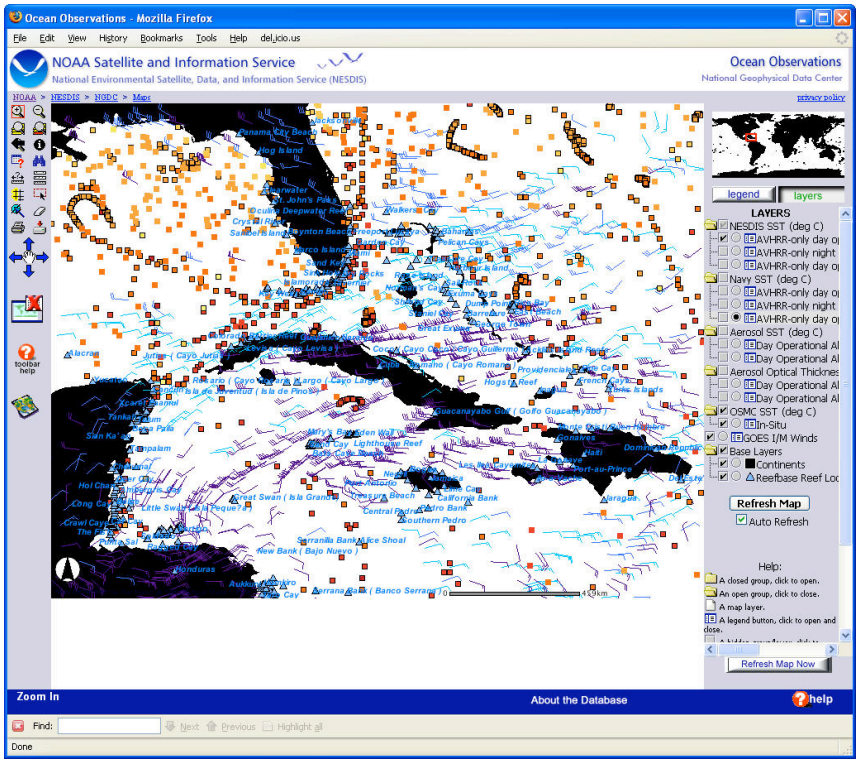
Task: Map Interfaces / Spatial Queries:

- The OSMC Interactive Map supported using ArcIMS at NGDC was used to draw an average of 233 maps / month during FY06.
- A new "next-generation" ArcIMS viewer was created that displays the locations of the last reported observation by a platform on each of the 10 most recent days by platform type. http://mapdevel.ngdc.noaa.gov/website/auerbach/2.0/osmc_gts There is also a hyperlink to a web interface table showing the parameters and their values measured in this most recent observation of the day. In the viewer, you can restrict the rendering of the data using a date constraint.

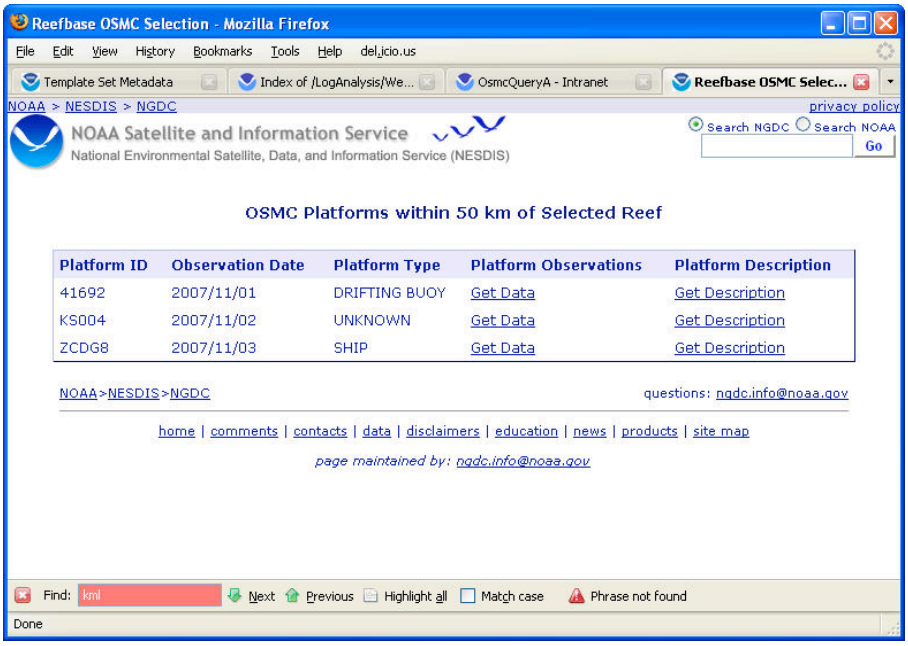


- An interactive map viewer was created that included OSMC observations, sea surface temperature and aerosol thickness observations from NPOESS satellites, wind speeds from

GOES, and coral reef locations from ReefWatch (see Figure). This map service demonstrated the capability to integrate OSMC data with NOAA satellite observations and potentially interesting geographic datasets. It also allowed users to download all of the data layers for some region and time.



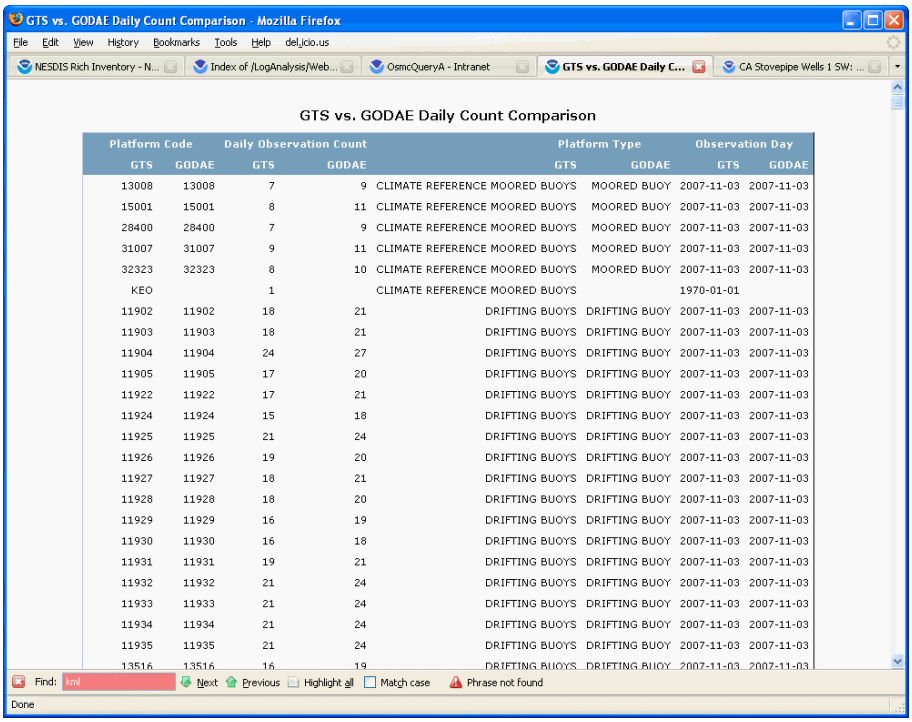
- A text interface that allows users to find OSMC observations within 50km of any Coral Reef in the world was demonstrated.



- We have an operational 10-day revolving window of the new "production" database schema tables (which is a combination of data reported on both the GTS and GODAE datafeeds), plus views pointing to the "production" and "test" tables of the entire databases at NDBC.
- We have provided web-view access to "latest observation" data in the ArcIMS viewer (described above) or through a text interface, e.g. for platform_code '21542': http://www.ngdc.noaa.gov/idb/struts/results?&op_7=eq&v_7=21546&t=102723&s=14&d=14. This view demonstrates some quality problems associated with differences in the precisions of locations reported by GTS and GODAE.
- We provide a map and text view that shows locations without ARGO observations during the most recent 5 days as an example of spatial capabilities with map and text output. See http://www.ngdc.noaa.gov/idb/struts/results?&t=102753&s=5&d=5.

Task: Support smooth transition and operation of OSMC database at NDBC

- We provided the database design and DDL for instantiating the new database schema at NDBC and developed, tested, and provided code to transition the old data to the new.
- Provided general database advice to NDBC on loading performance and database layout.
- Created a TRAC wiki page for database items that includes: LAS database query coding, Performance issue discussions, Platform Hierarchy correction/enhancement code (also listed below, re: optimization), Database QC findings, New database design requirements
- Temporal partitioning is in place in the observation and observation_value tables.
- Numerous queries have been examined, tested, and optimized using our 10 day database, e.g. https://intranet.ngdc.noaa.gov/wiki/index.php?title=OsmcQueryA
  - We have researched creating a decision-tree query approach. https://intranet.ngdc.noaa.gov/wiki/index.php?title=OsmcLas
  - We have researched creating a 10-day all-table-join table and queries. https://access.pmel.noaa.gov/trac/osmc/wiki/OSMCLasDatabaseQueryCode,DanaInfo=porter.pmel.noaa.gov+ https://intranet.ngdc.noaa.gov/wiki/index.php?title=OsmcAllTableJoin
  - We have researched translating "plain-language" queries. https://access.pmel.noaa.gov/trac/osmc/wiki/OSMCLasDatabaseQueries,DanaInfo=porter.pmel.noaa.gov+ https://access.pmel.noaa.gov/trac/osmc/wiki/OSMCLasDatabaseQueryCode,DanaInfo=porter.pmel.noaa.gov+
  - We have researched correcting the platform_table hierarchical search capabilities. https://access.pmel.noaa.gov/trac/osmc/wiki/PlatformHierarchy,DanaInfo=porter.pmel.noaa.gov+
- We have created a number of text query interfaces:
  - Current classification of all platforms listed in the OSMC.PLATFORM table, regardless of reporting activity. http://www.ngdc.noaa.gov/idb/struts/results?&t=102760&s=13&d=13



