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

Report for Calendar Year 2006

Dean H. Roemmich
Scripps Institution of Oceanography, La Jolla CA 92093-0230
Phone: (858) 534-2307 FAX: (858) 534-9820 E-mail: droemmich@ucsd.edu

Russ E. Davis
Scripps Institution of Oceanography, La Jolla CA 92093-0230
Phone: (858) 534-4415 FAX: (858) 534-9820 E-mail: rdavis@ucsd.edu

Stephen C. Riser
School of Oceanography, University of Washington, Seattle WA 98195-7940
Phone: (206) 543-1187 FAX: (206) 543-3354 E-mail: riser@ocean.washington.edu

W. Brechner Owens
Woods Hole Oceanographic Institution, Woods Hole MA 02543
Phone: (508) 289-2811 FAX: (508) 457-2181 E-mail: bowens@whoi.edu

Robert L. Molinari
NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami FL 33149
Phone: (305) 361-4344 FAX: (305) 361-4392 E-mail: bob.molinari@noaa.gov

Silvia L. Garzoli
NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami FL 33149
Phone: (305) 361-4338 FAX: (305) 361-4392 E-mail: silvia.garzoli@.noaa.gov

Gregory C. Johnson
NOAA Pacific Marine Environmental Laboratory, Seattle WA 98115
Phone: (206) 526-6806 FAX: (206) 526-6744 E-mail: Gregory.C.Johnson@noaa.gov

Award Numbers: *(NA17RJ1231 (SIO), NA17RJ1223 (WHOI), N00014-01-1-1064 (UW))*

LONG-TERM GOALS

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

By the middle of 2007, Argo will have deployed a global array of 3000 profiling CTD floats (Roemmich and Owens, 2000, Roemmich et al, 2002, Gould, 2004), and established a data system to meet the needs of both operational and scientific users for data delivery in real time and delayed mode. The Argo array will provide unprecedented views of the evolving physical state of the ocean. It will reveal the physical processes that balance the large-scale heat and freshwater budgets of the ocean and will provide a crucial dataset for initialization of and assimilation in seasonal-to-decadal forecast models. Argo is a major initiative in oceanography, with research and operational objectives, providing a global dataset for climate science and other applications. It is a pilot project of the Global Ocean Observing System.

OBJECTIVES

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

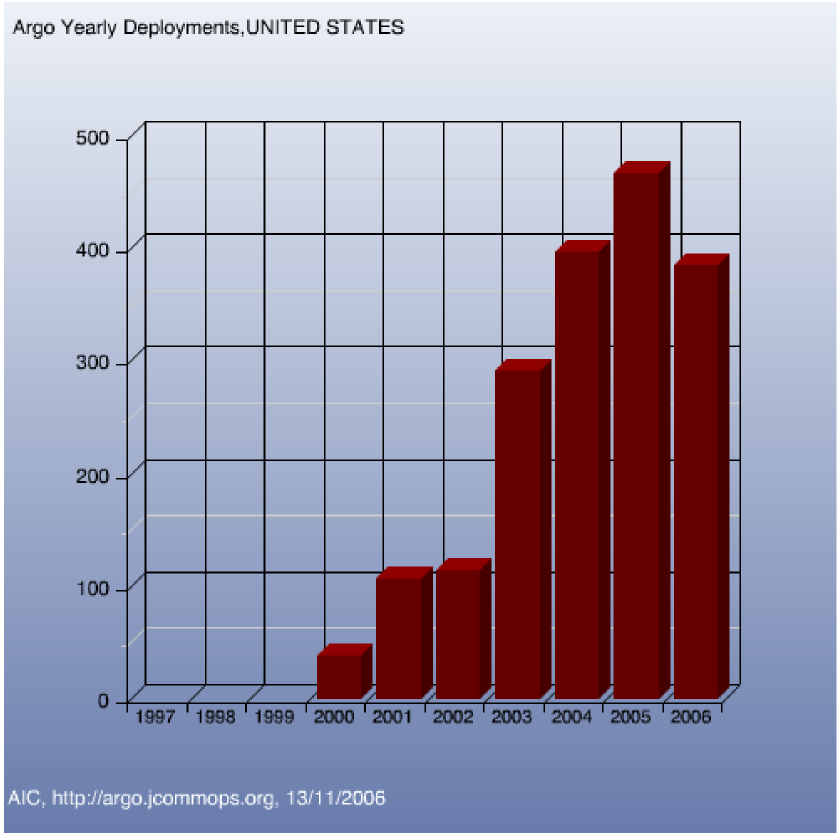

Figure 1: *Yearly deployments of United States Argo floats through October 2006. (As of 8 November 2006, 1313 are active – reporting at least once in the previous 30 days; floats being deployed on a cruise in September/October 2006 are not represented in this figure.)*

