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

Report on Progress in FY09, October 1, 2008 – September 30, 2009

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LONG-TERM GOALS

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 3 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).

OBJECTIVES

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_o spacing, to increase the mean lifetime of floats to 4 years, to operate the near-real time and delayed-mode data systems consistent with international agreements, and to provide substantial leadership and coordination roles for international Argo.

Phase 4 of US Argo is a follow-on 5-year project (7/06 – 6/11) aimed at improving and sustaining the US component of Argo. Float deployment rates should average around 400 per year. Objectives are to 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.

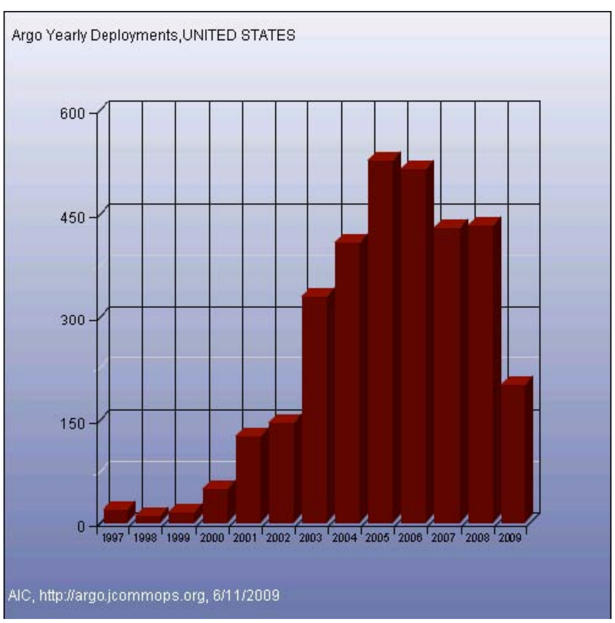


Figure 1: *Yearly deployments of United States Argo floats through 06 November 2009 (including Argo-equivalent), and growth in the number of active US floats. (Source:AIC)*

APPROACH AND WORK PLAN

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).

WORK COMPLETED

The goal of 1500 active US Argo floats has been achieved (Fig 2). As of September 2009 there are 1761 active US Argo Program floats, plus 83 US Argo-equivalent instruments that also feed data to the US Argo DAC. Floats are presently being deployed at a rate of 360 per year. The increase in float

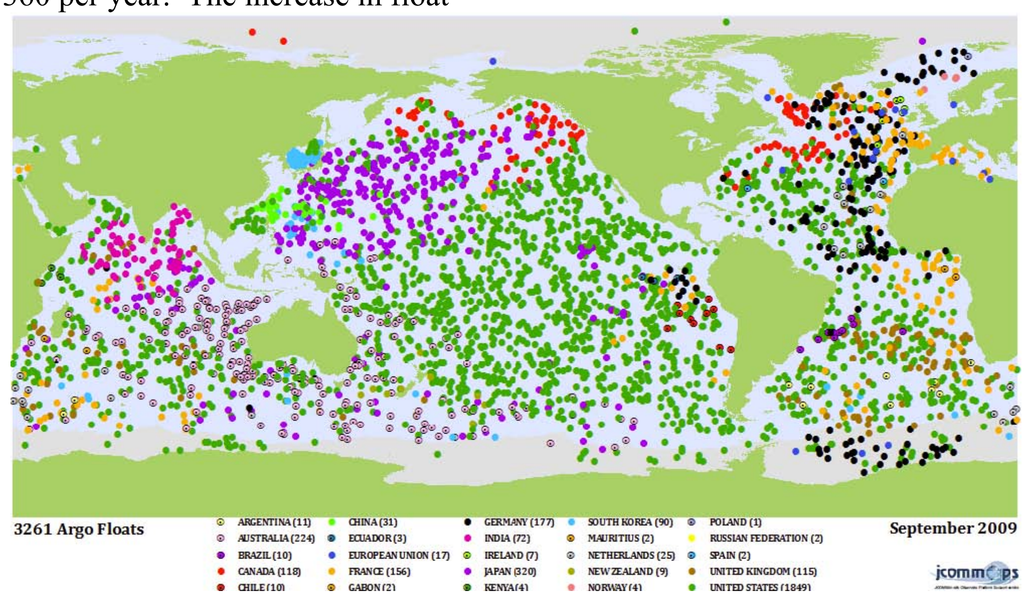


***Figure 2**: The Argo Array as of 30 September 2009. The 1849 active US floats (Green), included 1761 floats funded via US Argo, and 83 other US (Argo-equivalent) floats whose data are released by the PIs via the US Argo Data Assembly Center.*