- GTS feed vs. GODAE feed -- Daily Count Comparison
  (Individual platform_codes comparison--includes unidentified platforms)
  http://www.ngdc.noaa.gov/idb/struts/results?&t=102734&s=6&d=6
- GTS vs. GODAE platform type and subtype count comparisons
  http://www.ngdc.noaa.gov/idb/struts/results?&t=102734&s=6&d=10,7
  http://www.ngdc.noaa.gov/idb/struts/results?&t=102734&s=6&d=10&d=11
- GODAE platforms not in GTS
  http://www.ngdc.noaa.gov/idb/struts/results?&t=102734&s=4&d=8,4
- GTS platforms not in GODAE
  http://www.ngdc.noaa.gov/idb/struts/results?&t=102734&s=5&d=9,5

- We have used the “date_added” field in the OSMC database to characterize reporting histories and identify reporting anomalies. As of May 18, 2007, this field should be accurately populated. Up until that time, there were various influxes of data where the date_added field was set to be equal to the observation_date field) (e.g. the conversion of the "historic" data to the new schema and before 05/18, the date_added field was not being populated. Since 05/18, it should be correctly populated. The latency results look like:

Days	Count	Days	Count	Days	Count
0	33993845	15	152551	30	44390
1	18754835	16	90598	31	39182
2	1330285	17	98424	32	44501
3	1138827	18	100253	33	31545
4	295100	19	96785	34	4856
5	186579	20	115304	35	38034

6	189586	21	133394	36	41038
7	214612	22	95168	37	41045
8	124316	23	97193	38	35936
9	144218	24	95143	39	38934
10	107203	25	74566	40	39040
11	100026	26	95277	41	36756
12	153758	27	112402	42	43538
13	104700	28	140165	43	38428
14	101782	29	74425	44	33728

- Support access to recent OSMC data using Open Geospatial Consortium web services (WMS, WFS).

Acronyms

ArcIMS	Arc Internet Map Server
DDL	Data Definition Language
ESRI	Environmental Systems Research Institute
FTE	Full Time Equivalent
FY	Fiscal Year
GEO-IDE	NOAA's Global Earth Observation Integrated Data Environment
GIS	Geographic Information Systems
GODAE	Global Ocean Data Assimilation Experiment
JCOMMOPS	Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology Observing Platform Support
LAS	Live Access Server
NDBC	National Data Buoy Center
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
MS	Microsoft
OCO	Office of Climate Observations
OSMC	Observing Systems Monitoring Center
PMEL	Pacific Marine Environmental Laboratory
PP&I	Program, Planning & Integration
SDE	Spatial Database Engine
WMS	Web Map Service
WFS	Web Feature Service

World Ocean Database Project

Sydney Levitus
NOAA National Ocean Data Center, Silver Spring, MD

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 4960 times during the past 24 years.

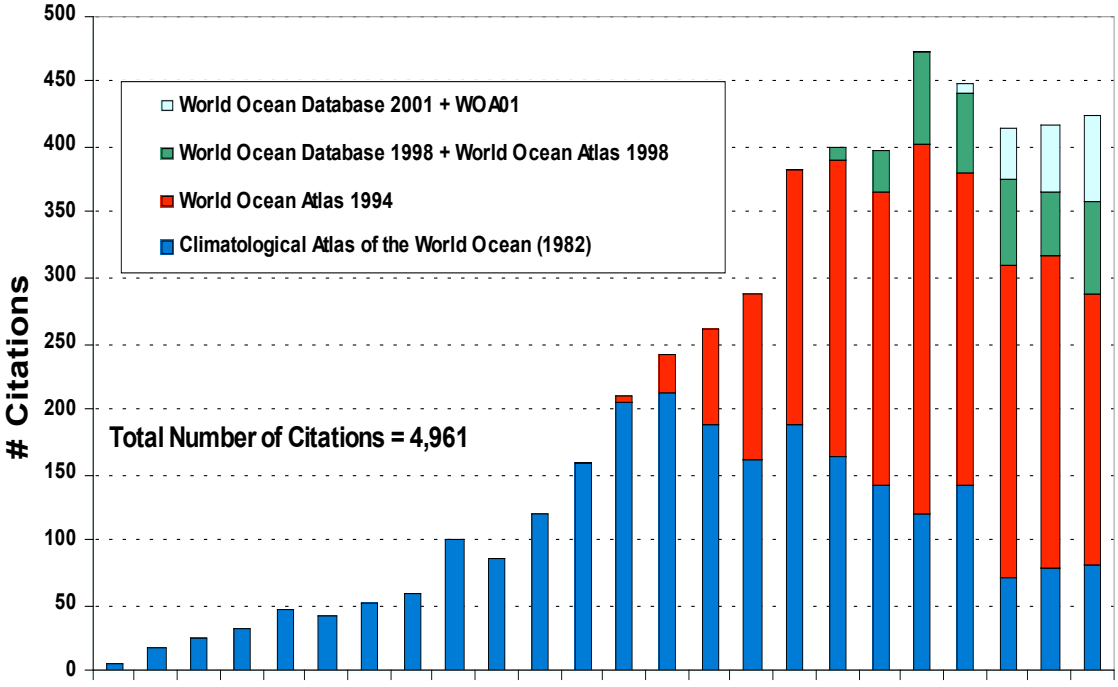


Figure 1. Time series of the number of citations as a function of year for NODC profile databases and products based on those databases.

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 shows that more than 700 million ocean profiles have been downloaded during the past four years alone.

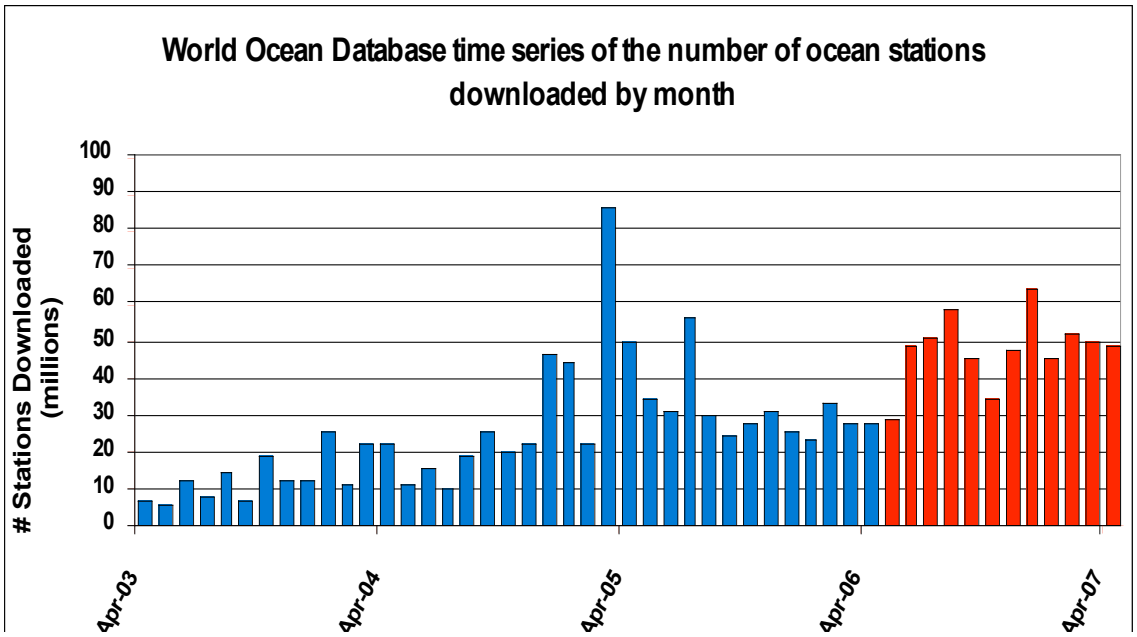


Figure 2. Number of casts in the World Ocean Database downloaded as a function of time.

Accomplishments

We published *World Ocean Database 2005* (WOD05) in FY06 as reported last year.

During FY07 we began processing data for WOD09 and the following amounts of data have been processed:

1) Ocean Station Data (Bottle):	98,676 casts
2) Conductivity-Temperature-Depth:	49,349 casts
3) Expendable Bathythermograph:	58,069 profiles
4) Mechanical Bathythermograph:	2,880 profiles
5) Profiling Float	205,474 casts
6) Moored Buoy	77,186 profiles

Publications and Reports

Bindoff, N.L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L. D. Talley, and U. Unnikrishnan, 2007: Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Maquis, K. B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, United Kingdom and New York, NY, USA.

Boyer, T., S. Levitus, J. Antonov, R. Locarnini, A. Mishonov, H. Garcia, 2007: Changes in freshwater content in the North Atlantic Ocean 1955-2006, 34, L16603, doi:10.1029/2007GL030126.

Stouffer, R. J., D. Seidov, and B. J. Haupt, 2007: Climate Response to External Sources of Freshwater: North Atlantic versus the Southern Ocean. Journal of Climate, 20, 436-448.

