# Report on the Deep Argo Implementation Workshop

## Hobart, May 5-7th 2015

Nathalie Zilberman and Guillaume Maze

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# 1. Introduction

**Speaker: Nathalie Zilberman**

Deep-ocean (> 2000 m) hydrographic observations are limited to sparse shipboard hydrographic sections repeated every decade and short-lived moored arrays of confined spatial coverage. Upper-ocean (< 2000 m) sampling, largely carried out by the conventional Argo array, has much higher resolution in space and time. The need for more intensive sampling in the deep ocean has been widely recognized by the scientific community. The development of deep profiling Argo floats, a new generation of autonomous instruments capable of diving and recording temperature and salinity down to 4000 to 6000 m depth, is underway. The Deep Argo Workshop was organized to initiate science and implementation planning for a global Deep Argo array, to satisfy broad-scale requirements for measurement of temperature, salinity, and ocean circulation and for combination with other observing system technologies that will complement the float array's large-scale attributes.

The main objectives of the Workshop were to

- Articulate key scientific issues for Deep Argo: (i) closing the heat, freshwater, and sea level budgets, (ii) characterizing decadal variability in deep ocean water masses, (iii) estimating the mean and decadal variability in deep ocean circulation including meridional overturning circulations.
- Determine sampling requirements to achieve Deep Argo objectives.
- Refine plans for the deployments of Deep Argo pilot arrays.
- Promote international collaboration within the Deep Argo community.

Early results of deep float deployments and research plans for Deep Argo regional pilot arrays were presented.

# 2. Watermass pathways, volume transport, and heat budget in the deep ocean: State of knowledge and uncertainties

## 2.1. Deep ocean heat and steric sea level

**Speaker: Sarah Purkey**

What is the present state of our knowledge concerning the trend in deep temperature in the ocean and its variability, and the closely related variability in the deep heat content of the ocean? The A16S section analyzed by Johnson and Doney (2006) showed a warming in the South Atlantic below 4800 m. On a global scale, the Purkey and Johnson (2010) analysis showed that this warming was ubiquitous, with the bottom waters warming at a rate near 0.01-0.02 °C/decade. The errors in this estimate are generally large, but the observed warming rates in the Southern Ocean and farther south generally exceed the error estimates. Kouketsu et al. (2011) made sub-basin scale estimates of deep temperature changes and found similar results. Purkey and Johnson (2013) examined the trend $d\theta/dt$ versus depth and found a generally positive global trend (i.e., > 0) below 4000 m. In the Southern Ocean, this trend was larger and more pervasive, with values generally > 0 below 1000 m. All of these results come from an examination of shipboard hydrographic data over broad areas. A few local sites, such as the Vema Channel in the South Atlantic, have long time series of repeated deep observations. The bottom waters of the Vema Channel (sill depth ~4800 m) were observed to be warming at a rate of about 0.03°C/decade between 1972 and 2006 (Zenk and Morozov, 2007). Similarly, in the Scotia Sea, Johnson et al. (2014) have observed localized warming on the order of 0.06°C/decade from repeated occupation of the A16 hydrographic section since 1989. From a synthesis of all of this work, there can be little doubt that vast regions of the abyssal waters of the Southern Hemisphere are warming at measurable rates.

Why should we care about this? This heating is equivalent to an increase of 0.027 W/m$^2$ in the abyss, and only generally has differences between the 1990s and the 2000s. The observed warming below 4000 m amounts to an equivalent rise in sea level of 0.09 mm/year, with an error estimate of about ±0.08 mm/year, which makes these estimates on the edge of significant. However, farther south in the Southern Ocean the estimates in sea level rise are greater and above the uncertainty (0.15 ± 0.1 mm/year). The work of Church et al. (2013), combining satellite altimetry, steric sea level changes, and mass changes estimated from the GRACE mission are consistent with these estimates from direct measurements of the water column. More recent work by Purkey et al. (2014) shows that the global heat budget cannot be closed using only observations from above 1000 m, further suggesting that deep warming of the water column is important and must be taken into account in climate models.

The overall conclusion is that the observed warming contributes to both important changes in global energy content of the ocean and sea level rise.

## 2.2. Deep freshwater content

### Speaker: Katsuro Katsumata

What about changes in the freshwater content of the deep ocean? At 65°S, for example, $T$ increases and $S$ freshens near the bottom, although $S$ increases at some other sites. $S$ can contribute an amount equal to $T$ to sea level change (Katsumata et al., 2011). Can we use $\Delta T$ and $\Delta\eta$ (here $\eta$ = sea level) to estimate $\Delta S$? This would appear to be difficult to do, especially without knowing the mass change in freshwater well.

There have been some direct observations of deep-ocean freshening, mostly in the South Pacific (Aoki et al., 2013; Rintoul, 2007; Jacobs and Giulivi, 2010). Yet data from the Labrador Sea shows similar signals, although not monotonically decreasing. The Purkey and Johnson (2013) analysis shows freshening of Antarctic Bottom Water at a rate sizable enough to cause measureable sea level changes. This freshening is attributable mostly to melting of Antarctic ice shelves at a rate of 50-100 GTon/year.

How do these observed changes connect to the global circulation? One explanation of the large-scale change is that there is heaving of deep temperature and salinity surfaces, at a magnitude of about 100 meters/decade in the Southern Ocean. If *T* increases at a given depth from heaving, and *S* also increases (as has been observed for both *T* and *S*), then there is some cancellation of these two effects in the density signal. A second explanation is that the changes are occurring via advection. Such changes in the Southern Ocean are observable through changes in the CFC distribution (Orsi and Bullister, 1996). The changes in CFC in the deep sea can be seen to translate all the way from the Southern Ocean to 17°S in about one decade. Models can perhaps help to clarify these two scenarios. Simulations (the Japanese ESTOC work) show clear freshening in the lower layers of the model, but the model changes occur in the wrong place compared to the observations.

In summary, (1) there is a clearly observed freshening at deep levels in the Southern Ocean; (2) there is an observed northwestward translation of this signal on decadal time scales by advection; (3) there are also observed changes in the deep salinity, likely due to heaving; (4) it is likely that our observations are under-sampled in time, perhaps leading to false conclusions (see the observed variability in the Labrador Sea, for example); (5) the observed changes in salinity are equivalent to a change of 0.1°C in temperature, which is about 7 times larger than the observed temperature changes in the deep waters, showing that salinity likely has a large effect in steric changes in sea level; (6) the errors in our estimates are large, and models can hopefully help our interpretation of the observations. A deep Argo float array could serve to greatly decrease the variance in the observed results over time.

## 2.3. Water mass variability based on Argo and hydrographic data

### Speaker: Damien Desbruyeres

Argo and ship-based hydrographic data can be combined to attempt to construct a full-depth heat budget. Purkey and Johnson (2010) described a warming of the deep sea, and Roemmich et al. (2015) showed an unabated warming of the upper ocean from the 1980s through the present, especially south of 30°S. If we tried to construct a full-ocean heat budget, where would the uncertainty be the greatest? On a global scale there appears to be a deep warming below 2000 m of perhaps 0.07 ± 0.05 W/m$^2$. By integrating zonally along repeat sections in an attempt to reduce the uncertainty, it can be seen that there is a deep warming nearly everywhere.