APPROACH AND WORK PLAN

Float production and float deployment has been accomplished by four facilities – SIO (D. Roemmich and R. Davis - float production and deployment), WHOI (W.B. Owens – float production)/AOML (S. Garzoli – float deployment), UW (S. Riser – preparation and deployment of commercially manufactured floats), and PMEL (G. Johnson – deployment of commercially manufactured floats). This distributed effort has been designed to safeguard the US contribution to the Argo project from unforeseen problems at any one component institution. It also makes Argo success independent of the participation of any individual PI and institution or of any single float design. It allows the large amount of effort to be shared. It encourages individual, technical innovation and enhancement. While the initial focus has needed to be on improving float performance, attention of the PIs will increasingly focus on exploiting the scientific value of Argo. The data system is also distributed, but by function rather than for load-sharing. AOML (R Molinari) is the national Argo data center, responsible for acquiring the float data received by satellite communications, for carrying out real-time quality control, and for distribution of data via the GTS and to the Global Argo Data Assembly Centers. The second step in data management is a semi-automated recalibration of the salinity sensor carried out by PMEL (G. Johnson), using a high quality temperature/salinity climatology for comparison with float temperature/salinity data (Wong et al, 2003). The final step is individual examination of all profiles by the float-providing PIs, in order to provide high-quality data suitable for research applications. US Argo PIs are involved in all of these components.

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

WORK COMPLETED

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

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

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

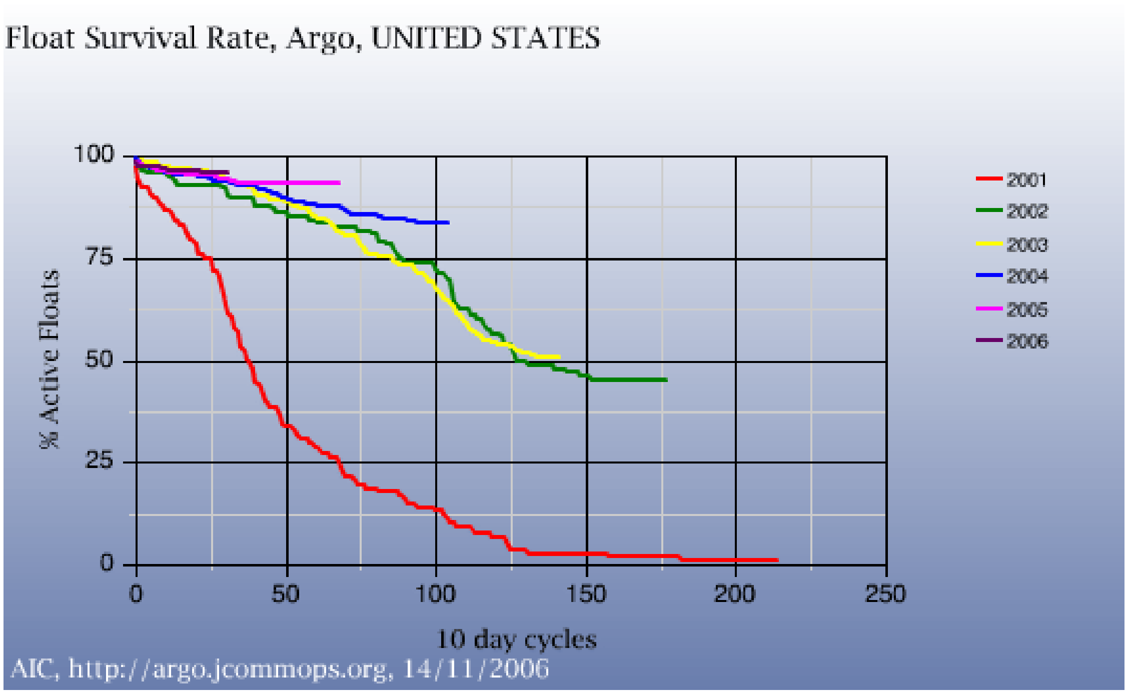

Figure 2: *Float Reliability*

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

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

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

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

The US is the technology leader in profiling floats, and these technical improvements have been shared with international partners. 85% of all of the present Argo array is made up of floats manufactured in the USA.