Haupt, B. J. and D. Seidov, 2007: Strengths and weaknesses of the global ocean conveyor: Inter-basin freshwater disparities as the major control. Prog. in Oceanogr., 73, 358-369.

Enhanced Ocean Climate Products from NCEP

Stephen J. Lord
NOAA NCEP Environmental Modeling Center, Camp Springs, MD

Project Summary

Following successful experiments with new observational data sets in GODAS during FY06 and early FY07 these improvements have been either been made operational or are in the final stage prior to becoming operational. The use of altimetry data in GODAS became operational in March 2007. The operational GODAS exists in two forms, a standard version that lags the current date by 14 days and a second version that is initialized by the standard GODAS but is brought forward to lag the current date by 7 days. A 1-day lag version of GODAS is in final parallel testing and is expected to replace the 7-day lag version in operations in January 2008. A new deep version of GODAS, designed to make full use of the Argo data, is also in parallel testing and is also expected to become operational in January 2008. All these versions of GODAS are based on MOMv3. Work has also been completed on a new GODAS that is based on MOMv4. This GODAS will be part of the Coupled Forecast System Reanalysis and Reforecast (CFSRR) scheduled to begin in early 2008. It will also be the basis for future upgrades of the operational GODAS.

1.0 Progress in FY07

The work in FY07 focused on two areas. First, we have made upgrades to the operational GODAS based on our successful experiments with new observational data sets and, second, we have completed development of a new GODAS based on MOMv4 that will be part of the CFSRR and future upgrades of the operational GODAS.

1.1 Upgrades to the current operational GODAS

The assimilation of Jason-1 altimetry became part of the operational GODAS in March 2007. This upgrade to GODAS has been designed to be sufficiently robust to tolerate occasional dropouts of altimetry data and it has run successfully since its implementation.

The standard operational GODAS assimilates observations in a window extending from 2 weeks prior to 2 weeks after the analysis date, weighting observations closer to the analysis date more heavily. The purpose of this strategy is to increase the number of observations going into the analysis, but it means that the standard GODAS analysis lags the calendar date by 14 days. To satisfy a need for a more current analysis, both for monitoring changes in the ocean state and for initializing forecasts with the CFS, there is a second operational GODAS analysis with a 7-day lag that is initialized by the standard analysis and then runs forward for an additional week. We have extended this procedure further to create a 1-day lag analysis that is currently in its final parallel testing. When this 1-day lag GODAS analysis becomes operational in January, it will replace the 7-day lag analysis.

The standard GODAS assimilates observations only in the upper 750 meters which does not take full advantage of the deeper Argo profiles. So in FY06 we tested a modified GODAS that assimilates observations down to 2200 meters. We found that the deep assimilation eliminated a warm bias in the Indian and Pacific Oceans and a cold bias in the Atlantic Ocean that occurred below 800 meters in the standard GODAS. Following the success of these tests we decided to implement a deep GODAS. The deep GODAS is also in final parallel testing and will also become operational in January.

The standard GODAS is the source of initial conditions for seasonal forecasts with the CFS and thus any upgrades to that version must not alter the calibration of the CFS forecasts. The new deep GODAS will be free of that constraint and the goal is to maintain that version as the current state-of-the-art at NCEP. We have begun by using deep Argo temperature profiles and we will soon introduce Argo salinity profiles in place of the synthetic salinity developed for the standard GODAS.

The broad impacts of the altimetry and the Argo salinity data on GODAS are described in Behringer (2007) and the impact of the Argo salinity on the GODAS analysis in the Indian Ocean is discussed in Huang et al. (2007).

1.2 Development of a MOMv4 version of GODAS

We have completed the development of a new version of GODAS based on GFDL's MOMv4. The tri-polar grid of MOMv4 allows us for the first time to have a fully global system that includes an Arctic Ocean and an ice model. The 3DVAR assimilation code of the current operational GODAS was completely rewritten to take advantage of the FORTRAN 90/95 data structures and coding practices in MOMv4. The result is a more flexible system, more readily adaptable to using different data sets and computational methods.

The MOMv4 GODAS will be part of the new CFS Reanalysis and Reforecast (CFSRR) that will begin in January 2008.

References

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)

Huang, Boyin, Yan Xue, and David W. Behringer, 2007. Impacts of Argo Salinity in NCEP Global Ocean Data Assimilation System: The Tropical Indian Ocean. (submitted to JGR)

Ocean Data Assimilation Research at GFDL

Tony Rosati and Brian Gross
NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ

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)

   A fully coupled data assimilation (CDA) system, consisting of an Ensemble Kalman Filter applied to CM2, has been developed to facilitate the detection and prediction of seasonal-to-multidecadal climate variability and climate trends (Zhang et al. 2007). The assimilation provides a self-consistent, temporally continuous estimate of the coupled model state and its uncertainty, in the form of discrete ensemble members, which can be used directly to initialize probabilistic climate forecasts.

2. Climate Detection

   The assimilation system has been evaluated using one CM2.1 simulation of the 20th century as "truth", and assimilating "observations" from that "truth" experiment into a second, independent experiment. "Observations" are taken from the model at places and times where real observations were taken. These observations are then assimilated into a coupled model ensemble that is subjected only to preindustrial forcings. By examining how well this analysis ensemble reproduces the "truth", the skill of the analysis system in recovering anthropogenically forced trends and natural variability is assessed, given the historical observing network. The assimilation is able to successfully reconstruct

twentieth-century ocean heat content variability and trends in most locations (Fig.1). The experiments highlight the importance of maintaining key physical relationships among model fields, which are associated with water masses in the ocean and geostrophy in the atmosphere.

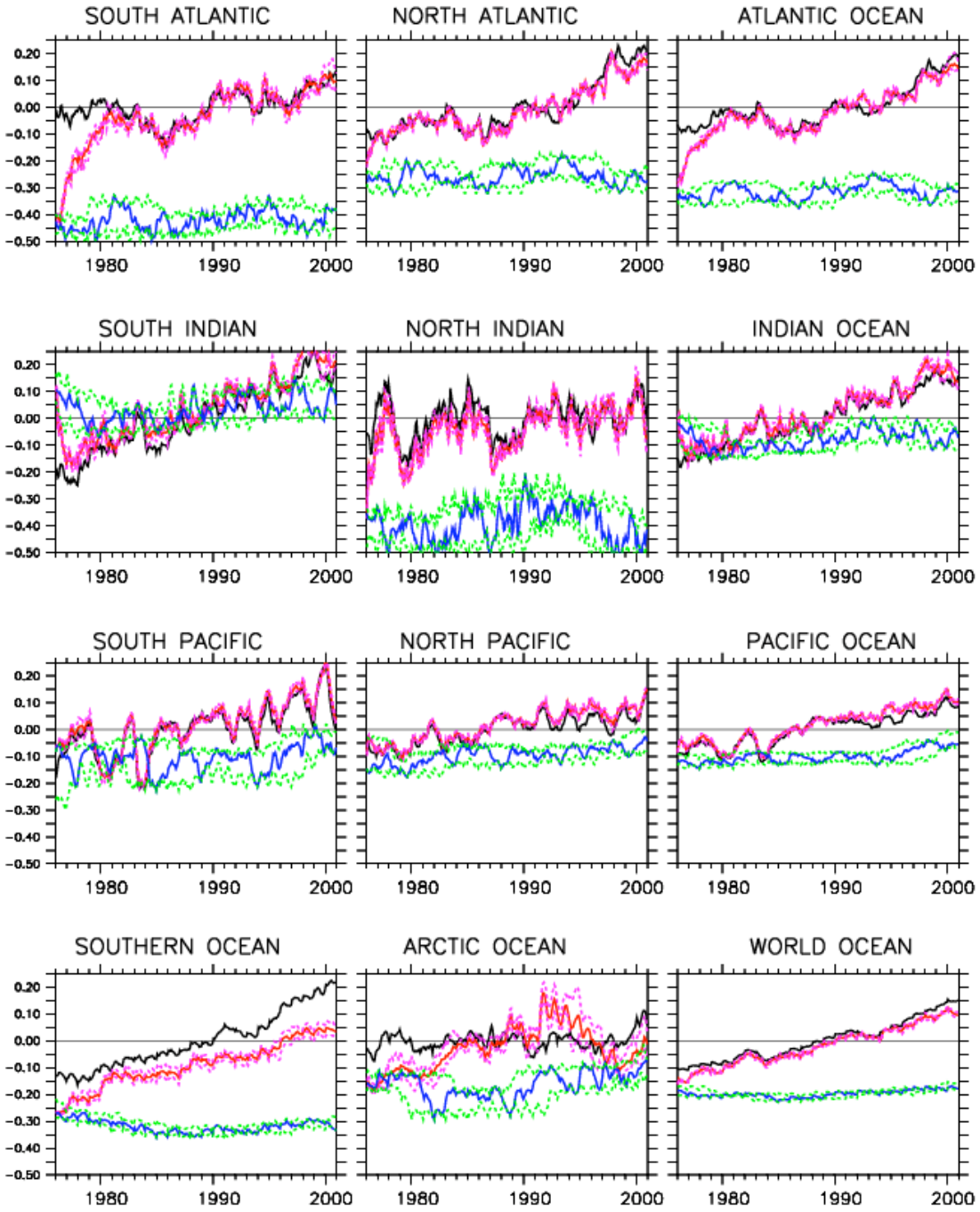


Figure 1 Time series of the anomalies of the top-500m ocean heat content (averaged temperature) in different oceans for the "truth" (black), the ODA (red), and the control (blue). The upper (lower) bounds of the control ODA spread are

plotted by the green-dashed (pink dashed). All anomalies are computed relative to the "truth's" climatology. This figure shows how well the ODA is able to converge to the true solution and capture the simulated warming trend. Sampling issues are noted, in regions that are well observed there is good convergence as in the North Atlantic whereas the southern ocean, where observations are sparse, does not converge to the true solution.

