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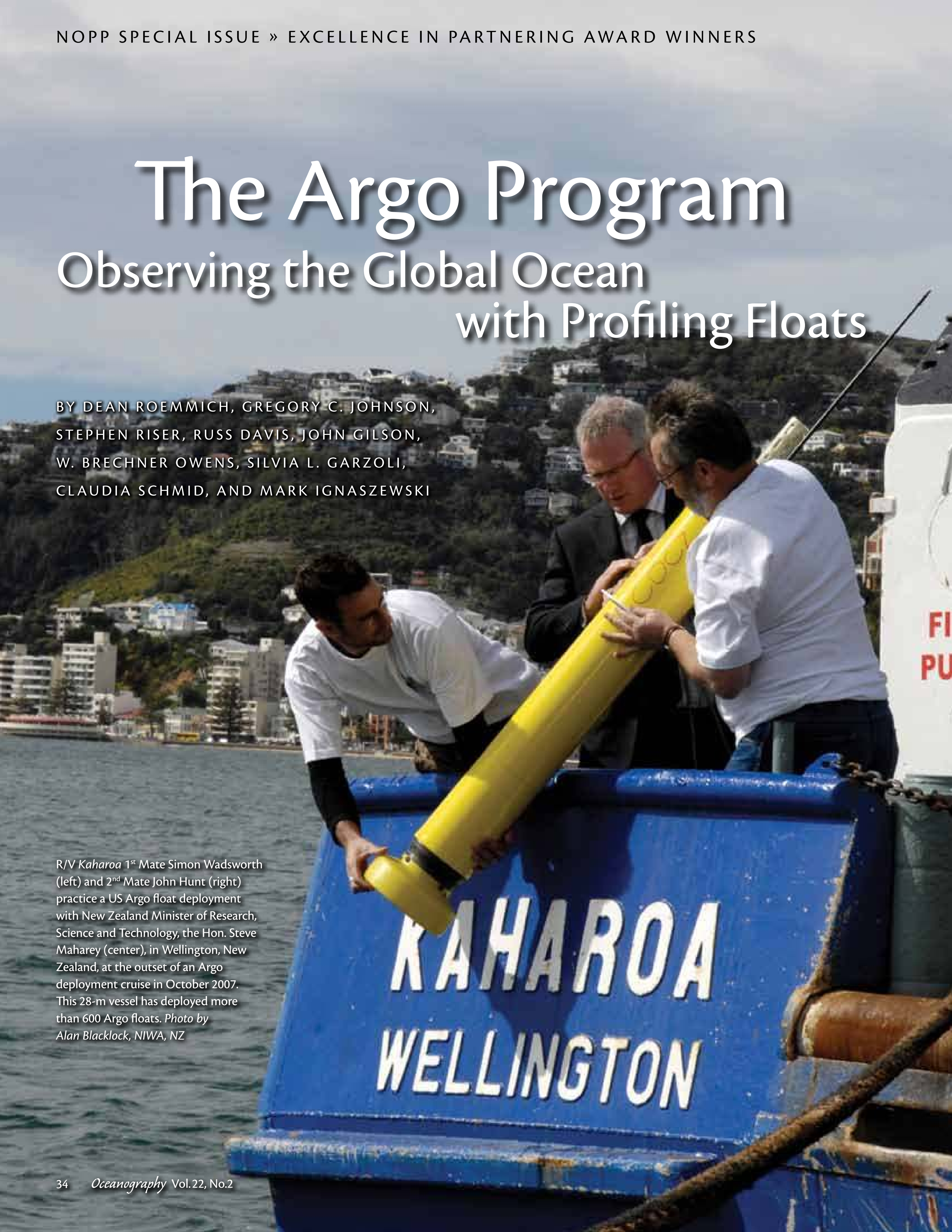
The Argo Program

Observing the Global Ocean with Profiling Floats

BY DEAN ROEMMICH, GREGORY C. JOHNSON, STEPHEN RISER, RUSS DAVIS, JOHN GILSON, W. BRECHNER OWENS, SILVIA L. GARZOLI, CLAUDIA SCHMID, AND MARK IGNASZEWSKI



R/V *Kaharoa* 1st Mate Simon Wadsworth (left) and 2nd Mate John Hunt (right) practice a US Argo float deployment with New Zealand Minister of Research, Science and Technology, the Hon. Steve Maharey (center), in Wellington, New Zealand, at the outset of an Argo deployment cruise in October 2007. This 28-m vessel has deployed more than 600 Argo floats. *Photo by Alan Blacklock, NIWA, NZ*