What drives these trends? The changes can be separated into changes caused by heaving of *T* and *S* surfaces and changes on isopycnals resulting from changes in water mass properties. Changes due to heaving appear greatest nearly everywhere (60% of the change globally in the depth range 2000-4000 m, 40% of the change below 4000 m). It is difficult to discern the effect of changing water mass composition in the deep waters due to the relatively large errors. Overall, the full-depth changes account for an equivalent heat flux of 0.425 $\pm$ 0.121 W/m$^2$.

What is the relationship of these changes to ocean dynamics? In the Southern Hemisphere subtropics, heaving (warming) appears to account for the observed vertical heat flux. In the northeast Atlantic, there appear to be changes on isopycnals due to water mass changes above 500 m, with changes due to heaving below this depth.

Conclusions: (1) the warming of the deep-sea (below 2000 m) accounts for perhaps 15% of the observed global heating, mostly due to heaving of *T* and *S* surfaces; (2) Deep Argo program could greatly help to refine these conclusions, by helping to separate the effects of heave and water mass changes with reduced uncertainty.

## 2.4. Circulation pathways, transports, and Meridional Overturning Circulations

**Speaker: Brian King**

What is our present knowledge of global circulation, transports, and the meridional overturning circulation (MOC)? What is the vertical structure of the MOC? Much of what we know about changes in these come from long sections from ships repeated at 5-10 year intervals and from mooring time series lasting several years at a few key locations. From these, we can examine the properties of water mass movements as a function of depth and time.

Kouketsu et al. (2009) and Smeed et al (2014) observed changes in the MOC in the North Pacific Ocean at 24°N. From their results, we can attempt to ask questions pertinent to the design of a Deep Argo program: is 4000 m a good level for detailed observations? Is 6000 m better? What are the differences, and what would be the rationale for making a choice? As for temporal resolution and the necessity of continuing observations in time, it should be noted that the work of Frajka-Williams et al. (2011) showed transport variations over 6 months at 24°N of 1-3 Sverdrups, which was larger than the variability observed on 6 similar sections at this latitude collected over 25 years. Thus, sampling from ships alone is problematic. The works of Bryden et al. (2011), McDonagh et al (2010), and McDonagh et al. (2008) all indicate that such vertically integrated transport changes are dominated by changes in the deepest layers of the water column, and that making useful estimates of the deep heat content require measurements to 6000 m.

Conclusions: (1) Both ship-based measurements and observations from deep floats are necessary to understand deep variability and heat transports; (2) fixed-point measurements, as from moorings, will also be necessary; (3) floats are likely to reveal more deep variability than can be observed from ships; (4) observations over the full depth of the ocean in space and time are needed for improved dynamical representation of ocean variability in models.

## 2.5. Use of Argo trajectories

**Speaker: Alison Gray**

How can we use Argo trajectories to examine the deep circulation? The trajectories allow for an estimate of the deep velocity, as has been done in the ANDRO and other syntheses of Argo trajectory data. There are errors inherent in using Argo trajectories for estimating velocity, such as contamination on the sea surface by inertial oscillations in older floats using ARGOS communications (which in many cases can be removed), and the vertical shear of the horizontal velocity field experienced by floats as they rise during their profiles, perhaps as large as 1 cm/sec. This is likely to be of the same order as the flow in the abyssal ocean, suggesting that perhaps the floats should profile at longer intervals than 10 days in order to reduce the uncertainty in estimating the velocity. In general the velocities are estimated by connecting the surface positions at 10-day intervals without knowledge of the intervening positions. Yet, Bowen et al. (2014) have shown that by imposing a requirement that the intervening positions follow bathymetry in order to conserve potential vorticity, the speed estimates might increase by as much as 20%. The direct use of Argo trajectory data can also be limited by a lack of knowledge of positions under sea-ice over a long time (winters).

## 2.6. Spatial patterns of climate change in the ocean. Use of high-resolution ocean and climate models to help inform Deep Argo

**Speaker: Matt Palmer**

Models can likely help in the design of Deep Argo. What are the “noise” and “signal” that characterize the deep circulation? Some of this can be addressed from observations of sea level variability (Church et al, 2011) and coherent climate variability (Morrison et al., 2015). In general it is difficult to examine the change in ocean energy (heat) content by considering only changes in ocean surface forcing. Changes in SST and in vertically integrated ocean energy content are not well correlated. Both the North Atlantic and Southern Ocean are seemingly good sites to study deep ocean heat content, as a warming signal from 2000-4000 m shows up in model projections in both regions. In the Southern Ocean, numerical simulations of the global ocean circulation show decadal changes in bottom water properties over time that are somewhat consistent with observations (Heuze et al., 2013). On longer time scales, Latif et al. (2013) show centennial-scale changes in deep bottom water properties. Can models help to guide us to optimal space/time sampling in Deep Argo? Some guidance towards this end can be found in the work of Rhein et al. (2013). Overall, the use of climate models in helping to design a sampling strategy for Deep Argo would seem to be an important area for future work.

# 3. First steps toward the implementation of the Deep Argo Program

## 3.1. Informing Deep Argo array design using repeat hydrographic section data

**Speaker: Greg Johnson**

Data from full-depth closely sampled oceanographic transects are analyzed to inform the design of a future Deep Argo array. Here, standard errors of local decadal temperature trends and global decadal trends of integrals of ocean heat content anomaly from 2000-6000 dbar are estimated for a hypothetical 5º latitude x 5º longitude x 30-day cycle Deep Argo array. These estimates are made using temperature variances from closely spaced, full-depth CTD profiles taken during quasi-synoptic transoceanic oceanographic cruises. The temperature data along the section are high-passed laterally at a 500-km scale, and the resulting variances averaged in 5º x 5º bins to assess temperature noise levels as a function of pressure and geographic location. The hypothetical Deep Argo array would be capable of resolving, on average, at one standard error, local trends of < 1 mºC per decade in the abyssal Pacific and < 20 mºC per decade within the deep Antarctic Circumpolar Current. Larger decadal temperature trends have been reported previously in these regions using repeat hydrographic section data, but those very sparse data required substantial spatial averaging to obtain statistically significant results. Furthermore, the array would provide decadal global ocean heat content trends estimates from 2000-6000 dbar with a standard error of ± 3 TW, compared to a trend standard error of ± 17 TW from a previous analysis of repeat hydrographic data.

## 3.2. Is the variability in SOSE consistent with that observed in the deep ocean?

**Speaker: Sarah Gille**

The deep ocean, below 2000 m depth, has been sparsely measured, aside from decadal-scale hydrographic surveys and isolated current meters. One of the challenges in planning for Deep Argo is projecting the types of processes that are likely to control variability in the deep ocean and evaluating the time scales at which this variability occurs. Numerical modeling studies of deep basins in the Southern Ocean, such as the Argentine Basin and the Australia Antarctic Basin, indicate barotropic basin modes with time scales of the order of 20 days. Barotropic modes may not formally be detectable from temperature/salinity profiles, but as these barotropic modes decay, they have the potential to force baroclinic variability at time scales that are somewhat comparable to their 20-day patterns. We use 5 years of data from the Southern Ocean State Estimate to evaluate patterns of variability in the deep Southern Ocean, below 4000 m depth. SOSE is a 4-dimensional variational assimilation that is constrained to all available observations, including standard Argo profiles and satellite altimetry. We detrended SOSE fields and removed low-frequency variability at time scales longer than a year, in order to consider only the more reliable high-frequency component of the SOSE field. This indicates deep ocean rms variability of the order of 0.02°C for temperature and 0.003 for salinity, meaning that Deep Argo will be more able to detect temperature fluctuations than salinity fluctuations, given current sensor performance. Decorrelation time scales for high-frequency motions are about 50 days in basin centers, but can be much faster, particularly along the periphery of deep ocean basins. Spatial decorrelation scales are short, consistent with eddy length scales.