3. Implications for Ocean Observing Systems

The experiments described above indicate that the Atlantic meridional overturning circulation is difficult to constrain using the twentieth-century observational network, but can successfully be reproduced when Argo measurements are available, thereby constraining ocean salinity and density. This preliminary work on assessing the capability of the CDA and ocean observing systems suggests that Argo profiles will be critical for developing a nowcasting capability for the AMOC (Fig.2). Using the CDA system a twenty-five year ocean analysis, for the period 1979-2006, was produced, using XBT, CTD, and Argo observations. The historic ocean state estimation has been extensively analyzed in term of mean and variability (Figs. 3 and 4). This pioneering fully coupled analysis was then used to initialize a set of retrospective seasonal/interannual twelve-month forecasts. It was found that the CDA system showed significantly improved ENSO forecast skill over the previous 3DVar scheme demonstrating the improvement in the initialization scheme.

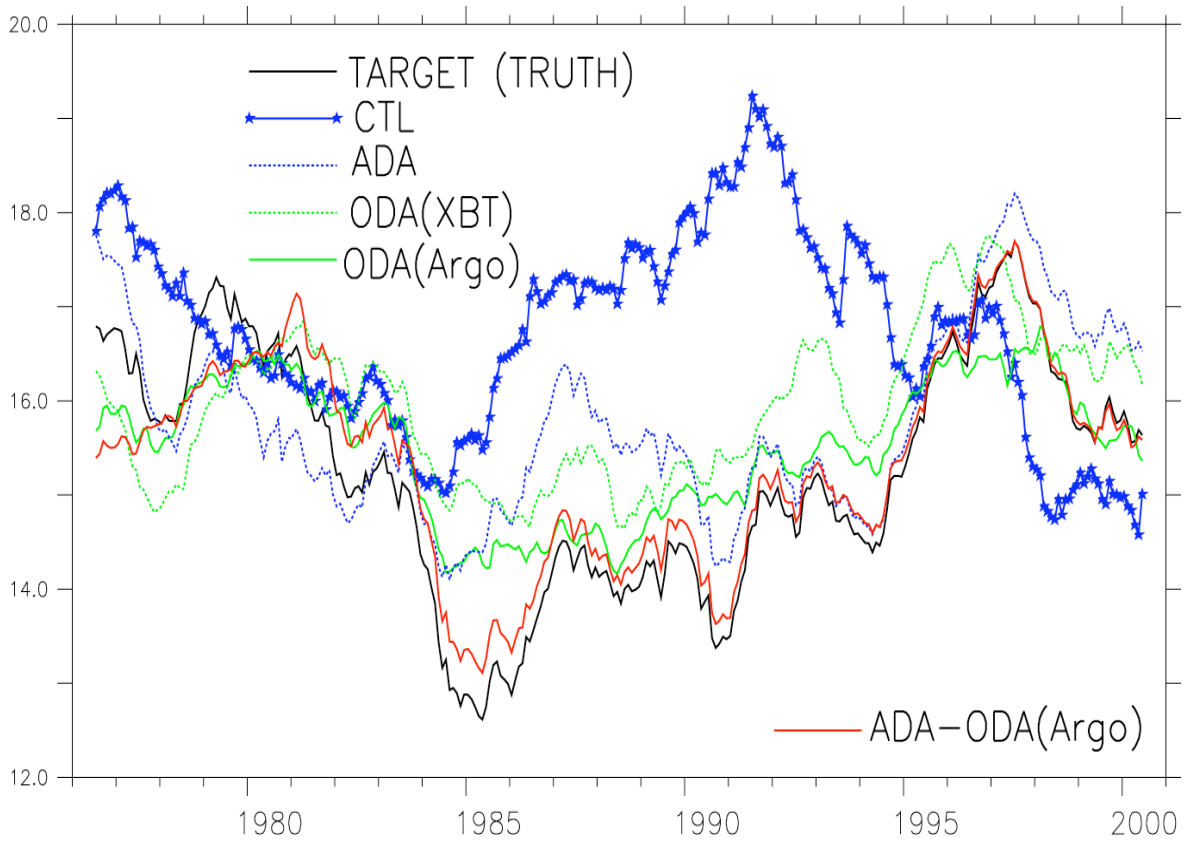


Figure 2 Perfect model studies of the capability of the CDA and observing systems to analyze the AMOC are being carried out at GFDL. The black curve represents a solution from a model simulation. The blue curve represents an independent simulation from which the CDA was initialized. The ADA curve represents only atmospheric data assimilation; the ODA curves represent only ocean data assimilation using the XBT network and the Argo network. The red curve is the coupled ADA and ODA(Argo) and shows the CDA fully recovers the targeted AMOC variability. The y-axis represents AMOC in Sv and x-axis is time in years.

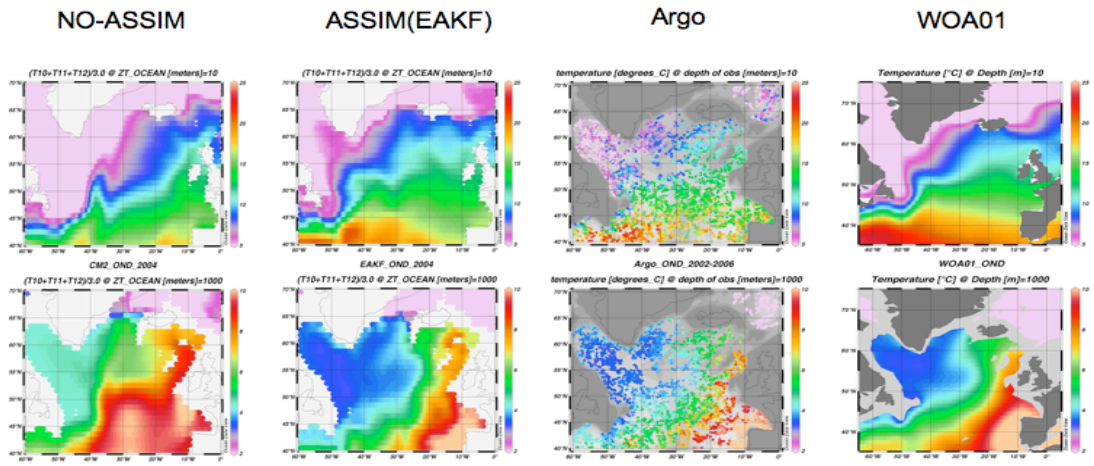


Figure 3 Comparison between ocean model with no data assimilation, with assimilation, just Argo data, and the World Ocean Atlas for OND temperature in the North Atlantic. Top figures are at 10m and bottom are at 1000m. What is shown is that the model without data assimilation has clear bias and that the assimilation case is capturing the data quite well including the variability as may be seen comparing to the WOA.

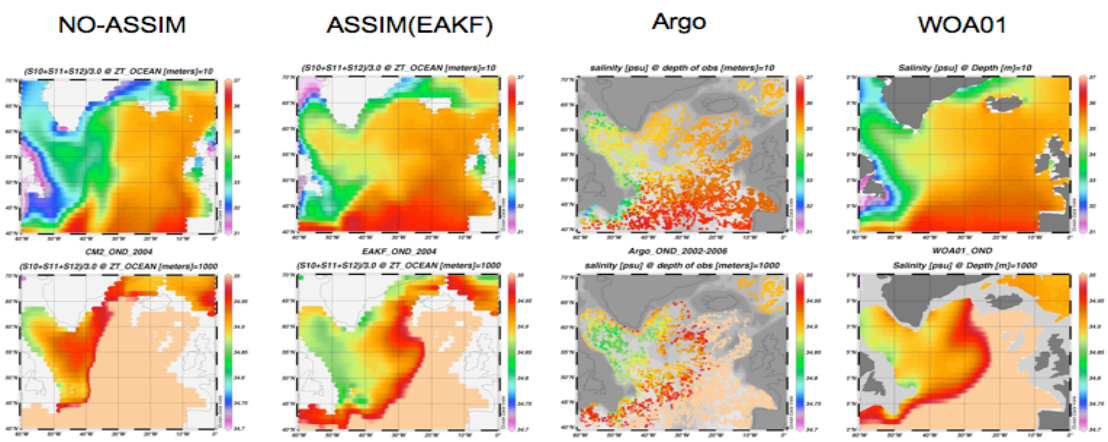


Figure 4 Same as Fig. 3 but for salinity.

4. Development of New Datasets

In order to support the assimilation effort we have had to undertake the task of assembling up to date global temperature and salinity data as well as altimetry data. A Quality Control (QC) system for the Global Temperature-Salinity Profile Program (GTSPP) has been implemented. We identified standard data types from the mixed GTSPP dataset in order to match them with the 20th century ocean assimilation based on the World Ocean Database. However, profiling data from Argo floats, the largest part of GTSPP in the 21st century, should be used with a higher quality delayed mode data. Therefore, another separate QC system investigating an artificial salinity drift is being operated and gradually updated. We now have put together a 25-year historic ocean data set and keep it up to date within one month of real time. In order to undertake the model data comparison, the observed data was optimally interpolated to model positions and times. This three-dimensional gridded dataset will make it easier for statistical analysis regarding the model assessment.