ABSTRACT. The Argo Program has created the first global array for observing the subsurface ocean. Argo arose from a compelling scientific need for climate-relevant ocean data; it was made possible by technology development and implemented through international collaboration. The float program and its data management system began with regional arrays in 1999, scaled up to global deployments by 2004, and achieved its target of 3000 active instruments in 2007. US Argo, supported by the National Oceanic and Atmospheric Administration and the Navy through the National Oceanographic Partnership Program, provides half of the floats in the international array, plus leadership in float technology, data management, data quality control, international coordination, and outreach. All Argo data are freely available without restriction, in real time and in research-quality forms. Uses of Argo data range from oceanographic research, climate research, and education, to operational applications in ocean data assimilation and seasonal-to-decadal prediction. Argo's value grows as its data accumulate and their applications are better understood. Continuing advances in profiling float and sensor technologies open many exciting possibilities for Argo's future, including expanding sampling into high latitudes and the deep ocean, improving near-surface sampling, and adding biogeochemical parameters.

INTRODUCTION

Autonomous profiling floats are a transformative technology for oceanography, enabling continuous, real-time subsurface observations of the global ocean and complementing satellite observations of the sea surface. The implementation of a global float array, named Argo to emphasize its synergy with the Jason satellite altimeter, began in 1999. The National Oceanic and Atmospheric Administration (NOAA) and the Navy, via the National Oceanographic Partnership Program (NOPP), forged the multi-institutional US Argo consortium. US Argo joined with over 20 international partners to deploy the global Argo array and implement its data management and quality control systems. The US consortium's focus on technology development has produced increasingly rugged and long-lived profiling floats with greater capabilities. In November 2007, Argo achieved the international target of 3000 active floats with a data system providing open access to the complete data set. About 90% of Argo profiles are available within 24 hours of collection.

Argo's user community includes operational centers engaged in ocean state estimation and seasonal-to-decadal prediction, plus diverse ocean and climate researchers. As the only global subsurface ocean network, and because it strongly complements satellite and regional in situ ocean observations, Argo is a key element of the Global Ocean Observing System (GOOS), the World Climate Research Program (WCRP) Climate Variability and Predictability (CLIVAR) project, and the Global Ocean Data Assimilation Experiment (GODAE). In 2007, Argo was recognized as a major success of the Global Earth Observation System of Systems (GEOSS).

Argo has progressed greatly in the decade between conception and achieving initial targets for global sampling and data management. The array's value is being recognized, along with the need to sustain Argo into the future. Nevertheless, Argo faces a challenging road ahead. Further improvements in data quality, uniformity, and delivery of delayed-mode data are of highest importance. Float deployments in the remotest ocean regions are increasingly costly. Finally, the expansion of the Argo Program into new domains, disciplines, and applications requires a review of the consensus on design and objectives, and also a matching multinational commitment to continue building Argo toward its potential.

The Argo Program is perhaps the most internationally collaborative effort in the history of oceanography. The array could not have been implemented and cannot be sustained without broad multinational participation. However, for this NOPP special issue, the focus will be on US Argo's unique contributions and the NOPP US Argo partnership. We gratefully acknowledge the large and essential contributions of our international partners while describing Argo's brief history, its present status, and its future evolution from a US perspective.

ARGO IMPLEMENTATION

Beginnings

Argo's first key ingredient was new enabling technology. By 1997, the autonomous profiling float's capability for global temperature/salinity/velocity measurements (Davis et al., 2001) had been demonstrated during World Ocean Circulation Experiment (WOCE) deployments. This instrument was built on earlier float technology (Gould, 2005) but was a revolutionary advance because it made collection and real-time reporting of high-quality ocean data possible anywhere and anytime, without the presence of a ship or mooring.

The second key ingredient was a scientific requirement for global observations of the physical state of the ocean. The WOCE and Tropical Ocean Global Atmosphere (TOGA) experiments, as well as other already established observing systems (e.g., tide gauge, expendable bathythermograph, and surface drifter networks) demonstrated that the ocean plays important roles in the climate system and its variability. By 1998, satellite altimetry was revolutionizing the study of climate variability patterns in sea surface height (SSH), such as that of El Niño, and a spatially resolved global trend of increasing SSH was emerging (Nerem et al., 1997). Systematic subsurface ocean measurements were needed to complement and interpret satellite observations. To meet this need, an initial plan for a 3000-float global Argo array (Roemmich et al., 1999) was endorsed by the CLIVAR project and by GODAE.

The final ingredient was the international Argo partnership, including both the scientific community and the government agencies needed to support Argo implementation. NOAA played a central role by engaging partner agencies in Europe, North America, Asia, and Australia to join the international effort and by supporting US Argo through NOPP. The international Argo Science Team (AST, later renamed the Argo Steering Team) held its initial meeting in March 1999 to begin planning Argo implementation. The AST decided that all Argo data would be publicly available without restriction, a policy that has aided Argo's international growth and acceptance enormously.