deployments that occurred in 2005-2007 was the result of a hiatus in float production in 2001-2003 to address problems leading to high, premature failure rates. Those floats were deployed beginning in 2004. It is not possible to deploy a global array entirely with opportunistic use of research vessels and commercial ships, and so chartered vessels are used to deploy some floats in the South Indian and South Pacific Oceans (description follows). Of the 1849 active US Argo floats, 1183 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 700 deployments since 2004 in remote ocean locations by NIWA's R/V Kaharoa.

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. Floats deployed in 2007 and 2008 exhibit a slightly higher failure rate due to a problem in CTDs manufactured by Sea-Bird Electronics – see next section. The re-design of the SOLO float (SIO) in order to attain increased lifetime and capabilities has been completed. A prototype SOLO-II float has been deployed twice for short periods and will soon be redeployed in an accelerated testing program. 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.

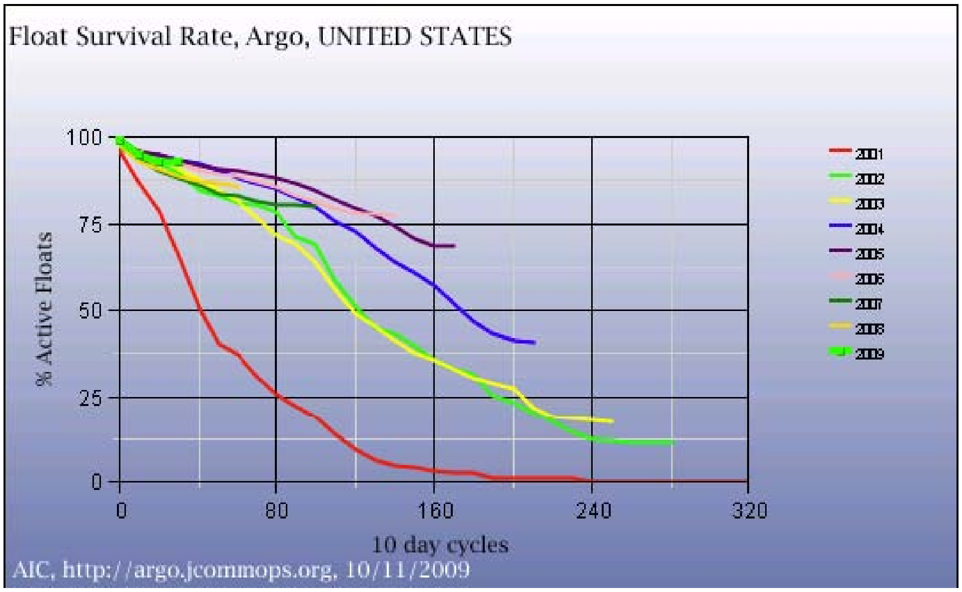


Figure 3: *Float reliability. Note that the percentage of floats surviving for at least 100 cycles increased from about 65% for 2002/03 deployments to about 85% for 2005 deployments.*