5. Assimilation with Multi-Model Ensembles

Some new and exciting work has begun on a multi-model ensemble assimilation scheme. Both GFDL's CM2.0 and CM2.1 coupled models are used in a unified ensemble system in which the filtering process is based on the error statistics from both models' ensemble integrations. The system construction is complete but the analysis is ongoing. The idea here is that often the ensemble forecasts tend to look

more like each other than reality. The goal is that the ensemble spread should span the possible solution space and to include the true solution. Some initial OSSE imperfect twin studies using this system uncovered some inconsistent constraints in the upper and deep ocean due to model biases and the nature of the low frequency of the deep ocean circulation. Although this issue may not be important for seasonal initialization it will most likely be for decadal initialization.

Publications

Zhang, S., M.J. Harrison, A. Rosati, and A. Wittenberg, 2007: System Design and Evaluation of Coupled Ensemble Data Assimilation for Global Oceanic Studies. Mon. Wea. Rev., 135, 3541-3564.

Zhang, S., A. Rosati and M.J. Harrison, 2007: Detection of Multi-Decadal Oceanic Variability within a Coupled Ensemble Data Assimilation System. Accepted JGR Oceans.

Ocean Data Management at NCDC

Huai-Min Zhang, Stephen Delgreco, Alan Hall, Eric Freeman, Neal Lott, Rich Baldwin and Richard W. Reynolds
NOAA National Climatic Data Center, Asheville, NC

Project Summary

The project "Ocean Data Management at NCDC" directly supports the mission of NCDC (NOAA National Climatic Data Center): "To provide stewardship and access to the Nation's resource of global climate and weather related data and information, and assess and monitor climate variation and change." This in turn directly supports the NOAA Mission: "To understand and predict changes in Earth's environment and conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs."

NCDC plays an active and important role in the national and international climate change monitoring and assessment programs [e.g., the US Climate Change Science Program (CCSP) Syntheses]. Climate change monitoring and assessment require meteorological and marine data over both land and ocean. Changes of environmental variables at and near the marine surface are important since they occur over approximately 70% of the Earth's surface and contain important climate change signals. Due to the drastic property differences between water and air (e.g., density and heat capacity), huge amount of water, energy, momentum and gases (e.g., carbon dioxide) are constantly exchanged at the turbulent air-sea interface. These exchanges regulate the weather in the short term and the climate change in the long term. Thus, NCDC has been actively archiving, serving and utilizing the world's surface marine data, and it will need to continue to do so.

Modern day Global Ocean Observing System (GOOS) consists of multiple platforms and instruments (both in-situ and remote sensing). Each of these observations contributes to the understanding and assessment of climate change signals. However, individual instrument observations have limitations in coverage (in both time and space) and limitations on accuracy. To maximize benefits and integrally use all the available observations, it is necessary to blend them together to produce higher resolution and higher accuracy products. For example, research on global water and energy budgets and numerical weather and ocean forecasts demand increasingly higher resolution forcing data (better than daily and 50 km; e.g., WMO/TD-No. 1036, 2000; Curry et al. 2004). The recent international Global Earth Observation System of Systems (GEOSS) and Global Climate Observing System (GCOS) also called for optimal combinations of the above platforms for integrated global observing system and service.

There are typically three types of errors in observations and blended products: 1) random error; 2) sampling error; and 3) bias error. The bias error is the systematic difference between one instrument (or a set of instruments, e.g., in-situ observations) and another (e.g., remote sensing/satellite observations). The combined error for all terms should be reduced to a required accuracy for meaningful climate change diagnostics. In the satellite era, satellite observations provide dense data coverage, thus in-situ data play a minor role in the reduction of random and sampling errors and in increasing resolutions in blended products. However, in-situ observations provide the "ground-truth", thus play an essential role in correcting the systematic biases of indirect measurements (e.g., remote sensing/satellite observations that are calibrated to in-situ observations).

The overall objectives of this project are: 1) to ingest the world's marine observations into the NCDC archives; 2) to quality control the data for various applications (such as for Reanalysis); 3) to produce blended products for optimal use of all the observations; and 4) to improve services for a wide variety of user communities. The highlighted accomplishments for the past fiscal year are described in the next section.

Accomplishments

1. ICOADS - Increased data volume of archive and service; online data for years prior to 2005; GIS capabilities.

NCDC continued to ingest, archive, quality control and serve the ICOADS data. The two key priorities for expanding data access capabilities have been: 1) making data prior to 2005 available online (via Climate Data Online—CDO) for selected data sources after additional quality controls; and 2) developing a prototype GIS map services linked to the CDO interface. Both of the objectives have been completed. Customers are now able to retrieve data from 1994-2005 for several data sources and all data sources from 2005 to present. ICOADS are available online. This replaces the off-line ordering and delivery of data as done in the past. The GIS map service will be available before the end of the calendar year. This provides a GIS-based map interface for users to locate and access marine data, and to overlay various features/layers which are available through GIS Services (http://www7.ncdc.noaa.gov/CDO/CDOMarineSelect.jsp).

2. VOSClim - Increased data volume of archive and service; improved VOSClim webpage

VOSClim is an ongoing project within WMO/IOC JCOMM's Voluntary Observing Ships' Scheme, to which NOAA is a major partner. As the VOSClim Data Assembly Center, NCDC continued to ingest, archive, quality control and serve the ICOADS data. Additionally, we improved the VOSClim website. Requested by the "Ship Observations Team III Meeting", NCDC undertook a revised design of the official VOSClim website. Elements of redesign included: a) a simpler, more aesthetically-pleasing suite of pages; b) a design that is more conducive to easy navigation with tabs indicating the main elements of the page; and c) an accessible data link, providing ASCII text files for scientific use. The redesigned page (Fig. 1) was developed in consultation with the VOSClim partners and is made available for comment and revision.

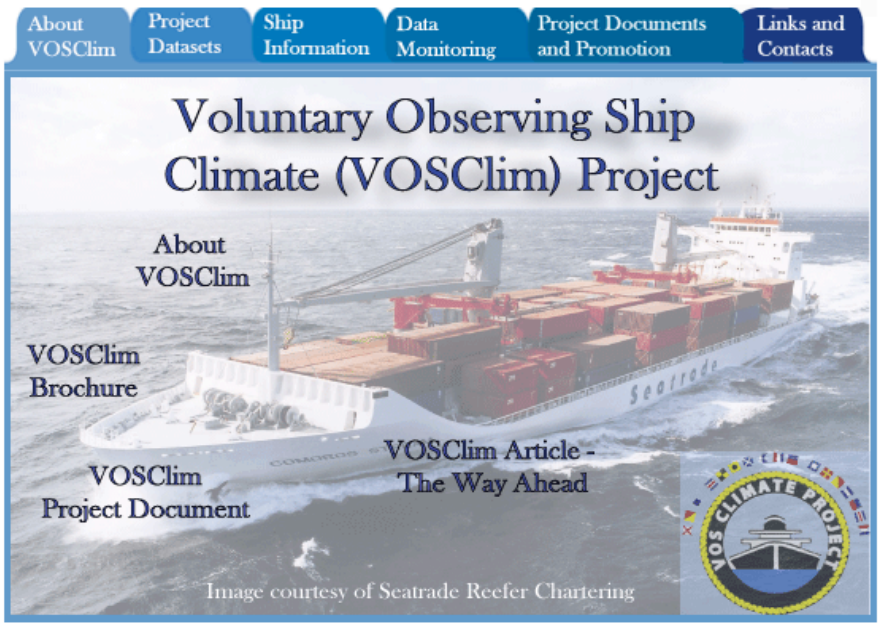


Figure 1. VOSClim webpage with links to access ship information and project datasets: http://www.ncdc.noaa.gov/oa/climate/vosclim/vosclim.html

ASCII data access is considered of more utility for the current level of scientific and general users and therefore is a critical addition. Drop down menus for access to monthly data monitoring statistics are provided as well as links to ship photographs and other metadata information. There are currently 247 active VOSClim ships, which in 2007 surpassed the project target of 200 participating vessels.

3. Re-processed blended high resolution sea wind speed - Version 1.1

Blended high resolution sea surface winds from all long-term US sea wind speed observing satellites were produced. Global 0.25° winds are available with time resolutions of 6-hourly, daily, and monthly. Data are available at several interactive data servers (see links at http://www.ncdc.noaa.gov/oa/rsad/blendedseawinds.html).

For long-term climate analysis and adherence to the principles of the long-term Climate Data Records (CRD) and the Ten Climate Monitoring Principles, reprocessing of the blended product for the whole time period (July 1987 onward) was completed. Major improvements in the satellite retrievals (input to the blended products) include: 1) Removal of spurious trends in the wind speed; 2) Implementation of a much-improved rain rate algorithm; 3) Achievement of better consistency for all retrievals over the 8 satellite platforms (i.e, 6 SSM/I, TMI, and AMSR-E); and 4) Minor improvements in other retrievals, namely SST and water vapor.

4. Development and production of vector sea winds and wind stress – Version 1.2

For the computation of turbulent air-sea fluxes of scalars (e.g., latent and sensible heat, fresh water by evaporation, carbon dioxide, etc), only sea surface wind speed is needed. However, for many other applications requested by users, vector winds and wind stresses are needed. Thus, we added directions to our blended wind speed products and compute the wind stresses. The wind directions were interpolated from the NOAA NCEP Reanalysis-2 output.