Although the scientific benefits of a global Argo array were clear from the outset, no one knew whether the effort to create it would succeed. Enormous hurdles existed, including the cost, the scalability of float technology, and the feasibility of global deployment.

Pilot Arrays

The first regional Argo deployments were carried out by Argo Australia in the Indian Ocean in late 1999. All of the national Argo programs were initially modest in size, gaining experience with float technology and data by deploying regional arrays totaling a few hundred floats. During 2001, 294 floats were deployed (Figure 1), with arrays taking shape in the tropics, the North Atlantic and Pacific oceans, and elsewhere.

In 2002, Argo floats were failing earlier than their estimated four- to five-year battery life. Most floats deployed in 2001 failed during their first two years in the water. With short float lifetimes, Argo would not be practical. Major efforts were devoted to identifying problems and correcting them in all float models and sensors. These engineering efforts were dramatically successful (Figure 2). Float lifetimes increased every year. For the years of global Argo deployments, 2004 and later, over 85% of the instruments have remained active after two years. It now appears certain that Argo will meet its target of four-year mean float lifetimes.

Early technical difficulties took about two years to resolve. Meanwhile, national Argo programs scaled up their capacity and gained valuable ocean deployment experience. Argo was also building its data system, including Data Assembly Centers (DACs) that acquire the raw data, subject it to automated quality checks, distribute it on the Global Telecommunications System (GTS), and forward it to the two Argo Global DACs (GDACs) for Internet access.

Global Deployment

Global deployments began in 2004 (Figure 1, middle), and the 869 floats deployed that year exceeded the target of 800 required annually to seed and sustain the array. To achieve cost-effective global

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coverage, Argo's strategy has been to use all kinds of ships opportunistically. Assistance from commercial ships, Antarctic supply vessels, research vessels, training vessels, school vessels, and others keeps deployment costs manageable. In western boundary regions, in the tropics, and at high southern latitudes, floats drift thousands of kilometers from their deployment positions. This drift helps disperse the array. However, the combination of ships-of-opportunity and float dispersion is not sufficient to populate the remotest regions of the globe.

Where there is no inexpensive means for deployments, several Argo nations (e.g., Argentina, Brazil, New Zealand, South Africa, and the United States) have staged deployment cruises and aircraft drops. A partnership between the United States and New Zealand Argo programs has deployed more than 600 floats in the Pacific and Indian Oceans by New Zealand's R/V *Kaharoa* (p. 34 photo and Figure 3). This cost-effective vessel has been critical in seeding the remote and infrequently visited South Pacific Ocean, thus achieving global Argo coverage.

International deployment rates reached 1003 floats in 2005, and the global array increased rapidly from 1500 active floats in late 2004, reaching the 3000-float target in November 2007 and maintaining it since then (Figure 1, bottom). In spite of this celebrated accomplishment, the Argo array is not yet complete. About 200 floats are not transmitting useful profile data due to malfunctions. Other instruments are located in marginal seas or in high-latitude oceans under seasonal ice cover. Although these instruments are collecting valuable data, the Argo design of 3000 floats was based on the open