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

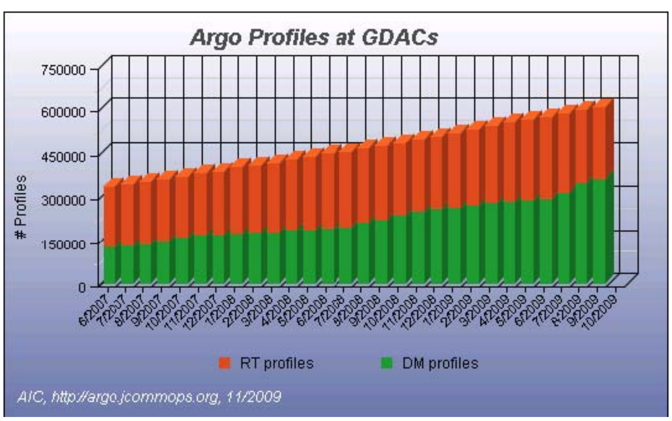
CTD RECALL

In May of 2009, Sea-Bird Electronics issued a recall of all CTDs used on Argo floats worldwide. An update of that recall was circulated in October 2009 and is attached as Appendix I. The problem has been identified as "micro-leaks" in the pressure transducer, manufactured by Druck Industries as early as 2006, used in the CTDs. Appendix I provides data on the possible extent of the impact of the defect as affecting possible 3% of the CTDs provided before 2007 and increasing since. Argo float providers have reanalyzed float data for possible indications of this failure that might have been attributed to other causes and these analyses suggest that the 30% level stated in Appendix I may be the case for the post-2007 CTDs. One of the problems in identifying this failure mode is that it may take up to nearly two years to manifest itself. Appendix I acknowledges the contribution that the University of Washington made to the impact of the problem. The University of Washington also played a critical role in identifying the problem.

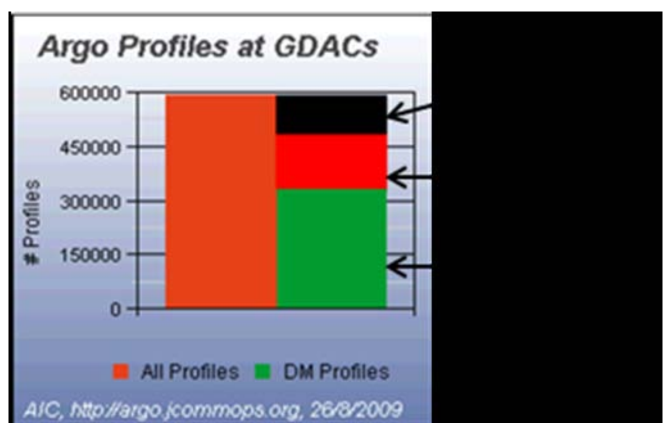
This recall has resulted in a hiatus in the shipment of CTDs and, thus, the provision of profiling floats by the instrument manufacturers. The eventual impact on the deployment of floats in 2009 and 2010 has yet to be determined. Appendix I makes reference to a small number of pressure transducers manufactured by Paine Industries that were used in CTDs prior to 2001 that Sea-Bird was able to make available for upcoming cruises. These transducers had a significant but quantifiable pressure drift that did not result in complete failure of the CTD. The Argo Science Team evaluated deployment opportunities and their requirements for CTDs and provided their evaluation as to the distribution of CTDs to the Argo Program to Sea-Bird. Their highest priority was to provide CTDs for being deployed during unique or one-time only cruises in difficult regions to access using research and/or vessels of opportunity. Sea-Bird has provided CTDs with pressure transducers used previously, transducers that have been determined to be "good" manufactured by Druck Industries, and transducers provided the new supplier – Kistler. Float providers are reluctant to move to the Kistler transducer in large numbers until a thorough evaluation of the performance of the CTDs with this transducer on deployed instruments can be made. This will take several years. The U.S. program has received enough CTDs to support a float deployment in the South Indian Ocean in November 2009 – January 2010.

RESULTS

A sparse global Argo array was achieved in 2004, and so there are now nearly 4 years of continuous global coverage. In 2006, Argo provided over 90,000 high quality profiles of temperature and salinity, most to 2,000 meters, homogeneously distributed over the global ocean, without seasonal bias. Beginning in 2007, more than 100,000 profiles a year are being received with 91% being distributed on the GTS within 24 hours of collection (U.S. – 96% within 24 hours), and approximate 96% available within 72 hours via the GTS and Internet. Figure 4 shows the growth of profiles available at the GDACs since June 2007 and the status of the Delayed-Mode Quality Control processing as of August 2009.



(a) Monthly statistics of profiles at the GDACs from June 2007 through September 2009.



(b) Status of the Delayed-Mode Quality Control (DMQC) processing as of August 2009.