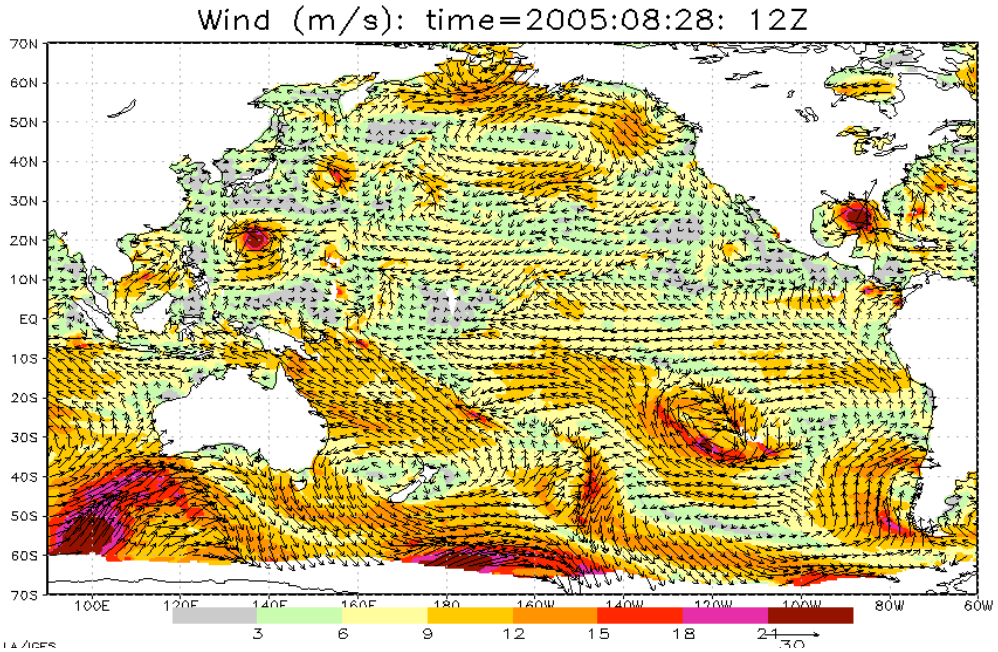


Figure 2. Example of the blended global 0.25° 6-hourly sea winds that show simultaneous Typhoon Talim and Hurricane Katrina. Vectors are sub-sampled for viewing clarity.

5. Development of blended sea winds using OI

In the blended wind speed, so far we employed a simple objective analysis scheme that weighs the observations by "distances" in both space and time to reduce alias effects when/where there are enough data. In this scheme, the error statistics in all observations are treated the same. However, in reality, observations may have different error statistics due to, for example, observations by different instruments (e.g., microwave versus radiometer) and in different atmospheric regimes (e.g., contamination in precipitation areas). Thus the blended winds will be improved by also weighting the observations by the more realistic error statistics, using the so-called objective analysis or optimum interpolation (OA/OI). In FY07, we have implemented Reynolds SST OI codes to sea winds, and some preliminary sea wind error statistics have been computed.

6. Development of a prototype interactive data server

The objective of this task is to establish an interactive web interface so that data from different sources (in-situ observations, satellite observations, numerical model results, and blended products) can be displayed and inter-compared in various ways. A prototype interactive web data server has been built.

Publications and Reports

Zhang, H.-M., G. Rutledge, R.W. Reynolds, F. Schwing and R. Mendelssohn, 2007: An Interoperable Marine Environmental Data and Web Service Across NOAA Line Offices. *PRIDE Investigators Meeting and Pacific Region Data Integration and Visualization Workshop*, 16 – 18 October 2007, Honolulu, HI.

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).

Xu, M., C.-P. Chang, C. Fu, Y. Qi, A. Robock, D. Robinson, and H.-M. Zhang, 2006: Steady decline of east Asian monsoon winds, 1969 - 2000: evidence from direct ground measurements of wind speed. *Journal of Geophysical Research –Atmospheres*, **111**, D24111, doi:10.1029/2006JD007337

Sections in "*2007 NCDC PRODUCTS AND SERVICES GUIDE*" & NCDC & NESDIS Annual Reports.

U.S. Research Vessel Surface Meteorology Data Assembly Center

Shawn R. Smith, Mark A. Bourassa and Eric Chassignet
Center for Ocean-Atmospheric Prediction Studies, The Florida State University, Tallahassee, FL

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 that are distributed with a delay of 10 days from the original data collection date. All quality-evaluated research vessel data from the SAMOS initiative and past DAC programs are freely available to the user community (http://www.coaps.fsu.edu/RVSMDC/html/data.shtml), and we continue to work with several

world data center archives (e.g., National Oceanographic Data Center, National Center for Atmospheric Research) to ensure long term stewardship of these data.

Accomplishments

Over the past year, our efforts have focused on the continued development of the SAMOS Initiative. In collaboration with partners at NOAA's Office of Marine and Aviation Operations (OMAO), Raytheon Polar Services (RPS), and the United States Coast Guard (USCG), the number of vessels participating in SAMOS has increased from 2 to 12. Data from all 12 vessels are routinely pushed through our automated data quality evaluation (DQE). In mid-2007, our research quality processing (including visual DQE) became operational. Many upgrades have been made to both our public access web site and our internal data base tools. Throughout the year, DAC personnel have been actively promoting the SAMOS Initiative through meetings and working groups, including the International Marine Technicians Symposium (17-19 October 2006) and the Fourth Session of the WMO/IOC JCOMM[1] Ship Observation Team in Geneva, Switzerland (16-21 April 2007). We continue to actively recruit new vessels to participate in the SAMOS initiative.

Deliverables for FY 2007 included:

1. Continue routine quality evaluation of meteorological data for 2 SAMOS vessels contributing to the DAC (and 2 delayed mode NOAA vessels, if necessary)
2. Recruit additional research vessels to the SAMOS initiative (focus will be on NOAA and UNOLS vessels)
3. Improve and enhance metadata collection from participating research vessels
4. Develop new data quality evaluation techniques
5. Create and distribute turbulent air-sea fluxes for vessels contributing to SAMOS
    - Subtask1: Compare SAMOS fluxes with available NWP products
6. Continue liaison activities with U.S. and international government agencies, archives, climate programs
    - Subtask1: Establish data exchange with GOSUD
    - Subtask2: Implement data exchange with NODC and NCAR archives
7. Expand user options on the SAMOS web site to ease user access to observations and metadata

The following accomplishments address the deliverables. Also noted are impediments to achieving the deliverables.

Vessel recruitment [Deliverable 2]

Recruitment of additional vessels to participate in the SAMOS Initiative was very successful during the reporting period. Ten new vessels were recruited (Table 1) in the past year. These vessels now routinely contribute SAMOS observations when they are at sea. Collaboration with NOAA OMAO resulted in eight new recruitments. OMAO developed a SAMOS data transmission applet as part of the version 4.0 release of their scientific computing system (SCS).

[1] World Meteorological Organization/Intergovernmental Oceanographic Commission Joint Technical Commission for Oceanography and Marine Meteorology

As the new SCS was installed in the fleet, the NOAA vessels began transmitting data to the DAC. In addition, Co-PI Smith attended the annual UNOLS RVTEC meeting and INMARTECH in October 2006 and had good conversations with several additional vessel operators. Most expressed interest in participating in SAMOS, but initiating new data transfers is still difficult in these times of tight operational budgets for research vessels.

Table 1: Ships transmitting observations to SAMOS DAC during FY 2006 and FY 2007.

		Number of ship days with data	
Vessel	Operator	1/10/2005 – 30/9/2006	1/10/2006 – 30/9/2007
Atlantis	WHOI	192	291
Gordon Gunter	NOAA		4
Healy	USCG		62
Henry Bigelow	NOAA		70
Hi'Ialakai	NOAA		107
Ka'Imimoana	NOAA		61
Knorr	WHOI	276	252
Lawrence Gould	NSF/Raytheon		32
Miller Freeman	NOAA		190
Nancy Foster	NOAA		122
Oscar Dyson	NOAA		170
Ronald Brown	NOAA		149
		468	1510

Daily SAMOS data processing [Deliverables 1, 2, and 3]

Preliminary processing of SAMOS observations received via daily email messages from participating research vessels is now an operational activity at the DAC. During FY 2007, 1510 days of shipboard meteorology data were processed for the 12 recruited vessels (see Table 1). Preliminary processing (Figure 1) starts once the data file arrives at the DAC as an attachment to an email. Each email attachment is unpacked, the data provided are verified that they conform to the format and parameters expected for the individual vessel, and finally the data are blended with vessel specific metadata and are converted to a common netCDF format. The data for each day are then passed through an automated quality evaluation program and data quality statistics are calculated prior to the file being posted for users on the SAMOS web and ftp sites. The entire process from arrival at the DAC to distribution of the preliminary data files is fully automated. Preliminary files appear on the data distribution site within 5 minutes of their arrival at the DAC (typically shortly after 0000 UTC).

A comparison of the spatial distribution of data received, processed, and on-line for 2006 and the start of 2007 is shown in Figure 2. Prior to 2007, the only two ships providing data were the *Knorr* and *Atlantis*. A rapid increase in vessels participating in SAMOS began in early 2007, leading to the present 12 recruited vessels (Table 1).