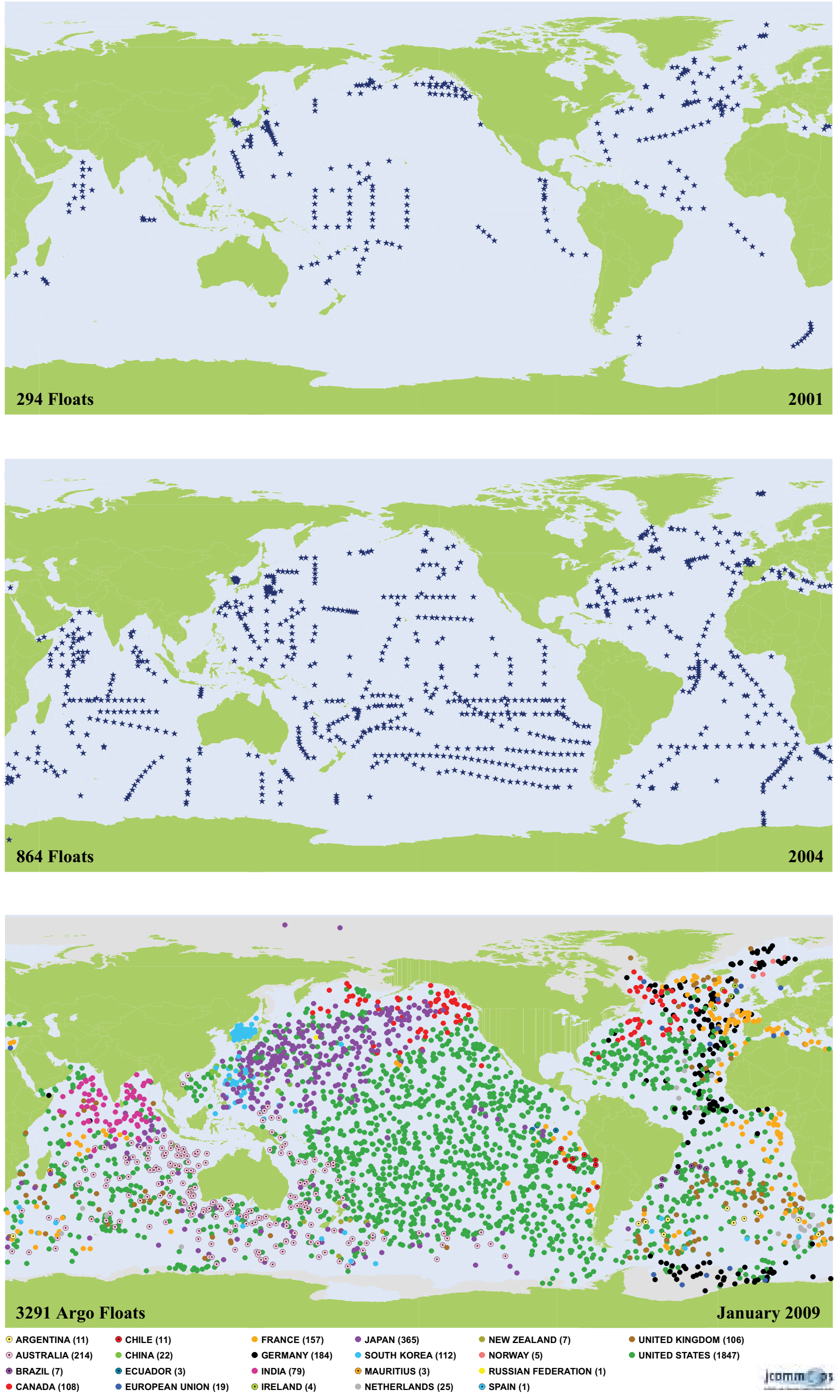

Figure 1. Progression of Argo implementation, from regional pilot arrays to global deployment, illustrated by yearly deployment maps from 2001 (top) and 2004 (middle), plus a recent map showing presently active Argo floats (bottom). *Source: Argo Information Center*

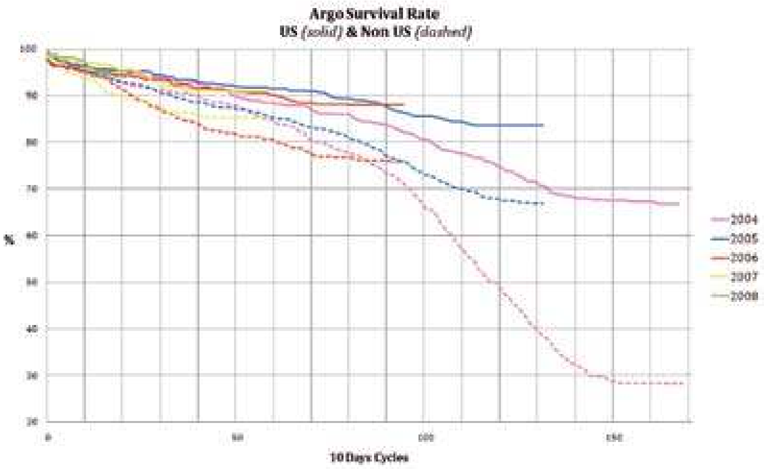

Figure 2. Float survival versus number of 10-day cycles for different deployment years for US Argo instruments (solid lines) and all other programs (dashed lines). *Source: Argo Information Center*

Figure 3. Pre-cruise diagnostic testing of a US Argo SOLO float in Wellington, New Zealand. *Photo by Alan Blacklock, NIWA, NZ*

ocean between 60°N and 60°S. A recent study (Roemmich and Gilson, 2009) found that by late 2008, approximately 2600 active open-ocean floats in this latitude range provided about 7800 high-quality profiles per month. During 2004–2008, there were about 350,000 high-quality open-ocean profiles. In the coming years, technical improvements will increase the number of fully functional floats through correction of problems and longer float lifetimes, if the deployment rate is sustained. However, to complete and maintain the global array, the Argo Program will require increased and long-term commitments from the international Argo partnership.

Data Management

Argo's data management system is operating as planned, with over 90% of profiles being available via the GTS and Internet within 24 hours of collection. US Argo has played a large role in this success, with the US DAC processing more than half of the total volume of international Argo data (Schmid et al., 2007). The US DAC has provided leadership in the development of data-processing guidelines and real-time quality control procedures, and in training and assistance for international partners. In addition, the United States hosts one of the Argo Regional Centers (ARCs) and one of two Argo GDACs. ARCs are involved in quality control, education, outreach, and deployment planning. GDACs serve data and develop interfaces for easy data access.