We used pilot Deep SOLO float behavior to model profiling Lagrangian particles in SOSE, assuming a 15-day cycle time. Numerical particles that park 500 m above the bottom travel relatively short distances in 5 years and do not leave the basin in which they start; particles that park at 1000 m depth, like current Argo floats, are advected out of their initial basin during the 5-year study period.

## 3.3. Observing system design for Deep Argo: a community perspective from GODAE Ocean-view

**Speaker: Peter Oke**

Under GODAE OceanView (GOV; www.godae-oceanview.org), the operational ocean forecasting community has developed a suite of global ocean forecast, reanalysis and analysis systems. Each system has a critical dependence on ocean observations – routinely assimilating observations of in-situ temperature and salinity, and satellite sea-level anomaly and sea surface temperature. Under GOV, the Observing System Evaluation Task Team (www.godae-oceanview.org/science/task-teams/observing-system-evaluation-tt-oseval-tt/) regularly coordinates analyses from the GOV community to demonstrate the value and impact of ocean observations on different global and regional data-assimilating forecast and reanalysis systems. Highlights of the latest suite of demonstrations are presented here. Results show that Argo data are critically important – the most critical for seasonal prediction, and as critical as satellite altimetry for eddy-resolving applications. Most systems show that TAO data are as important as Argo in the tropical Pacific, and that XBT data have an impact that is comparable to other data types in the vicinity of XBT transects. It is clear that no currently available data type is redundant. On the contrary, the components of the global ocean observing system complement each other remarkably well, providing sufficient information to monitor and forecast the global ocean.

Using the Mercator ocean reanalysis system, a series of Observing System Simulation Experiments (OSSEs) have been performed to assess the potential impact of deep Argo observations on an eddy-resolving (1/12 degree resolution), data-assimilating model. Preliminary analysis of these OSSEs shows that the assimilation of deep Argo observations, below 2000 m depth, are likely to significantly reduce the deep model biases that are common to global eddy-resolving models.

Ocean gliders are a key observation platform that may compliment the Argo array to monitor the volume, heat, and freshwater transport of western boundary currents and other regions that are difficult to monitor with Argo alone. Discussions are underway about the deployment of a fleet of 2 or 3 gliders off eastern Australia to monitor the East Australian Current (EAC). Preliminary calculations indicate that gliders could effectively occupy a zonal section at 26°S, provided that they are “deep gliders” – profiling to depths of 1000 m. By contrast, shallow gliders – profiling to just 400 m or shallower – will not be able to effectively occupy this line, and will be quickly swept away by strong surface-intensified currents. Investigations of the feasibility of piloting gliders off eastern Australia to monitor the EAC are ongoing.

### 3.4. Possible influence of the Deep Argo floats data on a deep ocean state estimation

**Speaker: Katsuro Katsumata**

We introduce a deep ocean state estimation by using 4D-VAR data synthesis system (ESTOC). ESTOC is a projection of an observed climate time-trajectory to a dynamical model. The deep ocean state in ESTOC can be well controlled by the system by using deep ocean observations and several advanced schemes. The product enables us to investigate a possible mechanism of climate change inclusive of a subtle bottom-water warming (http://www.godac.jamstec.go.jp/estoc/e). Further, an adjoint sensitivity analysis was applied to identify the influence of Deep float data on deep ocean state estimate. It shows a region, which can be possibly corrected by JAMSTEC deep floats in the data synthesis experiment. We need more cases to deduce more concrete conclusions.

### 3.5. Status of national planning for Deep float deployment

In this session, the presenters were asked to report on the Deep Argo float models, number of Deep floats to deploy in 2015-2019, and plans of pilot arrays.

#### 3.5.1. U.S

**Speaker: Dean Roemmich**

U.S. Deep Argo is carried out by the same 5-institution consortium as U.S. Argo (PMEL, SIO, UW, WHOI, AOML), and is funded by NOAA as part of U.S. Argo. Funding for FY2014 and FY2015 included support for 12 Deep Argo floats per year, plus modest data management and planning activities. FY2015 includes ship-time for float deployment and recovery. Two prototype Deep SOLO floats were deployed in June 2014 during a collaborative U.S./N.Z./Australia cruise in the southwest Pacific, and have each completed over 80 cycles to 5700 m. FY2015 is Year 1 of a new 5-year cycle for U.S. Argo. The 5-year Work Plan included a large increment in Deep Argo in Year 3 (FY2017). A regional pilot deployment is planned for the southwest Pacific in January-February 2016. Additional floats for pilot arrays will be available in late 2016, and partners are sought.

#### 3.5.2. France

**Speaker: Guillaume Maze**

The Novel Argo Ocean Observing System (NAOS) project provides funding to support the construction, development, and deployment of 24 Deep Arvor floats in 2015-2019. As part of the NAOS project, 6 Deep Arvor will be deployed in 2015 (during the RRX campaign in June and later OSNAP opportunity), 12 Deep Arvor in 2016 (during the OVIDE-2016 campaign and other OSNAP opportunity), and 6 Deep Arvor in 2017. Pilot arrays will be carried out in the northeast Atlantic and the Labrador Sea. Post-2019, Argo France is hoping to contribute to 8-10 Argo-Deep floats per year, (10% of the total national contribution to Argo: 80 floats per year for the global array). These deep floats would replace standard floats and would not be additional to the standard fleet.

#### 3.5.3. U.K

**Speaker: Brian King**

U.K Argo acquired 2 Deep APEX and 2 Deep Arvor in 2014. All floats will carry the Anderaa Optode. Deployment will be in the Atlantic Ocean at 24.5°N. U.K Argo plan is to either focus on the western Atlantic, or to deploy in the western and eastern Atlantic. Deployment would take advantage of the GO-SHIP cruise of 12/08/2015-01/22/2016.

#### 3.5.4. Japan

**Speaker: Shuhei Masuda**

15 Deep NINJA floats were deployed in cooperation with TSK: 3 floats were deployed in the North Pacific for deep field tests and 12 floats were deployed in the Southern Ocean. The 12 Deep NINJA in the Southern Ocean have collected about 200 profiles in total; 160 of those are deep (z > 2000 m) profiles. JAMSTEC will deploy 2 Deep NINJA in the Indian Ocean and 1 Deep NINJA in the Pacific Ocean in 2015. A tentative plan is to deploy 1-2 Deep floats in the Pacific Ocean in 2016, and 2-3 Deep floats in the Pacific and Indian Ocean in 2017-2018. Competitive funds could possibly provide additional 1-3 Deep floats in 2016-2018.