Each individual data file has been augmented with extensive metadata that is stored in a ship profile database. In addition, the shipboard database uses a strict version control to track individual data files received from their original email attachment to the final files released to the public (Figure 1). Individual data quality statistics are stored in the ship database and these can

be accessed through the data availability link on the SAMOS web site (http://samos.coaps.fsu.edu/html/data_availability.php). A sample of data quality graphics for the *Knorr* is provided in Figure 3.

Delayed-mode SAMOS processing [Deliverables 1 and 4]

Due to data logging problems on the ship or communication dropouts, some data arrive several days after they were collected. Often the data are noted to be missing by the analyst at the DAC and arrive after the analyst notifies the vessel technician at sea. In addition, data for a single day may be fragmented and may arrive in multiple files attached to a single email. As a result, the DAC developed a method to merge multiple files for a single observing day into a combined, delayed-mode data file. This merged file undergoes additional automated and visual data quality evaluation and is then released as a "research-quality" SAMOS data file for the particular observation day (Figure 1).

The process to merge multiple files for a single observing day and the visual data quality evaluation are 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 database. Currently the merge occurs 10 calendar days after the observation day (when the preliminary data should arrive at the DAC). Using the 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.

Each day, the data quality analyst at COAPS reviews the latest merged files and conducts a visual quality evaluation. The visual analysis is accomplished using SVIDAT, a graphical user interface developed by COAPS programmers. SVIDAT allows the analyst to review, add, or modify data quality flags on the merged files. Once the analyst is satisfied with the data quality, the file is saved and posted automatically to the SAMOS ftp and web sites. This process also updates all necessary tracking information in the ship database and creates the copies of the original, preliminary, and research quality files for delivery to the national archive centers.

D*elayed-mode evaluation of NOAA ship data [Deliverable 1]*

We have received delayed-mode data from the *Ronald Brown* for the period February – December 2006. These data have been converted to our internal netCDF format and are awaiting quality control. For the *Ka'Imimoana*, we have received data for the period September 2004 – August 2007. The data for September 2004 – December 2005 have completed visual quality inspection and their data quality report is being written. Data from January – September 2006 have been converted to our format and are awaiting visual quality control. The remaining *Ka'Imimoana* data are awaiting conversion and quality evaluation. We note that in 2007 both the *Ronald Brown* and *Ka'Imimoana* were recruited to the SAMOS initiative and will no longer be providing delayed-mode data to the DAC. The outstanding delayed-mode data for the *Ronald Brown* and *Ka'Imimoana* will be evaluated and released by mid-2008. Future data for these vessels are being processed as part of the SAMOS initiative.

Metadata enhancement [Deliverable 3]

The SAMOS DAC continues to work to improve access to the metadata (e.g., instrument heights, sensor locations, averaging methods, etc.) necessary for scientific application of these observations. This continues to be a struggle. It is easier to get the SAMOS data from recruited vessels, but some critical metadata is lacking. We have had several telephone and in-person conversations to improve the situation. Recently, Mr. Smith has been asked to serve on the Data Management Best Practices Subcommittee of the UNOLS council. The committee will be reviewing data management practices (including metadata) for the UNOLS fleet. Finally, at the request of several vessel operators, the DAC has developed a web interface that will allow vessels participating in SAMOS to upload their metadata. The interface is in beta testing.

Liaison activities [Deliverable 6]

The SAMOS DAC serves as the project office for the entire SAMOS initiative. In this capacity, DAC personnel facilitate U.S. and international collaborations on topics ranging from data accuracy, data acquisition and exchange, training activities, and data archival.

Foremost of these activities was participation by Mr. Smith at the International Marine Technicians Symposium (17-19 October 2006) at WHOI. The symposium provided an opportunity to introduce the activities of and plans for the SAMOS initiative to the international research vessel community. Throughout the week, Mr. Smith participated in dialogs with ship operators as part of the SAMOS vessel recruitment effort. Mr. Smith also visited one of the NOAA OMAO vessels in port at WHOI and received a demonstration of the NOAA OMAO SAMOS data applet in SCS 4.0. This meeting led directly to the recruitment of many of the NOAA vessels in 2007. The symposium was also the venue where the "A Guide to Making Climate Quality Meteorological and Flux Measurements at Sea" was first released to the technician and operator community. This guide was co-authored by Frank Bradley (CSIRO) and Chris Fairall (NOAA/ESRL) and was a collaborative effort between the WCRP Working Group on Surface Fluxes and the SAMOS initiative. Several scientists participating in SAMOS activities contributed to the guide.

Mr. Smith also was invited to participate at the Fourth Session of the WMO/IOC JCOMM Ship Observation Team meeting in Geneva, Switzerland (16-21 April 2007). The SOT is responsible for overall coordination of the Voluntary Observing Ship (VOS) program and the meeting brought together VOS participants from many countries. Participants included several countries that are working towards full automation of their standard VOS meteorological reports. Mr. Smith presented the activities of the SAMOS initiative and had productive discussions with the VOS automation community. They were keenly interested in the SAMOS approach to data quality evaluation and long-term access to observations for future climate research.

A dialog with Steve Rutz from NODC and Steve Worley at NCAR established guidelines for pushing SAMOS data to these data archive centers (subtask 2). Initial plans for the first submission to the archives in mid-2007 were pushed back by delays related to making the delayed-mode SAMOS processing operational. The SAMOS DAC started delayed mode processing on 1 September 2007 and we are working towards our first archival submission at the end of 2007.

Public access to observations and metadata [Deliverable 7]

A web presence for SAMOS 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. Through these pages, the DAC provides access to the preliminary quality controlled data for all 12 ships currently recruited to the SAMOS initiative. 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.

The data distribution system is under constant development. New in the reporting period is the "Data Availability" link under "Data Access". This new page provides the user with more options to select desired data than the older "Data Download" page. Through "Data Availability" users can select one or more ships and a time range to determine whether observations are available. The data are displayed graphically by day and each day is color-coded according to the overall quality of the days observations. The user can then select to download data of one or more ships and has the option of selecting only good quality or all available data. Drill down capacity allows the user to select a single day and ship from the graphic to display detailed data quality graphics (similar to Figure 3). A new metadata interface is being developed and will be launched in 2008. These new tools will be added to the web site for users when testing is complete.

Deliverables 5 and 6 (subtask 1) pushed forward to FY 2008

The rapid increase in ships participating in SAMOS, the need to shift our priorities to get our delayed-mode processing operational, and staffing turnover limited activity on these two deliverables.

Figures And Images

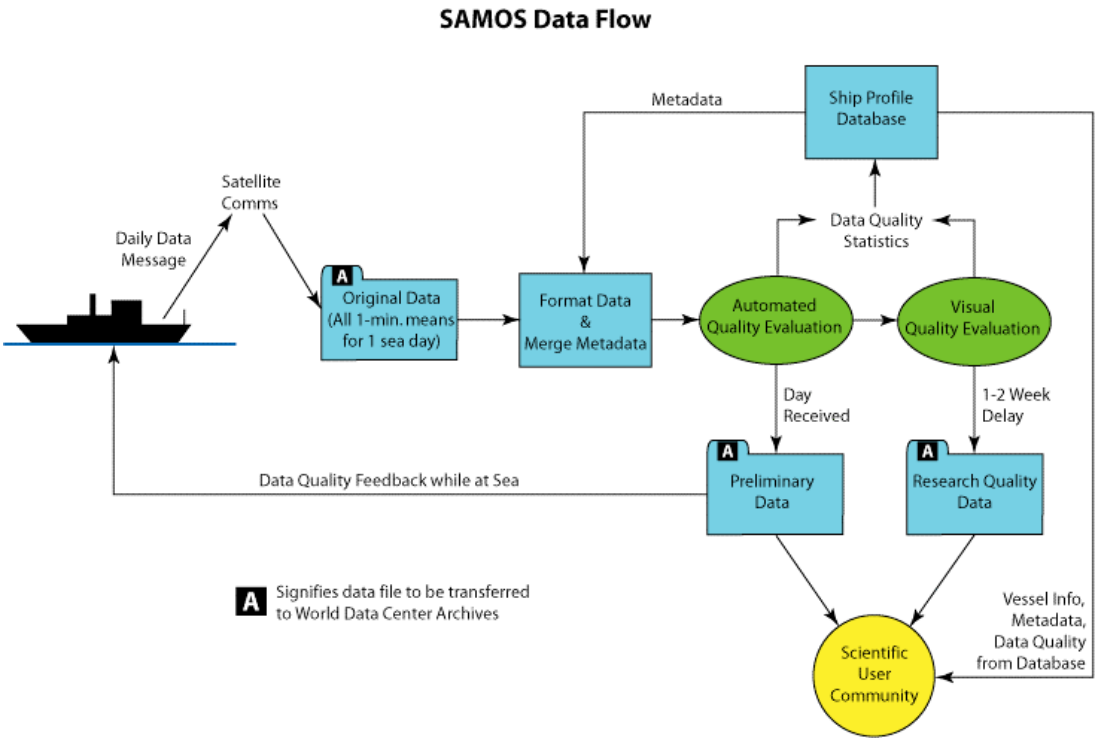


Figure 1. Operational data flow between research vessels at sea and the SAMOS DAC. Data transfers take advantage of 24/7 broadband satellite communications. Real-time data quality feedback to vessels at sea and their home institutions have proven successful to reduce the amount of poor quality data caused by sensor failures.