Figure 4: *Argo Profiles at the Global Data Assembly Centers (GDACs)*

Because of the need to obtain extended data records to assess instrument drift, profiles are considered "eligible for DMQC when a one-year record has been obtained from the instrument. As of this report, approximately 67% of the total number of profiles eligible for DMQC processing have been processed. The U.S. has processed approximately 80% of its eligible profiles. DMQC processing is a labor intensive process. Three different software routines have been published and been used to process profiles in an automated mode, however, a large fraction (80% or so) have to be manually inspected to determine if a signal represents sensor drift or represents changing water masses. Assessing water mass changes requires inspection of the T-S profiles, an understanding of the dynamics of the region, and often access to other datasets such as high-quality, shipboard CTDs.

One major impact of Argo has been in the amount of data now being received from the Southern Hemisphere, more than half of the ocean. A number of factors, many related to the geographic isolation of the Southern Ocean and lack of population in the southern hemisphere contribute to the lack of data from the Southern Hemisphere. Opportunities for the collection of routine observations is limited to a very few, major shipping routes in the tropics and subtropics. Observations in high latitudes are generally limited to research programs occurring at irregular frequencies and Antarctic research and supply vessels which transit specific routes. Very few observations are taken during the Austral winter, with those that are, taken north of 30º S.

Figure 5 presents the temperature profile data received by the Coriolis Operational Oceanography Center Data Service in Brest, France which is also one of the Argo GDACs (the other being at the Fleet Numerical Meteorology and Oceanography Center in Monterey, California). The data are from January (Austral summer) and July (Austral winter) 2009, months with an equal number of days. The number of Argo profiles delivered is over 4,200 in both periods, relatively uniformly distributed except south of 60º S, the region subject to seasonal ice cover (Argo floats can operate under ice, storing profiles for later transmission). The number of XBT plus CTD profiles drops 900 to 400 between summer and winter with virtually no profiles south of 30º S (there are a few off Perth, Australia). This means that any operational ocean model would lack any in situ temperature profile data from a vast portion of the ocean during the Austral winter if not for Argo data. Even in the Austral summer, there would only be around 30 temperatures profiles a day, on average, from the Southern Hemisphere ocean if not for Argo.