# 4. Deep profiling float prototypes: performances, limitations, and results

## 4.1. Deep SOLO

**Speaker: Nathalie Zilberman**

The Deep SOLO floats are designed and built at Scripps Institution of Oceanography (Figure 1). Deep SOLO maximum depth is 6000 m. The target depth for the 2 prototypes deployed in June 2014 is 5500 m. At present, Deep SOLO prototypes are expected to achieve 160 (3.5-day long) cycles. Telemetry is iridium, and surface time is 15-30 minutes. The Deep SOLO floats weigh 25 kg. The housing is a 13 inches glass ball. The hydraulic pump runs at 50 m (to target depth), again at max depth, and during ascent to maintain speed. The speed of float ascent and descent is 6 cm/s. The float uses a 2-m wire rope to “feel” the ocean bottom. Temperature and salinity are measured using the SBE-61 CTD from Sea-Bird. Deep SOLOs use 25 kJ per 5500-m cycle (89% buoyancy, 10% CTD, 1% telecom). The temperature-salinity profile is continuous to 500 m and discrete at depth greater than 500 m. Two Deep SOLO prototypes were deployed in the southwest Pacific Ocean onboard the R/V Tangaroa in June 16-25th 2014. U.S (Scripps) Argo and New Zealand (NIWA) Argo jointly funded the construction of the two prototypes. The deployment location was chosen for its strong deep warming signal, and deep (> 5500 m) and relatively flat bottom. The Deep SOLO prototypes were deployed away from the deep western boundary current on the eastern side of the Tonga-Kermadec Ridge. Ship-time was contributed by NIWA, with contribution from Australian Argo and US Argo. The two prototypes deployed in 2014 are measuring temperature and salinity on the way down. Each prototype has completed over 80 cycles over 11 months since deployment. One Deep SOLO (6003) CTD has a small salty bias (+0.005-0.006) relative to shipboard SBE 9plus and historical CTD data. The other Deep SOLO (6002) CTD has a larger (0.03-0.05) fresh bias, showing depth-dependency. The 6003 and 6002-mounted CTDs show a slight sign of TBTO wash-off during the first 8 cycles (0.001-0.002 PSS-78). The bottom-landing device is efficient for avoiding snagging on the bottom or entraining mud.

**Conclusion**

- Both Deep SOLOs may be recovered in September-November 2015 after ~110 cycles (~75% of expected battery capacity), and replaced by a pilot array of 10 Deep Argo floats (Deep SOLOs and Deep APEXs) spread around the south-west Pacific Basin in January-February 2016.
- SBE-61 fresh (6002) and salty (6002) biases are not understood yet.

### 4.2. Deep APEX

**Speaker: Steve Riser**

The Deep APEX floats are manufactured by Teledyne Webb. Deep APEX maximum depth is 6000 m (Figure 1). Temperature and salinity are measured using the SBE-61 CTD from Sea-Bird. The housing of the Deep APEX is a glass sphere of 19 inches diameter. Webb has done 2 test deployments over the Puerto Rico trench (36 profiles in total, 6000 m in a number of profiles). Sampling is at 2 dbar. Cycling is at about 1.5 days. Each Deep APEX float has 10 Lithium DD-packs (14 MJ total), and uses 100 kJ per 6000 m cycle. Maximum number of dive cycles is 133 profiles at 2-dbar reporting (continuous profiling).

**Conclusion**

- ❖ The Deep APEX floats are at earlier stages of development compared to the Deep SOLOs.
- ❖ The Teledyne Webb Deep APEX appears to be mechanically sound design, based on several months of test deployments.
- ❖ The prototype SBE-61 worked well and was stable to < 0.005 PSU over the several months of deployments tests.
- ❖ Energy projections suggest that missions of several years in duration, with continuous 2-dbar sampling are possible with this float.
- ❖ Important issues remain with the electronics and firmware and have delayed further testing for over a year. It is hoped that these issues can be solved and that the first long-term deployments will begin early-2016.
- ❖ Bottom avoidance: Talk of an altimeter, but not a great solution perhaps.
- ❖ Iridium RUDICS

### 4.3. Deep NINJA

**Speaker: Tayio Kobayashi**

The Deep NINJA floats are developed by JAMSTEC and Tsurumi Seiki Co. Ltd. (TSK) and have been commercially available since April 2013 (Figure 1). Deep NINJA floats cycle down to 4000 dbar. Temperature and salinity are measured on the way up. The aluminum-alloy hull is 210 cm in length. Typical weight is 50 kg. A SBE41CP CTD sensor is attached on the top of the housing. The float is designed to have sufficient capacity to load additional sensors (e.g. dissolved oxygen). The Iridium bi-directional data transmission allows high-resolution sampling throughout the profiling (up to 1 dbar between the sea surface and 2000 dbar). Operational parameters (cycle time, profile depth, parking depth, CTD sampling in continuous or discrete mode) are changeable during the float's mission. Depth levels for discrete CTD sampling are set prior to shipping (not changeable). The float locations at the sea surface are fixed by the GPS. Theoretical lifetime is estimated at 50-70 cycles. TSK has made an effort to extend its operation period. Deep NINJA are equipped with ice-avoidance (temp < -1.75 ºC shallower than 50 dbar) and bottom-avoidance (based on pressure record) algorithms. Data collected under the ice are stored for transmission when the float surfaces. Landing on the bottom can cause fatal damage to the buoyancy engine. Deep NINJA are programmed to ascend 50 m after touching the bottom. Probably due to sea ice extension, some floats off the coast of Antarctica lost contact: two at the end of May 2013 and four at the end of March 2014. Among them, one float survived the austral winter of 2013, and two floats survived the winter of 2014. The measurements under sea ice were transmitted to the land-based station successfully. At present (May 2015), two floats are under operation in the open ocean, and two are expected to collect data under sea ice. Deep NINJA floats have observed interesting features of seasonal/inter-seasonal changes of Antarctic Bottom Water off the Adelie Coast.

**Conclusion**

- SBE-41CP CTD shows a fresh bias compared to shipboard data. TSK plans to change to SBE61 when these are commercially available.
- Need to improve ice detection function (3-5 floats lost under sea ice) and mechanical reliability.
- Need to increase Deep NINJA lifetime. Current lifetime is 50-70 cycles, shorter than other deep floats.

### 4.4. Deep ARVOR

**Speaker: Guillaume Maze**

Deep Arvor floats are developed at IFREMER and manufactured by NKE (Figure 1). The Deep Arvors are designed to perform 150 P/T/S profiles down to 4000 m. Typical weight is 26 kg. Deep Arvors are equipped with the SBE-41CP CTD, Aandeera optode (optional), and a two-way Iridium communication system. Temperature and salinity are measured during the float ascent. Vertical sampling is 1-meter (adjustable). The CTD pump runs continuously during the float ascent. The averaged vertical speed during the float ascent and descent is 9 cm/s (adjustable). Grounding detection is based on pressure record. Parking depth is programmed at 1000 dbar. A deep Arvor float can alternate its profile depth. All mission parameters are changeable. Four prototypes were deployed in the northeast Atlantic between 2012 and 2014. Two IFREMER 3500-dbar prototypes performed 71 and 88 cycles; two NKE 4000-dbar prototypes performed 32 and 141 cycles. The 141-cycle float may have ended its mission because of power shortage. The reason for all prototypes to stop transmitting prematurely is not yet understood. The 4 floats performed appropriately, following mission parameters and sampling schemes as expected. Data analysis and comparison with reference CTD profiles performed at deployment time revealed no clear issues with pressure and temperature measurements. SBE-41CP exhibits a fresh salinity bias of 0.01-0.02 in deep (z > 2000 m) layers compared with SBE-9+ CTD. The salinity bias does not appear to be depth or time dependent.

**Conclusion**

- Need to improve performances of SBE41-CP.