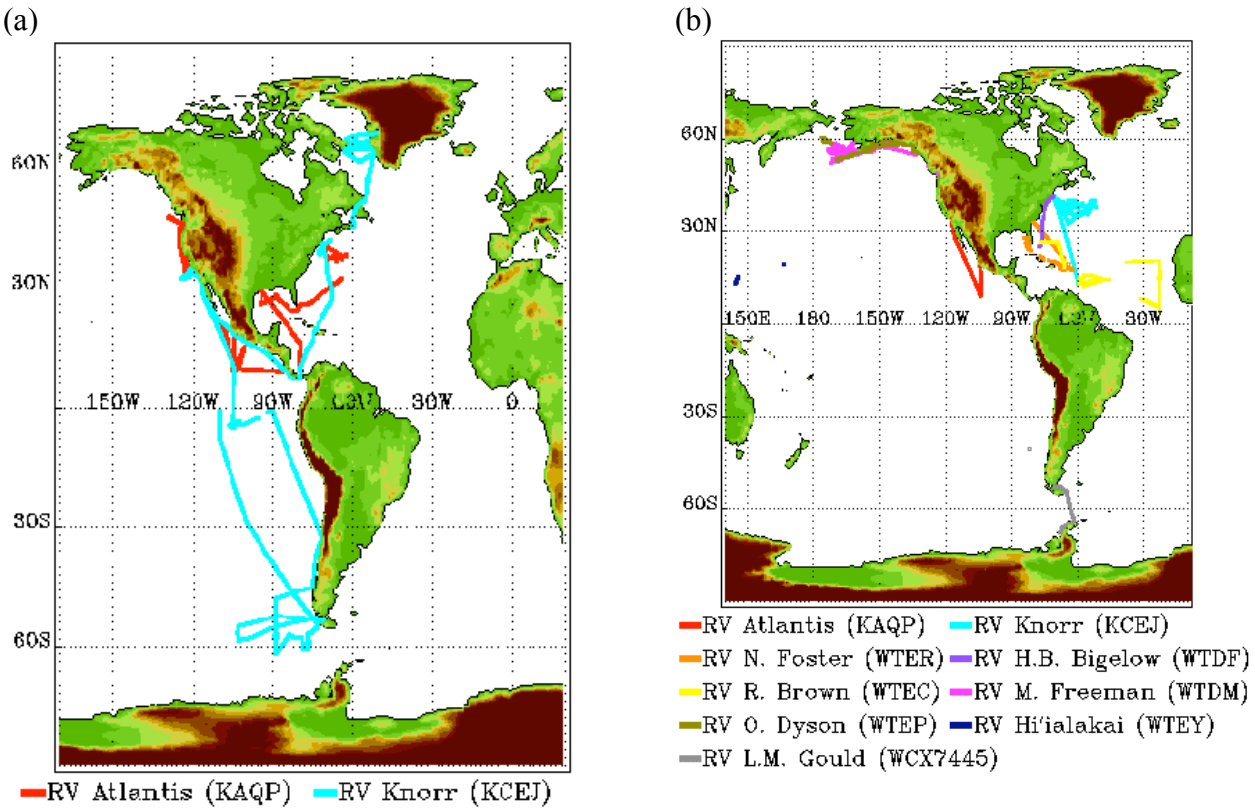
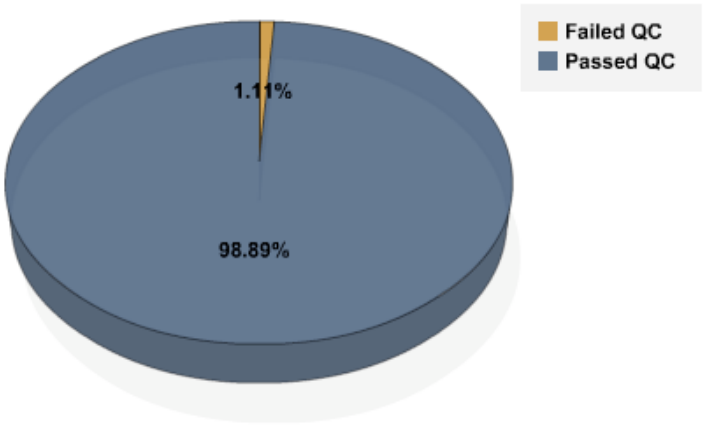
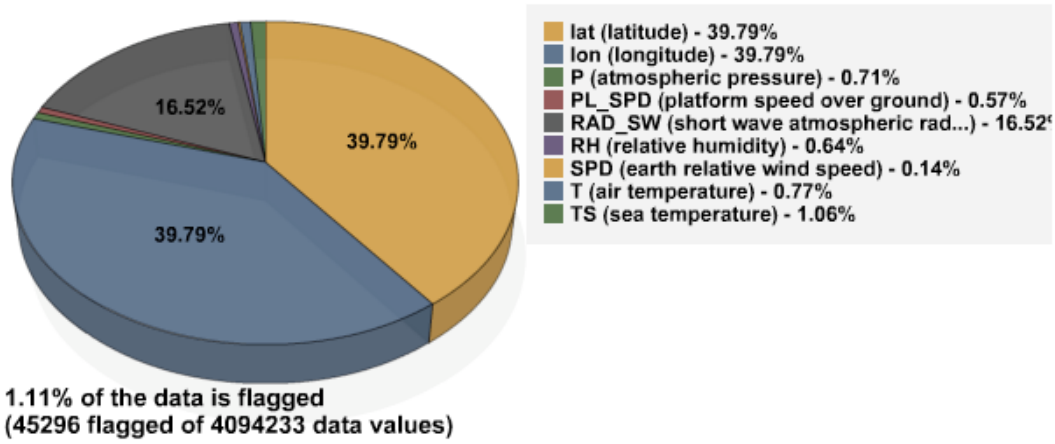


Figure 2: Cruise tracks comparing SAMOS data coverage for 2006 (January 1, 2006 – December 31, 2006) and the first half of 2007 (January 1, 2007 – May 21, 2007). An additional 3 vessels began reporting to SAMOS after May 2007 (not shown).

(a)



(b)



(c)

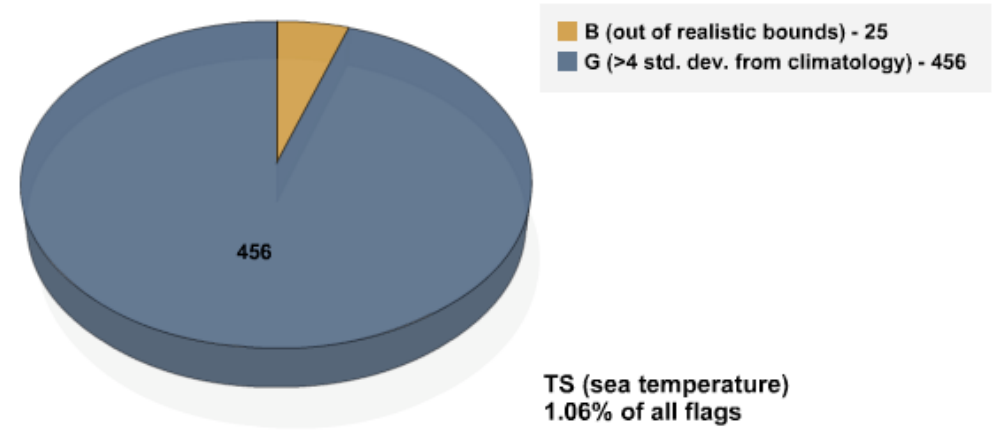


Figure 3: Data quality statistics for SAMOS observations received from the RV *Knorr* for the period 1 July 2006 – 30 June 2007. (a) Total percentage of data that passed or failed preliminary QC. (b) Breakdown by measured parameter of 1.11% of data that failed QC tests. (c) Flags applied to sea temperature (1.06% of the 45,296 values that failed QC tests).

Publications and Reports

Refereed

Smith, S. R., 2006: A Partnership between Shipboard Oceanic and Atmospheric Data Programs. *EOS, Trans Amer. Geophys. Union*, **87**, 463, 466.

Technical reports

Smith, S. R., 2007: Shipboard Automated Meteorological and Oceanographic System (SAMOS) Initiative. Report for 4rd session of the JCOMM Ship Observation Team meeting, 16-21 April 2007, Geneva, Switzerland, 2 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., and S. R. Smith, 2007: Improving air-sea flux estimation with a new wave-dependant parameterization and high-quality research vessel observations. *ONR Progress Review – Southeast Region*, Tallahassee, FL, USA, 1-3 May 2007.

Smith, S. R., J. Rolph, and M. A. Bourassa, 2007: Progress of the Shipboard Automated Meteorological and Oceanographic System (SAMOS) Initiative Data Assembly Center. *Climate Observation Division 5th Annual System Review*, NOAA, Silver Spring, MD, USA, 5-7 June 2007.

Smith, S. R., 2007: The SAMOS Initiative. *4th session of the JCOMM Ship Observation Team*, Geneva, Switzerland, 16-21 April 2007, CDROM.

Josey, S. A. (presented by S. R. Smith), 2006: Evaluation of Air-Sea Fluxes. *2nd CLIVAR Global Synthesis and Observation Panel meeting*, La Jolla, CA, USA, 8 and 9 December 2006.

Smith, S. R., 2006: The SAMOS data assembly center. *International Marine Technicians Symposium*, Woods Hole, MA, USA, 17-19 October 2006.

Smith, S. R., F. Bradley, and C. Fairall, 2006: A guide to making climate quality meteorological and flux measurements at sea. *International Marine Technicians Symposium*, Woods Hole, MA, USA, 17-19 October 2006.