Argo's delayed-mode system for processing research-quality data from Argo floats is unique. Wong et al. (2003) developed a system that is now used internationally for validating salinity sensor calibrations, and for correcting sensor calibration drift when needed. This semi-automated system enables expert examination of large volumes of profile data. To further improve data quality, Johnson et al. (2007b) quantified sensor response corrections for the Sea-Bird Electronics Inc. conductivity-temperature-depth (CTD) sensors used on most Argo floats. Periodic Argo workshops on delayed-mode processing aid uniform and prompt production of research-quality data by all national programs.

ARGO DATA USES

Argo's most valuable contribution will be its observations of climate-related ocean variability on seasonal to decadal time scales and beyond. To realize this goal, Argo's global coverage must be maintained for decades. Heat and water are the fundamental elements of climate, and the ocean is by far the largest reservoir of both on Earth. Argo observes the storage and large-scale transport of heat and freshwater in the ocean, complementing other parts of the climate observing system.

Over 15 operational agencies around the world ingest Argo data into models for ocean state estimation, short-term forecasting, and seasonal-to-decadal prediction. (See http://www-argo.ucsd.edu for links to all operational centers known to be using Argo data.) In the United States, ocean data assimilation modelers using Argo data include the NOAA/National Center for Environmental Prediction (NCEP), the National Aeronautics and Space Administration (NASA), and the Navy, in addition to academic institutions. Because Argo is the first global subsurface ocean observing system, this work entails model development and testing as well as experimentation with different approaches to maximize the information from Argo and other data sources. Already, operational centers, including NCEP, the European Centre for Medium-Range Weather Forecasts, and the UK Met Office, are reporting improvement in their products due to the impact of Argo data.

The research community has rapidly adopted Argo and is using the data widely. In 2007 and 2008, over 100 Argo-relevant research papers were published each year. This work includes a broad range of studies of water-mass properties and formation, air-sea interaction, ocean circulation, mesoscale eddies, ocean dynamics, and seasonal-to-decadal variability. Argo's open data policy has resulted in the global data set being at the fingertips of researchers around the world. The rapid acceleration in the use of Argo data for research attests to the high demand for climate-relevant ocean data.

Argo data also find valuable applications in tertiary and secondary education. Ocean, atmosphere, and climate science must be an integral part of educational curricula so that tomorrow's adults have a better understanding of the world and its changing climate. Argo and other ocean data sets now afford students desktop explorations of the planet. Early in Argo's development, Pacific island nations, via a regional intergovernmental body (the Pacific Islands Applied Geoscience Commission, or SOPAC), named education as their highest priority among Argo applications. SOPAC, New Zealand's National Institute of Water & Atmospheric Research (NIWA), the United Nations Educational, Scientific, and Cultural Organization, and US Argo are collaborating on development of curricular units using ocean data for regionally relevant examples in the study of climate and sea level. US Argo created display tools for easy viewing of Argo data (Figure 4) by students and other non-experts.

Argo floats are also deployed by students and scientists from developing nations from educational and training vessels, involving them directly in building an ocean observing system for climate. For example, the US-sponsored South Atlantic ARC has conducted training activities in South America and Africa targeting float deployment, data acquisition, and use of the Argo float data. The latest activity, onboard the US Navy's HSV-2 *Swift* in the Gulf of Guinea, gave 24 participants from West Africa hands-on experience with floats, data processing, and interpretation in a historically undersampled region (Figure 5).

Despite Argo's brief history, major findings are emerging from the data. Comparison of Argo with historical data climatologies reveals a global pattern of multidecadal ocean warming (Roemmich and Gilson, 2009) as well as continuing surface (Johnson and Lyman, 2008) and subsurface salinity changes that are consistent with an acceleration of the hydrological cycle. Argo's unprecedented coverage of the Southern Ocean is showing large globe-circling increases in heat content and changes

> “ARGO'S MOST VALUABLE CONTRIBUTION WILL BE ITS OBSERVATIONS OF CLIMATE-RELATED OCEAN VARIABILITY ON SEASONAL TO DECADAL TIME SCALES AND BEYOND.”