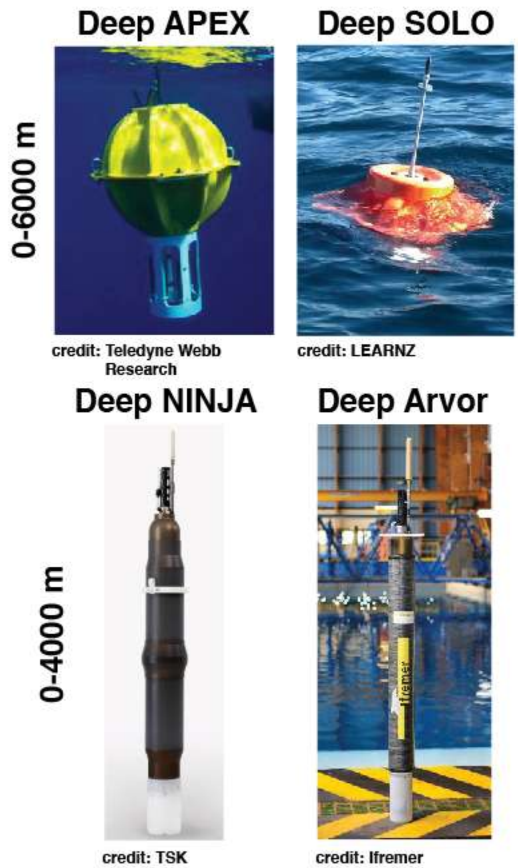


**Figure 1**: The four Deep Argo float models: the Deep APEX floats, developed by the University of Washington and Teledyne Webb, the Deep SOLO floats, developed by Scripps Institution of Oceanography, the Deep NINJA floats, developed by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Tsurumi-Seiki Co. (TSK), and the Deep Arvor floats, developed by Institut Français de Recherche pour l'Exploitation de la Mer (Ifremer), Centre national de la recherché scientifique (CNRS), and nke instrumentation.

# 5. Technical aspects of Deep profiling floats for discussion

## 5.1. CTD calibration and accuracy

### 5.1.1. SBE-61

**Speaker: Phil Sutton**

The SBE-61 Deep Argo Sensor will be a critical component of Deep Argo. The aspirational accuracies are pressure: ± 3 dbar, temperature ± 0.001°C and salinity ±

0.002. These are effectively “WOCE for life” and are ambitious.Three SBE-61 CTDs were integrated into the shipboard system (with a further SBE-61 internally recording) during a Deep Argo voyage on R/V Tangaroa in June 2014. The shipboard CTD (SBE 911plus) had freshly-calibrated dual temperature and salinity sensors and a further SBE-35 reference thermometer was mounted on the rosette. The data from the shipboard sensors together with salinity analyses of bottle samples were compared with the SBE-61s.

- ❖ Temperature

The first interesting finding from the temperature data was that the shipboard primary and secondary sensors disagreed by ~ 0.001°C, i.e. even freshly calibrated shipboard units only just meet the Deep Argo target. The primary sensor was deemed to be more accurate through comparison with the SBE35 at the bottle stops. The three SBE61s were within 0.001°C below 2000 dbar with the exception of 5 points out of 185.

- ❖ Salinity

The bottle samples were analyzed by 3 labs: NIWA (on board), CSIRO (samples shipped to Hobart) and SBE (samples shipped to Seattle). The SBE calibrations gave the tightest agreement with the primary shipboard sensor, with mean differences below 3400 of - $0.05 \times 10^{-3}$ while the NIWA agreement was - $0.53 \times 10^{-3}$. Unfortunately the CSIRO samples were damaged in transit and the CSIRO comparison was almost an order of magnitude larger. Having validated the primary shipboard sensor, two of the SBE61s were fresh by 0.0 to -0.004 while the third was salty by 0.001 to 0.005. There were pressure signals in all of the salinity comparisons with the primary shipboard sensor.

- ❖ Pressure

Comparing the three SBE61 pressure results with those of the shipboard sensor indicated differences of ± 4.5 dbar at 5500 m. It is noted that any pressure error impacts the temperature and salinity errors through interactions with the property vertical gradients. The calculation of salinity from conductivity also means that errors in pressure and temperature impact on accuracy in salinity.

The three SBE61s were found to be close to the aspirational targets. Temperature is meeting the accuracy goals. Salinity is close to the goal and refining the sensors calibration across pressure may yield improvements. Pressure is also close to the goal, but needs some improvement, with mechanical design work needed to improve transient temperature errors and further work on calibration.

### 5.1.2. SBE-41

**Speaker: Guillaume Maze**

Four Deep Arvor have been deployed between 2012 and 2014: 2 Ifremer prototypes sampling down to 3500 db and two NKE industrial prototypes sampling down to 4000 m. All floats were equipped with an A4330 optode and a SBE41CP CTD. The 4 Deep Arvor performed appropriately, following mission parameters and sampling schemes as expected. Data analysis and comparison with reference CTD profiles performed at deployment time revealed no clear issues with pressure and temperature measurements. However, salinity data have a clear systematic fresh bias of the order of magnitude 0.01-0.02. No clear dependence to pressure or time was found for this bias.

Although the fresh bias appears to be correctable at this time using a reference profile, this technical issue needs to be fixed for the deep floats to provide the necessary accuracy for the targeted scientific questions. France aims to collaborate with Sea-Bird and other partners using SBE41CP in order to fix this issue.

**Speaker: Taiyo Kobayashi**

Pressure, temperature, and salinity measurements by SBE41CP on Deep NINJA were evaluated by comparison with the shipboard CTD observation conducted at float deployment. Among the 15 floats deployed, the first profiles of 11 floats were compared with shipboard CTD observations (by 4 cruises onboard 3 ships). All pair observations were conducted simultaneously (within about 10 km and about 30 hours) except for 1 case (S/N 7) in 4 days. Compared with shipboard observations obtained at float deployment, float temperature and pressure were deviated negatively. However, they were not concluded to be biased statistically. For salinity, float measurements have a bias with fresher pressure dependence, besides an offset component. It means that a well-calibrated CTD sensor yields fresher salinities at 4,000 dbar by 0.005 on average and by almost 0.01 at worst. The cause of this fresher pressure dependency has not been clarified. The salinity bias can be corrected to a sufficient accuracy by means of shipboard observations conducted at the time of float deployment.

### 5.2. SBE-61 CTD development progress

**Speaker: Norge Larson**

**SBE-61 instrument**

*Complete*

- Stand alone design, electronics and mechanics, build and test processes
- Power budget: similar to SBE-41CP or better
- Accuracy: 7 dbar, 2 m°K, 0.005 psu (similar to SBE-41 but with 7K sensor)
    - Includes calibrated accuracy and expected lifetime deployed drift
- Aspirational accuracy: 2-3 dbar, 1 m°K, 0.002 psu (WOCE for life)
- Integrated SBE-63 oxygen sensor

*In process*

- Large offsets in deployed sensors
- Calibration and characterization improvements (pressure and conductivity)

*Contemplated*

- Dynamic error (not found in the calibration environment) reductions or corrections

**Temperature**

*Complete*

- Pump-induced noise in temperature signal removed by shielding

*Contemplated*

- Assess and correct viscous heating and compression errors
- Longer sample integration interval (conflict with power budget)

**Pressure**

*Complete*

- Improved thermal isolation of pressure sensor (required mechanical redesign of end cap)

*Contemplated*

- Better calibration characterization to get within ± 3 dbar error
- Dynamic pressure-temperature error correction
- Revisit mechanical design for further improvement in thermal isolation