The consortium plays strong leadership roles in the international Argo project. In the past year this support has included the employment of Dr. John Gould as Argo Director, working closely with Dr. Dean Roemmich (Argo Science Team Chairman). US consortium members provide coordination for deployment planning in the Pacific, Atlantic, and Southern Oceans.

RESULTS

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

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

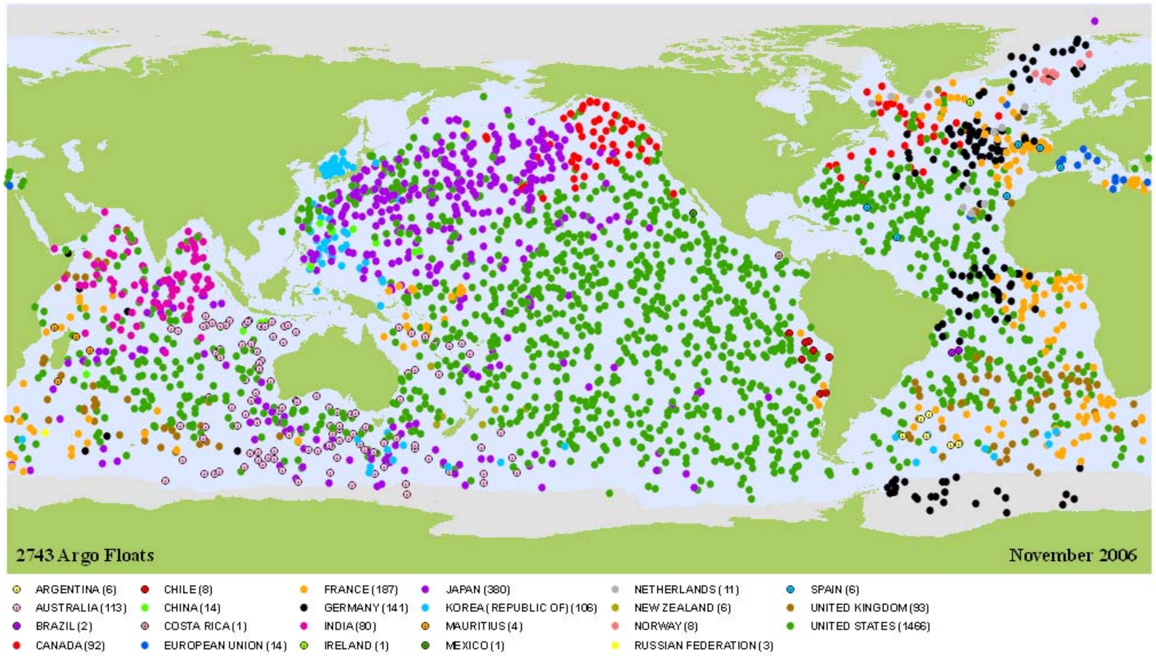

Figure 3: *The Argo Array as of 30 November 2006 (US floats in Green)*

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

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

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

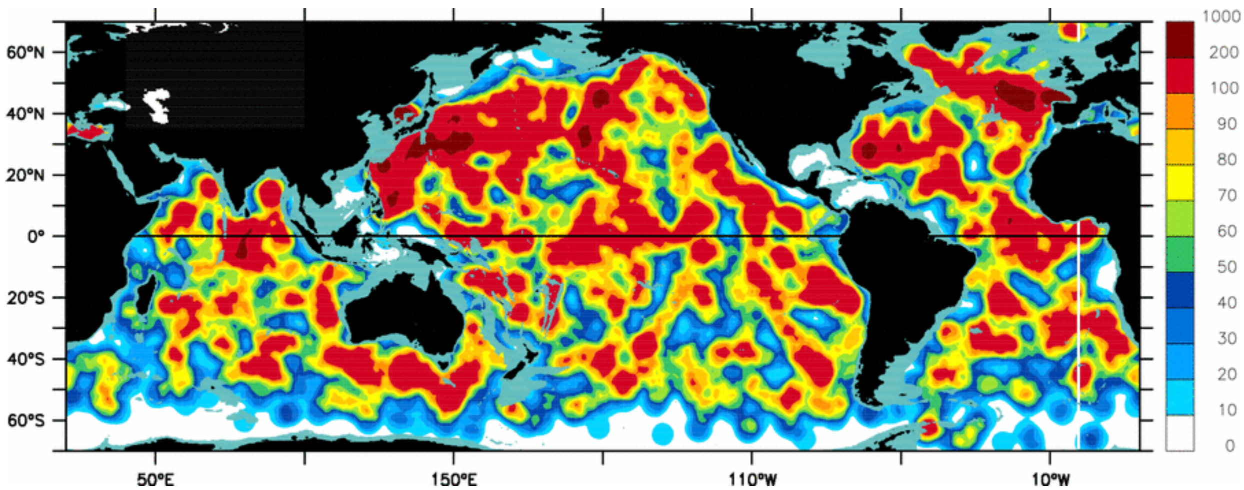

Figure 4: *Worldwide density distribution of the Argo profiling floats based on a global array of 3000 floats on a 3° x 3° grid.*