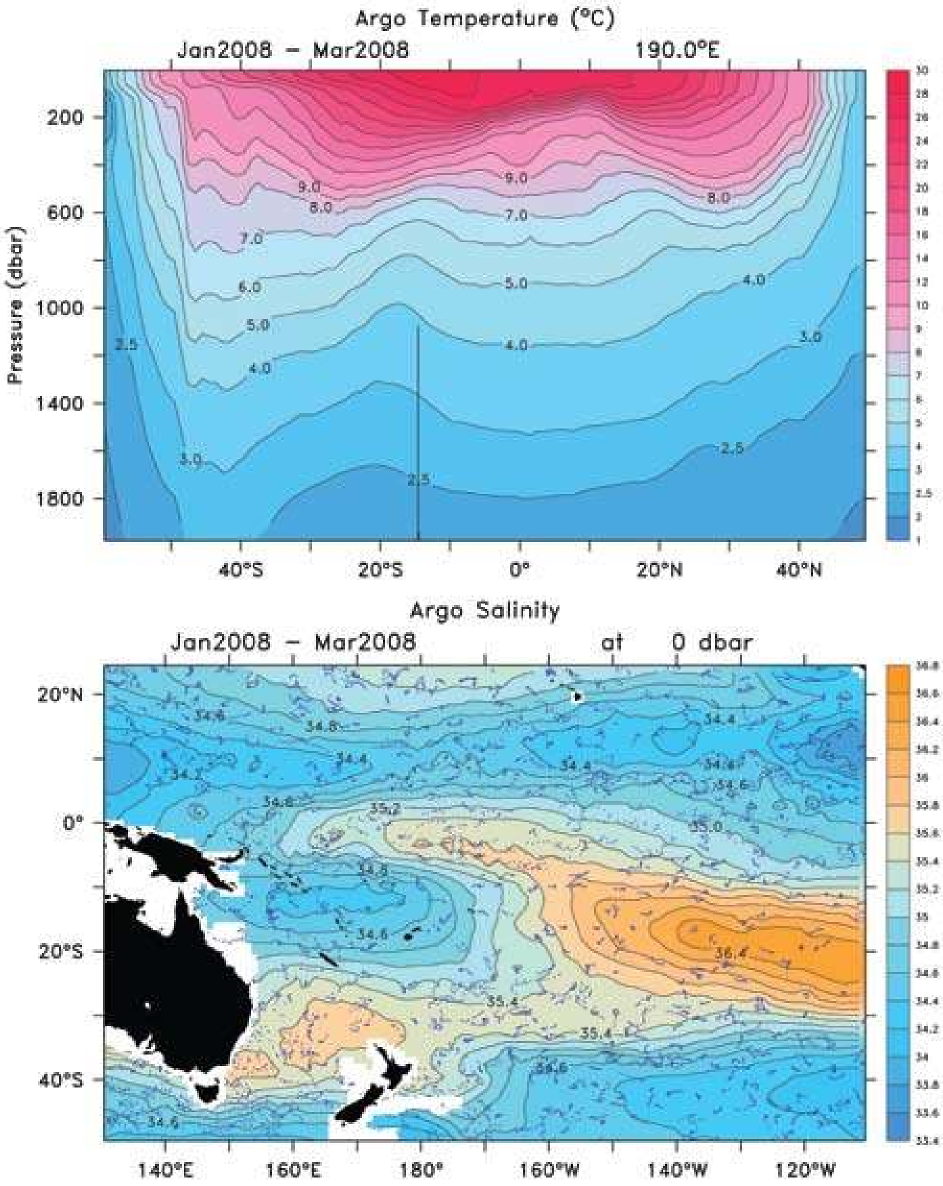

Figure 4. Temperature along 170°W (top) and sea surface salinity in the southwest Pacific (bottom), both averaged over January–March 2008, generated from Argo data employing an easy-to-use Argo data display tool, the Global Marine Atlas, that provides students and researchers with PC-based maps, vertical sections, and time-series plots from Argo and other data sets. The Global Marine Atlas uses Ferret plotting software.

Figure 5. Participants of the training organized by the South Atlantic Argo Regional Center onboard the US Navy vessel HSV-2 *Swift* listen for pump sounds during predeployment testing of an Argo float. *Photo by Augustus Vogel, US Navy*

in ocean circulation there (Roemmich et al., 2007; Gille, 2008). A five-year analysis of Argo, satellite altimetry, and satellite gravity measurements (Willis et al., 2008) shows little change in global ocean heat content during 2003–2007, but it cannot yet close the global sea level budget in that period.

PROFILING FLOAT TECHNOLOGY ADVANCES

Profiling float technology development made Argo possible, and continued technological evolution is central to Argo's future. Because floats and deployments are expensive, float lifetimes must be maximized. US Argo leads in float technology through a partnership between the University of Washington and Teledyne Webb Research to improve design and performance of APEX (Autonomous Profiling Explorer) floats, and similarly through improvements in the SOLO (Sounding Oceanographic Lagrangian Observer) float designed by Scripps Institution of Oceanography. This leadership is evident in US Argo float performance (Figure 2). As of mid 2008, 68% of the US Argo floats deployed in 2004 remained active, compared to only 29% for all other programs. The manufacturer passes Argo-developed APEX float improvements to all APEX users, leading to subsequent increases in worldwide survival rates (Figure 2).