**Conductivity**

*Complete*

- Environmental isolation of electronics within the SBE-61 pressure housing

*In process*

- Experimentation on cell construction, experimental cells deployed on SBE owned floats in the North Pacific and Hawaii (plus SIO owned 5579)
- Investigating positive drift mechanisms with deployed microcats
- “Composite” compression correction (composite bulk modulus)

*Contemplated*

- Frequency counter architecture change to achieve full 32 bit resolution (conflict with power budget)

**Salinity**

*Action Item*

- Identify and eliminate large (0.01-0.02 psu) offsets in deployed instruments

*Contemplated*

- Cell thermal mass correction (June 2014 Tangaroa dataset; WHOI stratified tank dataset)
- Salinity spiking bias: real time conductivity advancement to minimize spiking

**Actions for discussion**

- Understand salinity offsets on a number of deployed SBE61s
    - More than half of reported errors are initial negative offsets drifting positive – in a manner consistent with antifoulant stain and wash out.
- Bulk modulus correction
- Pressure characterization for ± 3 dbars

### 5.3. Quality control of Deep Argo data

**Speaker: Brian King and Esmee Van Wijk**

Brian King and Esmee van Wijk prepared some notes to stimulate discussion of how the Argo data system would need to be adapted to handle data from Deep floats. Some of the key points are included below. These issues will need to be addressed as the Deep Argo program develops.

The Deep Argo data system will require (i) Suitably structured data files with metadata; (ii) Procedures for RTQC; (iii) procedures for DMQC; and (iv) reference data for DMQC. All four aspects will require adaptation from the 2000 m Argo stat system.

- RTQC

All the tests will need to be reviewed to decide if they are appropriate; some will need to be modified from the 2000 m tests, e.g. limits for vertical gradient tests.

- Data files

Meta, tech, traj and prof NetCDF files will probably all need to have extra variables not presently defined for 2000 m floats.
Deep floats will require extra data. This should be captured early, to avoid later pain.
For example:

New parameters to define missions
Detailed sensor metadata
Vertical sampling. A mixture of bin-average and spot sampling will be common.
Parking strategy; Bottom avoidance method.
New engineering parameters names in the tech files

- Reference data for QC

GO-SHIP is a good start, but there will be non GO-SHIP data that are useful for Deep Argo (E.g. Data of comparable quality to GO-SHIP collected by comparable research groups, but not tracked by GO-SHIP). Deep Argo needs to be pro-active in identifying those data and ensuring there is a procedure for getting access to them.
Questions:

How do we track the availability of these data?
How do we know they are of suitable quality?
Can GO-SHIP help with this task in some way?

Eventually, Deep Argo will be its own best source of reference data.

- Procedures for DMQC

Deep Argo needs conceptual models of sensor drift (e.g. linear trend, jumps,…)
Deep Argo needs to consider each of P, T and C, rather than focusing mainly on C.
The statistical (WJO/OW) approach provided valuable information early in Argo for 2000 m floats because the ocean variability (mapping error) was comparable to or smaller than the instrument uncertainty (~ 0.01 in S). This may no longer be the case, unless we select the reference data very wisely. Therefore a new approach may be required.

The delay period for best quality data may be greater than for 2000 m floats. CTD data acquired (e.g. 1 or 2 years) after the float measurement may be more relevant as a quality indicator than CTDs from 5 years before when determining the difference between sensor drift and genuine ocean property change.

# 6. Deployments of Deep Argo pilot arrays

## 6.1. Southern Ocean and Indian Ocean

**Speaker: Shuhei Masuda**

JAMSTEC plan for November 2015 to March 2016 is to deploy two Deep NINJA in the Indian Ocean and one Deep NINJA in the Northern Pacific (Figure 2). The objective is to do engineering testing (Pacific Ocean), and study deep-ocean circulation (Indian Ocean).

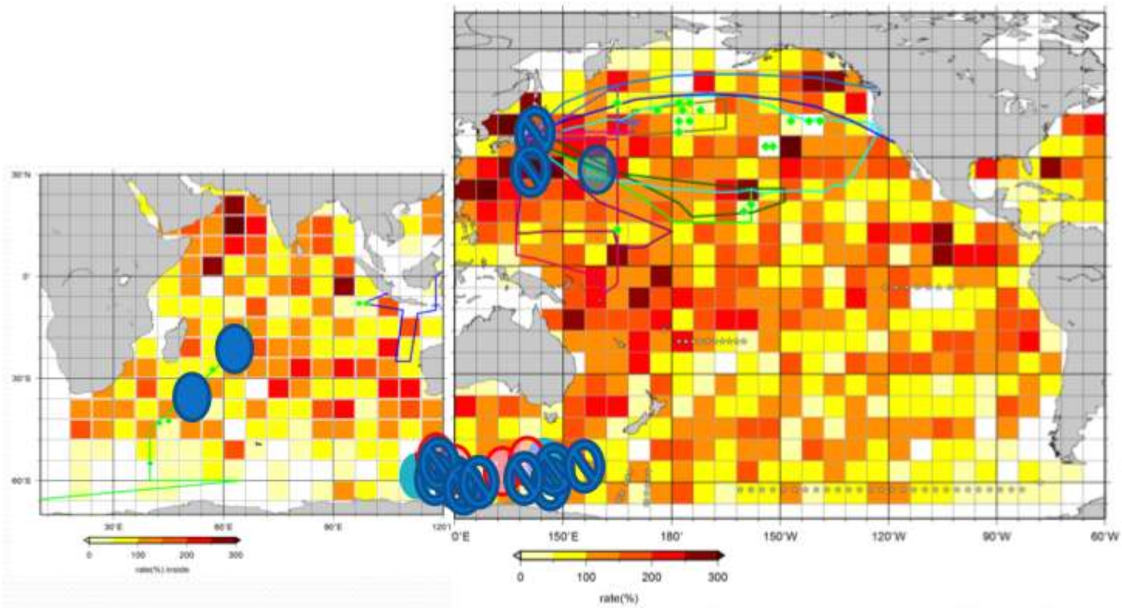


**Figure 2**: of Deep Ninja deployments in 2012-2014 (crossed blue oval shapes) and planned Deep Ninja deployments in 2016 (solid blue oval shapes).

## 6.2. Atlantic Ocean

**Speaker: Guillaume Maze**

The main scientific objective of the project is to study the interannual variability of the formation and circulation of deep water-masses formed by deep convective events in the subpolar gyre of the North Atlantic. Using deep oxygen measurements from Deep-Arvor floats (from an A4330 optode), our objective is to characterize more precisely the deep ventilation pathways of the North-Atlantic ocean. Longer-term objectives include an improved characterization of the heat and fresh water storage rates and their contributions to steric sea level variability in the region.

A pilot array of 8 Deep Argo floats (6 Deep Arvor and 2 Deep-SOLO) will be deployed in 2015 in the North Atlantic during the RRX campaign onboard the R.V. Thalassa (Jun.-Jul. 2015) and during the RAPID campaign (Dec. 2015/Jan. 2016) (Figure 3). 4 Deep-Arvor will be deployed in the North-East Atlantic (3 floats in the Irminger Sea, and 1 in the West European Basin). The remaining 2 Deep Arvor and 2 Deep Solo floats will be deployed by UK along 26°N. Our plan is to deploy 2 deep floats in the western side of the Atlantic basin, and 2 the eastern side. The 8 Deep Argo floats add to 1 Deep Arvor already deployed in the Canary Islands by the Argo Spain program. The North-East Atlantic ocean is chosen by Argo France for the pilot North Atlantic array because it has a large interannual signal of deep water masses variability and the bottom topography is such that sampling down to 4000 m with a Deep Arvor captures the vast majority of the signal targeted by the project (interannual variability of the formation and circulation pathways of deep water masses formed by deep convective events in the subpolar gyre of the North Atlantic). Our future plan is to deploy 12 Deep Arvor in 2016 (during the OVIDE-2016 GO-SHIP campaign and other OSNAP opportunity) and 6 Deep Arvor in 2017. Most floats will be deployed in the North-East Atlantic and the Labrador Sea.