Argo's uniform distribution provides the ideal complement to satellite altimetry data (Willis et al, 2003) so as to address the issues of global heat and fresh water storage and sea level rise and for data assimilation into global models. Recent work (Lyman et al, 2006) has combined Argo profile data with other, in situ data to identify a global cooling of the upper ocean (Figure 5). This appears to be a robust signal present in both Argo data and other data. Argo data are being used to identify spatial distribution and processes associated with this cooling (D. Roemmich, personal communication).

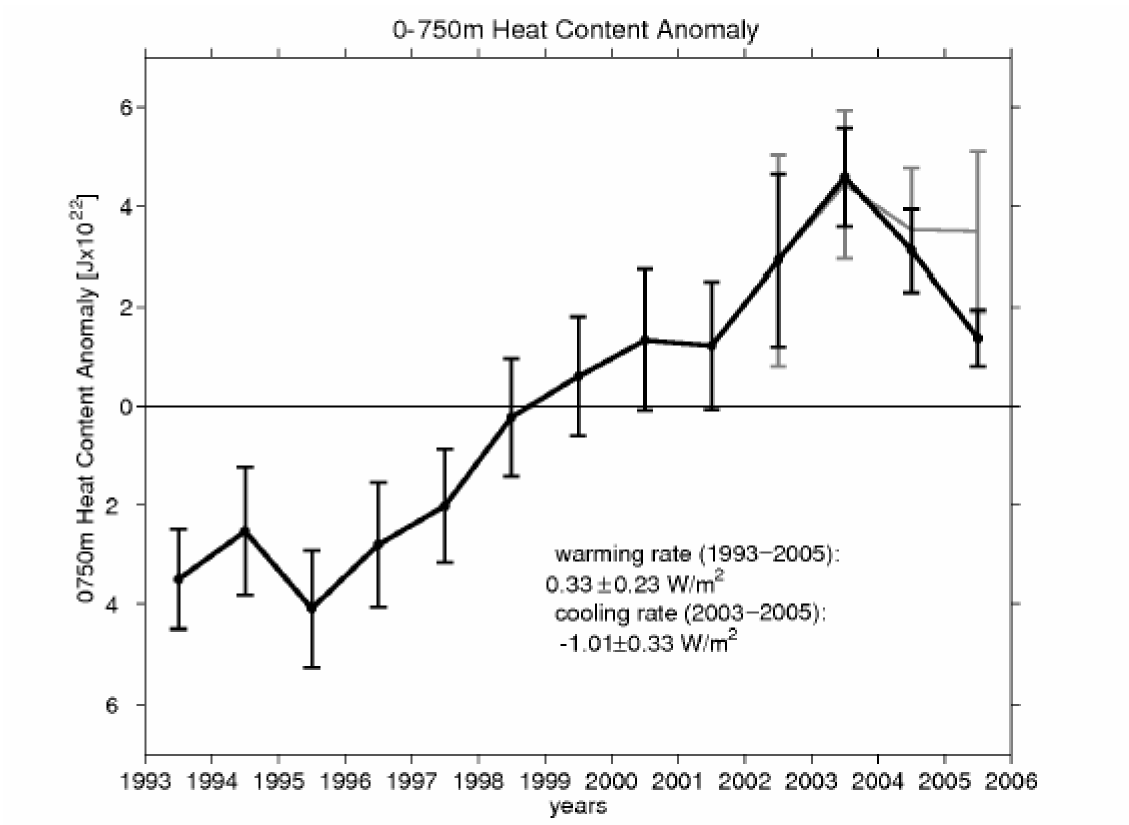

Figure 5. *Globally averaged annual Ocean Heat Content Anomaly (OHCA) [10^{22} Joules] in the upper 750 m estimated using in situ data alone from 1993 through 2005 (black line) and using in situ data excluding profiling floats (gray line). Error bars reflect the standard error estimates discussed in Section 3. Linear trends are computed from a weighted least square fit and reflect the OHCA estimate made using all available profile data. Errors for inset linear trend estimates are quoted at the 95% confidence interval (Lyman et al, 2006).*