US Argo also provides its floats an extra level of technical care and attention usually found only in research programs.

This pays substantial dividends in longer lifetimes of these mechanically complex instruments. Value-added steps are different for each US partner, but include in-house production and/or assembly, and careful quality checking and testing of instruments. Additional care taken in shipping, field testing, and deploying floats led to sharp reductions in early float mortality. International partners take a wide range of approaches. Some programs have adopted US practices through international exchanges and float technology workshops. When greater care is taken with float preparation and checkout, the long-term survivability of floats is greatly improved.

Argo floats are valuable only while their CTDs collect useful data. Sea-Bird Electronics, working in partnership with Argo, has made great strides in providing low-power CTDs that are highly accurate and stable over multiyear deployments. As a result, Argo data are more accurate and uniform than was imagined possible ten years ago. Most Argo CTDs continue to have no detectable salinity drift after several years at sea, and when drift does occur, it is usually slow and steady enough to allow accurate adjustment in the delayed-mode, quality-control process.

In addition to float lifetime, efforts also have succeeded in increasing the capabilities of floats in several important ways. Early floats did not have sufficient buoyancy adjustment capacity to ascend from 2000 m through highly stratified tropical surface waters. As a result, until recently, most low-latitude floats cycled only to about 1000 m. The addition of an optional canister of compressed nitrogen gas in parallel with the instrument's single-cylinder pump, to increase float compressibility, has solved this problem in the APEX floats (Figure 6). New, optional APEX carbon-fiber composite pressure cases also increase float compressibility. A recent SOLO float redesign is increasing its buoyancy control for 2000-m profiling worldwide, with simplified assembly, reduced weight, volume, and energy consumption, and eliminating the problematic air bladder.

Argo floats have been improved in a number of other ways. Use of the Iridium satellite network for float communications is one example. Floats using Argos communications spend about 10 hours on the sea surface, while those using Iridium spend just a few minutes. This change saves energy, limits biofouling, decreases risks of drifting into shallow water, and affords greatly increased vertical resolution. Also, modifications in float software and hardware now enable floats to survive in regions of the sea with seasonal ice cover (Klatt et al., 2007), and to store profiles collected during extended periods under the wintertime ice for later transmission. These changes expand the potential domain of Argo sampling into these high-latitude regions, where measurements of climate-related changes in temperature and salinity are especially valuable. Floats that sample additional variables, such as dissolved oxygen (Riser and Johnson, 2008) or bio-optical properties (e.g., Bishop et al., 2002), are also available. Although these new sensors are not part of Argo, their specifications, sampling protocols, quality control, and usefulness are under discussion both inside and outside of the Argo community. Such developments will provide new scientific understanding of both physical and biogeochemical processes in the ocean, and they may lead to an expanded Argo.

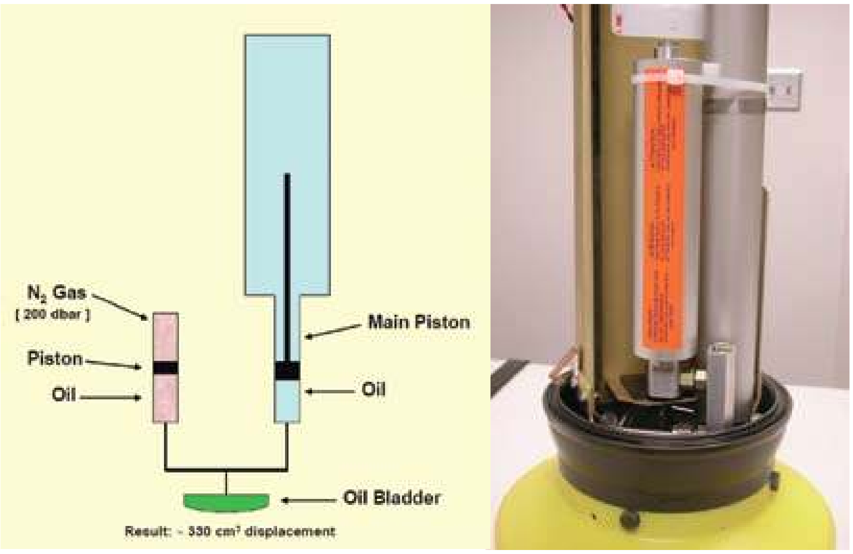

Figure 6. Schematic diagram of the main piston and nitrogen gas canister arrangement on a Webb N2 APEX profiling float. Normal APEX floats have only the main piston and oil reservoir. For N2 floats, the additional oil and piston connected to the gas canister provide a means to store energy as the gas is compressed during the float descent, recover this energy, and use it to increase the float's buoyancy during the ascent phase.