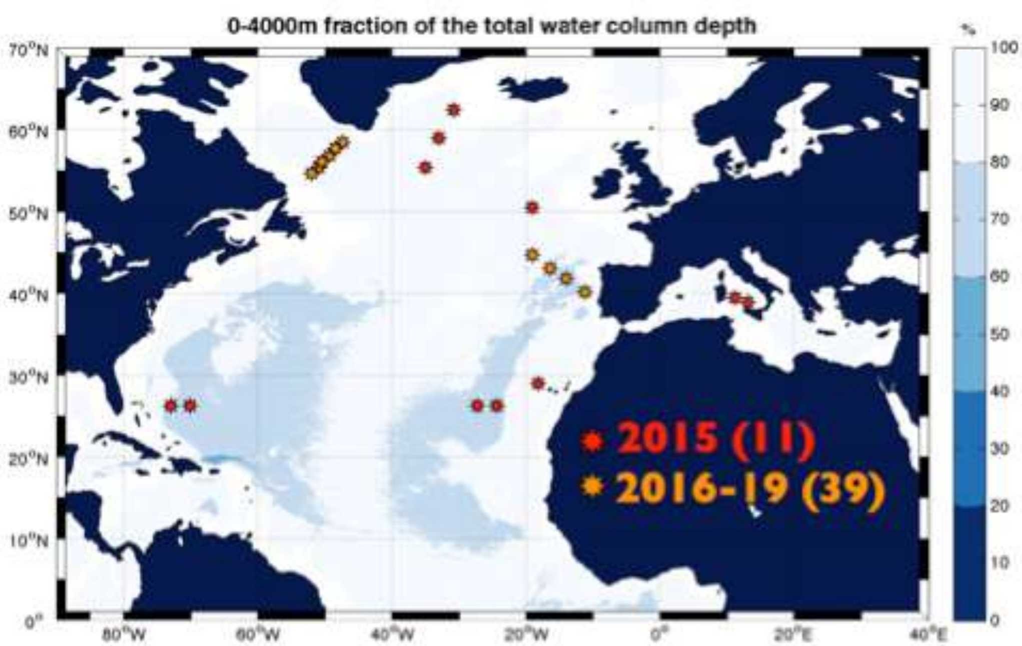

**Figure 3**: Location of planned Deep Arvor and Deep SOLO float deployments in the North Atlantic Ocean in 2015 (red stars) and 2016 to 2019 (orange stars).

### 6.3. Pacific Ocean

**Speaker: Dean Roemmich**

An attempt will be made to recover the 2 prototype Deep SOLO floats (6002 and 6003) that were deployed in the Southwest Pacific Basin in June 2014, and which will have accumulated about 110 profiles each, during a joint U.S./New Zealand/Australia voyage on RV Kaharoa from 09/08-11/08 2015 (Figure 4). The voyage will also deploy about 100 conventional (0-2000 m) Argo floats. Recovery of 6002 and 6003 is for CTD re-calibration and possible recycling, and for assessment of wear and tear on pump, glass ball, etc. A pilot Deep Argo array consisting of 8 Deep SOLO and 2 Deep APEX floats will be deployed in the same basin during a joint U.S./New Zealand/Australia voyage on RV Kaharoa in January-February 2016.

The southwest Pacific Basin was chosen for the pilot Deep Argo deployment because it has a significant decadal warming signal in abyssal layers, the eddy noise is not excessive, and the bottom is relatively flat over a large area with depths between 5000 and 6000 m. Also, the region is easily accessible from New Zealand, and New Zealand Argo provides joint sponsorship of the voyage. The southwest Pacific has been identified as a “hot spot” in global ocean heat gain studies (Roemmich et al., 2015). Oceanographically, the Deep Western Boundary Current flows northward along the Tonga/Kermadec Ridge just to the west of the pilot array, feeding the transport through Samoan Passage that renews the deep layers of the North Pacific. A GO-SHIP cruise (P15S, Australia) through the pilot array in 2016 will provide additional high quality CTD data for comparison with the floats and an opportunity for further deployments.

Mission parameters for the Deep SOLOs include profiling in descent, mixed continuous and spot sampling with SBE-61 CTD, parking on ascent at about 5000 m, and cycle time of 12 days. A 3-m bottom dragline will allow the float to approach the bottom while becoming neutrally buoyant without bottom contact by the instrument. Most parameters are adjustable via Iridium communications.

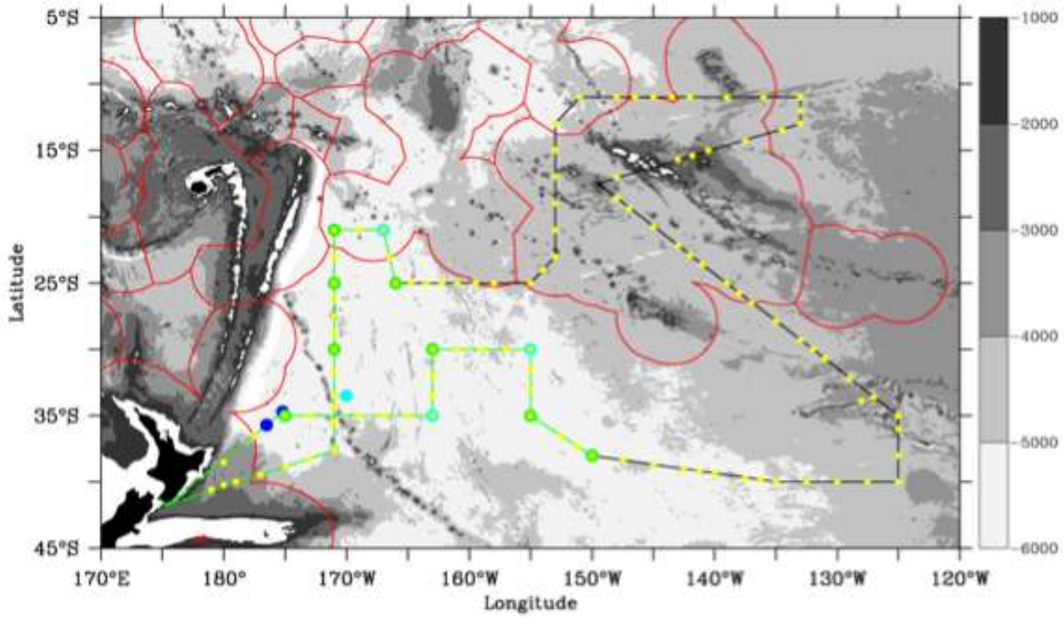


**Figure 4**: Location of planned Deep Argo float deployments (green spots) in the Southwest Pacific Ocean, January-February 2016, and present location of prototype floats (dark blue spots), whose recovery will be attempted during the U.S./N.Z./Australia voyage on RV Kaharoa in September 2015.