IMPACTS, APPLICATIONS, AND TRANSITIONS

National Security

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

Economic Development

The Global Ocean Data Assimilation Experiment (GODAE) has identified a number of applications with substantial economic impacts arising from ocean observations, including improved seasonal-to-interannual (S-I) forecasting, state estimation (now-casting), and coupled physical/biological modeling (e.g., for fisheries). The El NiZo/Southern Oscillation (ENSO) Observing System in the tropical Pacific has demonstrated over the past decade that economic gains in energy, agriculture, and insurance sectors are possible from successful seasonal forecasts. Improvement in S-I forecasting is expected as the tropical observing system is extended and expanded to global coverage, and Argo plays a key role in that expansion.

Quality of Life

Argo is central to an unprecedented capability for global assessment of the evolving climate state of the ocean. The thermal structure of the upper ocean controls the temperature of the lower atmosphere, and is the primary variable defining the physical environment of ocean ecosystems. Over 90% of the increased heat content due to global warming of the air/sea/ice climate system in the past 40 years occurred in the oceans. Climate stresses on ocean ecosystems have serious consequences, and sometimes dramatic ones, such as coral reef bleaching. In the future, the impacts of a varying climate on the health of the seas and coastal ecosystems will become an increasingly important aspect of resource management. The unique niche of the Argo array is to provide global broadscale observations of the upper ocean.

Science Education

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

RELATED PROJECTS

GODAE: The Global Ocean Data Assimilation Experiment uses satellite and in situ ocean datasets in data assimilation models for practical applications. Argo plays a special role in GODAE because it is the only globally repeating subsurface ocean dataset, and is strongly complementary to its satellite counterparts. GODAE's vision is "A global system of observations, communications, modeling and assimilation, that will deliver regular, comprehensive information on the state of the oceans, in a way that will promote and engender wide utility and availability of this resource for maximum benefit to the community" (http://www.bom.gov.au/bmrc/ocean/GODAE/).

CLIVAR: (Climate Variability and Predictability experiment of the World Climate Research Program). Argo provides a primary ocean dataset for this experiment targeting better understanding of the climate system, including its variability and predictability. (See http://www.clivar.org.) CLIVAR's aim is to exploit the research value of broadscale climate observations and focused process experiments. In this context, Argo measures the storage and transport of heat and freshwater globally on broad spatial scales.

Global CO_2 Flux Map Project: Argo provides near surface salinity and temperature to the NOAA Office of Global Programs funded project directed at providing global maps of CO_2 surface fluxes. The float data will be used in algorithms (developed from pCO_2 observations) that provide estimates of surface carbon fluxes from surface salinity and temperature data.

US Argo Consortium RELEVANT WEB SITES:
Argo Science Team home page http://www-argo.ucsd.edu
Argo Information Center http://argo.jcommops.org
Scripps Institution of Oceanography http://sio-argo.ucsd.edu
Woods Hole Oceanographic Institution http://ursa.whoi.edu/~argo/
University of Washington http://flux.ocean.washington.edu/argo/
NOAA PMEL http://floats.pmel.noaa.gov/argo
NOAA PMEL(Delayed Mode QC)) http://www.aoml.noaa.gov/phod/ARGO/HomePage/
NOAA PMEL (General) http://floats.pmel.noaa.gov/floats
US GDAC http://www.usgodae.org

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.

Davis, R.E., J.T. Sherman and J. Dufour, 2001. Profiling ALACEs and other advances in autonomous subsurface floats. Journal of Atmospheric and Oceanic Technology, 18, 982-993.

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.

Lyman, J. M., J. K. Willis, and G. C. Johnson, 2006. Recent cooling of the upper ocean. Geophysical Research Letters, 33, L18604, doi: 10.1029/2006GL027033.

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.

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

OTHER REFEREED PUBLICATIONS:

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