Although Argo floats generally do not sample at depths shallower than about 5 m, there is strong interest in measurements of temperature and salinity near the air-sea interface. As a result, new secondary CTD units able to collect high-resolution temperature and salinity profiles between 5 m and the sea surface have been developed by Sea-Bird and are now being tested.

Finally, the deep sea below 2000 m is a new frontier for future development of profiling float technology. Climate-related changes on decadal time scales, including warming of abyssal waters (e.g., Johnson et al., 2007a) that in turn contribute to sea level rise (Domingues et al., 2008) are present in the deep ocean. Profiling floats may be the most feasible technology for observing these signals on a global basis. Deep-ocean floats will require stronger pressure cases and greater buoyancy control. Temperature and salinity signals are smaller in the deep ocean than in the upper kilometers. Thus, deep-ocean floats may need to be recovered for post-mission CTD calibrations. All of these factors will raise the cost of deep profiles relative to the present mid-depth ones. The global requirements for deep observations need to be studied, with deep profiling floats compared to other options such as repeat shipboard hydrographic surveys or moorings, to determine the optimum mix of observations.

ARGO'S FUTURE

As profiling float capabilities grow, Argo's original mission of broad-scale observations of temperature, salinity, and circulation in the upper 2000 m of the ice-free ocean could be extended. Should oxygen and biological sensors be added to Argo floats? Should Argo's domain be expanded to include the seasonal ice zones? Should deep-ocean floats be deployed, and if so, how many are needed to observe decadal signals? Should systematic high-resolution sampling of boundary currents by gliders be added to complement Argo's broad-scale observations? Each of these exciting options would add both value and cost to the array, so they must be weighed carefully, with new resources found for any extensions to the original mission.

> “ARGO HAS ACHIEVED MORE THAN ANYONE IMAGINED IT WOULD TEN YEARS AGO, BUT THE HARDEST WORK LIES AHEAD...”

Just as float technology has been the key to Argo implementation, continuing technological development is the key to Argo's future. Argo is operational in the sense of providing a sustained data set that meets requirements for data coverage, quality, and timeliness of delivery. This achievement does not mean the technology should cease to evolve. Indeed, float technology is presently evolving along two lines. Larger floats, such as the existing APEX and SOLO models, wherein buoyancy changes occur by extending a piston to fill a bladder with oil, have sufficient payload to carry additional sensors and batteries. Newer, smaller floats (SOLO-II and ARVOR, developed by the French Research Institute for Exploitation of the Sea), with reciprocating pumps employed for buoyancy control, could prove more efficient and cost-effective for long-term CTD profiling. Continued encouragement for instrument development is essential to improve float capabilities, efficiency, ruggedness, and lifetime. Technical support is equally essential to get the most value out of these complex devices.

Data quality is another key to Argo's future. Sensor performance and stability need continued attention to make the task of data quality control manageable. Many problems in floats and sensors have occurred during Argo and will inevitably occur from time to time, so Argo must improve its procedures for rapid detection of systematic problems. It is ill affordable, financially and scientifically, to discover serious flaws in large batches of deployed instruments. Promising developments include the use of satellite altimetry to detect bias in profile sequences (Guinehut et al., 2006), and the use of Argo climatologies (Gaillard et al., in press) in quality control.

A key strategy of the NOPP US Argo partnership is the multi-institutional distribution of effort and the diversification of hardware. The benefits of this approach, while building Argo's largest national program through combining of efforts, are to ensure that the continuity of US Argo is not contingent on any individual scientist, institution, or float manufacturer, and to maximize the rate of progress in ongoing instrumentation development. There are also costs, as each of the partners has suffered losses from problems that might have been avoided through standardization. When such problems are not immediately evident, they are discovered through comparative examination of data, which is a strength of both the international and national Argo partnerships. We continue to believe the multi-institutional approach is a healthy one, and essential until such time as the technology is sufficiently mature and robust for a standardized and uniform implementation.

Finally, while the Argo array and data set continue to improve, the Argo Program will continue only if the high value of the array is convincingly demonstrated. Argo is now at an awkward age. The array is deployed and must be maintained. It will take ten years and more to realize the full benefits of measuring global patterns of interannual-to-decadal variability. Meanwhile, the cost must be borne by many national programs, and all nations must concur on the need to collect this data set, for societal benefit, throughout the world's ocean. Argo has achieved more than anyone imagined it would ten years ago, but the hardest work lies ahead—sustaining the program, broadening its applications and user base, and ensuring that its global observations benefit people in all nations.

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