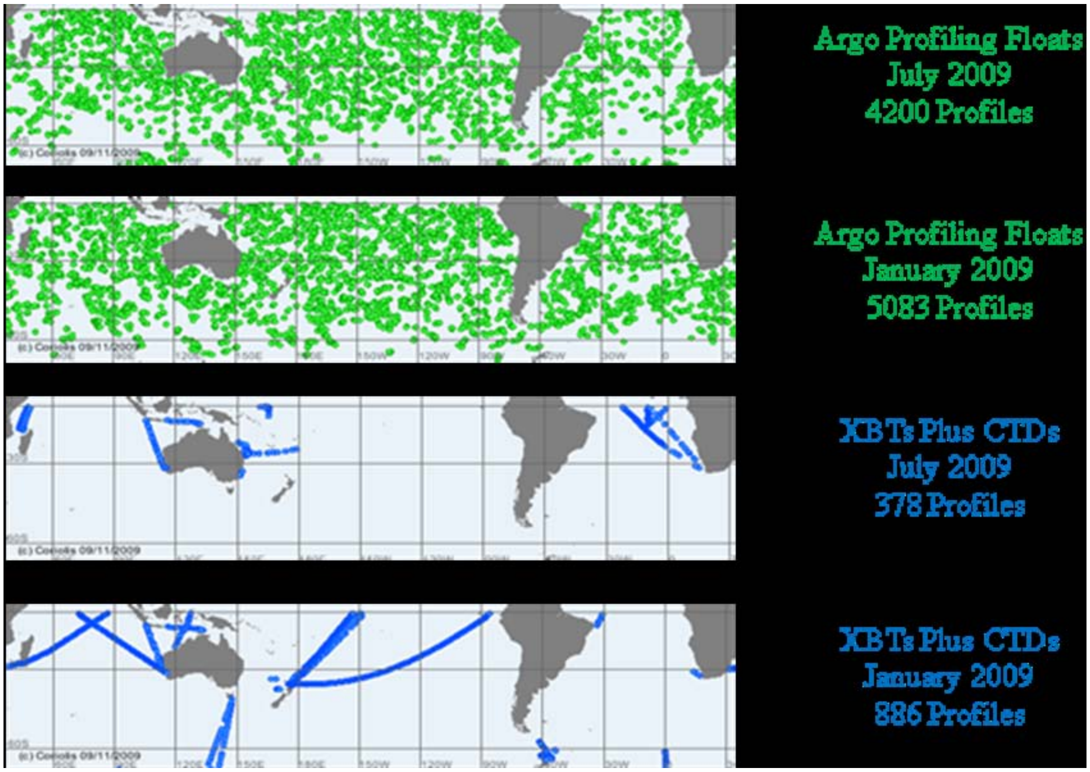


Figure 5: *Profiles from the Southern Hemisphere received at the Coriolis Data Service*

Globally Argo provides approximately three times as many temperature profiles in a year as XBTs plus CTDs received at Coriolis. XBTs account for about 70% of the total profiles received. The major portion of the XBT profiles are to 750 meters while CTD data often goes to 2,000 meters and deeper and includes salinity data. With only four years of global coverage, as of the end of 2008 Argo data provide 20% of all the temperature profiles from the Southern Hemisphere in the World Ocean Database, 43% of all the salinity profiles and 62% of all the salinity profiles below 500 meters in the Southern Hemisphere.

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.
The 4-year global dataset provides a baseline of the present climate-state of the oceans 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. Figure 6 is a plot of the global averages of T, S, and σ_θ minus the average of these parameters from World Ocean Atlas 01. With 4-years of data we have, for the first time, a stable estimate of the mean of the global ocean over a fixed period of time.

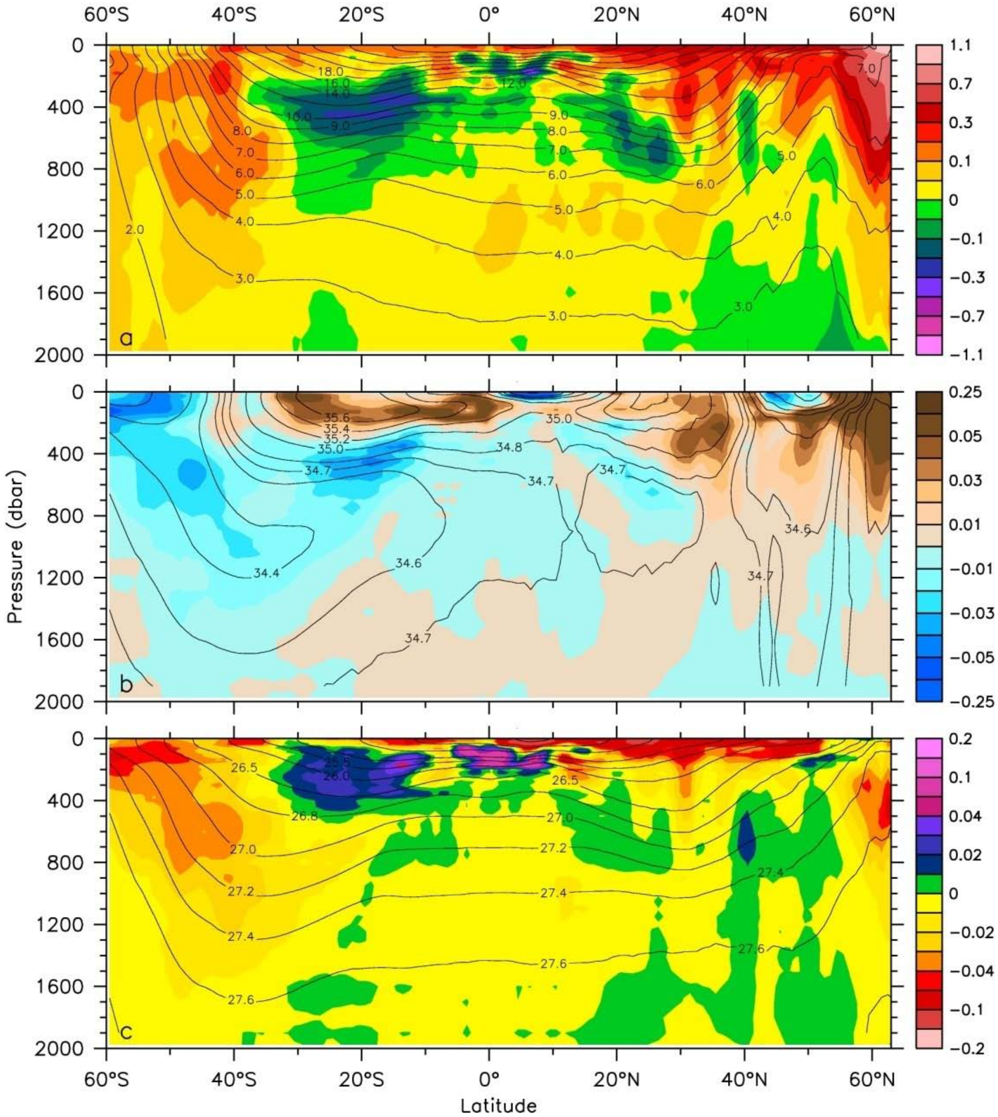


Figure 6: *Zonal averages of (top to bottom) T, S, and σθ from Argo (contours), and the Argo- minus-WOA01 differences (colors).*

These data indicate that (1) the southern hemisphere ocean is warmer and fresher in the Argo era than in WOA01; (2) the northern hemisphere is warmer and saltier; (3) heat gain is dominated by the southern hemisphere (because of a larger area); (4) surface layer stratification is increased; and (5) the Argo ocean is fresher in high rainfall regions, saltier in regions of high evaporation (indicating a global increase in the cycle of evaporation and precipitation.

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. Operational centers have noted that the use of Argo data has had positive impacts in all the above applications .

About 535 research publications have resulted so far from Argo data, including 172 in 2008-2009 (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 U.S. Argo to building, sustaining, and utilizing the array.

IMPACT, 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 Niño/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 80% of the increased heat content due to global warming of the air/sea/ice climate system in the past 50 years occurred in the oceans (Levitus *et al.*, 2001). Climate stresses on ocean ecosystems have serious consequences, and sometimes dramatic ones, such as coral reef bleaching. Conversely the ocean can impact the atmosphere even on short time-scales such as through intensification of tropical cyclones. 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 OceanView: GODAE OceanView follows on from an experiment (Global Ocean Data Assimilation Experiment – GODAE) towards a long-term International Programme for Ocean Analysis and Forecasting. Argo plays a special role in GODAE OceanView because it is the only globally repeating subsurface ocean dataset, and is strongly complementary to its satellite counterparts. GODAE OceanView will provide coordination and leadership in: "(1) consolidating and improving global and regional analysis and forecasting systems (physics); (2) the progressive development and scientific testing of the next generation of systems covering biogeochemical and ecosystems and extending from the open ocean into the shelf sea and coastal waters; (3) the exploitation of this capability in other applications (weather forecasting, seasonal and decadal prediction, climate change detection and its coastal impacts, etc); and (4) assessing the contribution of the various components of the observing system and scientific guidance for improved design and implementation of the ocean observing system" (http://www.godae.org/oceanview.html) .

CLIVAR: (Climate Variability and Predictability program of the World Climate Research Project). 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.

GOOS: (Global Ocean Observing System, see http://www.ioc-goos.org): "GOOS is a permanent global system for observations, modeling and analysis of marine and ocean variabiles to support operational ocean services worldwide. GOOS provides accurate descriptions of the present state of the oceans, including living resources, continuous forecasts of the future conditions of the sea for as far ahead as possible, and the basis for forecasts of climate change." As the only subsurface ocean element of GOOS with global extent, Argo plays a key role.

Global CO2 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 CO2 surface fluxes. The float data will be used in algorithms (developed from pCO2 observations) that provide estimates of surface carbon fluxes from surface salinity and temperature 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

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

Over 525 research publications have resulted so far from Argo data (see above link), including 54 in the first half of 2009. These publications span a wide variety of research topics from small spatial-scale/short time-scale phenomena such tropical cyclone intensification, to studies of mesoscale eddies, to large-scale phenomena such as water mass variability, basin-scale ocean circulation, and climate change. Almost none of this work would have been possible without the contributions of US Argo to building, sustaining, and utilizing the global Argo array.