# 7. Key relationships between Deep Argo and other programs

## 7.1. GO-SHIP: Global ocean reference data and deployment and calibration opportunities

### Speaker: Bernadette Sloyan

The Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) brings together scientists with interests in physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems, and other users and collectors of ocean interior data to develop a sustained global network of hydrographic sections as part of the Global Ocean/Climate Observing System. GO-SHIP provides approximately decadal resolution of the changes in inventories of heat, freshwater, carbon, oxygen, nutrients, and transient tracers, covering the ocean basins from coast to coast and full depth (top to bottom), with global measurements of the highest required accuracy to detect these changes.

The GO-SHIP principal scientific objectives are: (1) understanding and documenting the large-scale ocean water property distributions, their changes, and drivers of those changes, and (2) addressing questions of how a future ocean that will increase in dissolved inorganic carbon, become warmer, more acidic and more stratified, and experience changes in circulation and ventilation processes due to global warming, atmospheric $CO_2$ increases, altered water cycle and sea-ice will interact with natural ocean variability.

The 2012-2023 decadal survey is well underway and to date is meeting most targets. A summary of the status of the program to 2014:
- Percentage of the 2012-2023 survey completed: 47%
- Percentage of the 2012-2023 survey completed and funded: 71%
- Percentage of the 2012-2023 survey completed, funded and planned: 87%
- Percentage of the 2012-2023 survey unplanned: 13%

We note that 2014 is 30% of the way through the 2012-2023 decadal period.

Data have been sent to the appropriate data centers. In particular bottle and CTD data submitted to the designated GO-SHIP repository at the CLIVAR and Carbon Hydrographic Office (CCHDO, http://cchdo.ucsd.edu/) and Carbon Dioxide Information Analysis Center (CDIAC, http://cdiac.ornl.gov/oceans/).

GO-SHIP is a coordinating mechanism and provides clear guidelines on execution of sections. The implementation of the core measurement requirements (see http://www.go-ship.org) is highlighting measurement gaps that are addressed through GO-SHIP. The data flow and submission protocols are now clearly presented at the GO-SHIP website with links to data centers that receive GO-SHIP data and data submission protocols. An ongoing risk is securing national funding for currently unplanned sections and ensuring that all sections complete the level observations once every 10 years.

## 7.2. GODAE Ocean View: scope and deep ocean issues

### Speaker: Andreas Schiller

The GODAE Ocean View (GOV) Science Team is the international body that coordinates global (and regional) scientific efforts in the rapidly growing area of ocean forecasting and analyses, and supports the research, development and operational implementation of physical, biogeochemical and ecosystem ocean forecasting systems (www.godae-oceanview.org). The group represents both academic and operational teams focusing on daily-to-weekly ocean forecasting capabilities, and the ways to build and improve them. The enhancements of the observing, modelling, and end-to-end service capacity are key issues for GOV, together with sustainability concerns. The objectives of the GOV Science Team are closely aligned with the World Weather Research Program, via the WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), their work plans and targets. The Science Team activities are driven by dedicated task teams that focus on critical scientific aspects in terms of understanding and improving ocean monitoring and forecasting systems, covering data assimilation, intercomparison and validation of operational systems, observing system evaluation, coastal ocean and shelf seas, coupled (oceanatmosphere-wave-sea-ice) initialisation and prediction, and marine biogeochemical and ecosystem prediction.

The proposed Deep Argo program is expected to benefit ocean forecasting and reanalyses systems below 2000 m by possibly

- Removing the need for deep restoring/bias correction in these systems, and
- Resolving deep ocean time-varying signals of relevance to upper ocean (>2000 m) dynamics. This includes, but is not limited to, planetary wave motions, overflows, western boundary current variability and interior eddy variability.

To achieve these scientific goals a sufficiently large number of deep Argo floats on horizontal (decorrelation) scales appropriate for removing large-scale biases are required. A similar requirement applies to resolving temporal features in the deep ocean of relevance to upper-ocean forecasting and reanalyzes.

The GOV community is very much interested in assisting the Argo community in its efforts to assess and quantify the expected scientific and societal benefits from a Deep Argo array.

# 8. Science motivation and future work

## 8.1. Value of Deep Argo for estimating sea level and planetary heat balance

### Speaker: John Church

Both science and policy needs require an ability to track the planetary energy budget on shorter time scales, decadal periods, and interannual periods. This will be important feedback to the public and policy makers. New satellite data, such as the CERES radiation information, suggest that most of the energy in recent years is being stored south of the equator. Ocean data seem to confirm this, but the missing deep component makes this uncertain. A very important problem is the regional distribution of sea level and for this, the deep component will be quite important as it has a very different spatial footprint to steric changes in the upper ocean. Deep Argo will also be very important in probing the mass/volume budget of the oceans via syntheses of gravity, sea level and steric profile data. Closing this budget is essential to bound ice melt rates globally. Accurate spatial patterns for the steric component opens the way to “finger print” the residual gravitational signatures of ice-sheet and glacial ice loss, helping to attribute melt to these different sources which have very different projected rates of loss. Thus Deep Argo can help in efforts to reduce the huge uncertainty in sea level projections associated with ice sheet behavior. Salinity change patterns from Argo can also be used in this endeavor.

In summary we can expect Deep Argo to advance

- Sea Level and energy budget – decreased uncertainty and higher temporal resolution

- Model evaluation, detection, attribution, and constrained projections
- Ocean heat uptake efficiency drives 30% of spread of model response
- Regional distributions and backing out implication for ice sheets

## 8.2. Value of Deep Argo for studying ocean circulation and MOCs

### Speaker: Steve Rintoul

Stommel's (1958) conceptual model provided the theoretical underpinning for our understanding of the deep circulation for many decades. In this model, deep western boundary currents carried dense water away from the source regions, while uniform upwelling drove weak poleward flows in the interior of each basin. From an observational point of view, our knowledge of the global deep circulation is largely based on sparse measurements of the density and tracer fields, assumption of a steady state, geostrophy and an inferred reference level. Examples include Wüst's tracing of "core layers" in the deep Atlantic in the 1930s; Reid's global synthesis based on geostrophy and a reference level velocity chosen to balance mass; the inverse models pioneered by Wunsch and colleagues; and recent ocean state estimates based on assimilation of data into general circulation models with more complete dynamics. Over time, the analysis techniques have become more sophisticated, and the database has slowly grown, but the information content on which each is based has changed relatively little.

A growing number of observations have called into question some of the assumptions on which our ideas about the deep circulation have been based. Floats deployed in the South Atlantic as part of the WOCE Deep Basin Experiment revealed zonal jets rather than the broad poleward flow anticipated from Stommel's model, and direct measurements showed that mixing in the thermocline was too weak to support uniform upwelling of the strength required by the model. Long-term moorings and repeat hydrographic sections have revealed significant variability and trends in the deep ocean, inconsistent with the steady-state hypothesis. Sustained, broad-scale observations of the deep ocean are essential.

Deep Argo offers the prospect of genuinely measuring the deep ocean for the first time on basin scales. Given how poorly the deep ocean has been measured, Deep (> 2000 m) Argo will be even more transformative for the abyss than core (< 2000 m) Argo has been for the upper ocean.

A global Deep Argo array will:

- Provide basin-coverage of the deep ocean (at present, our knowledge of deep variability is derived from a few repeat hydrographic transects in each basin);
- Resolve seasonal and interannual variability (and so help interpret the intermittent historical record);

- ❖ Over time, measure the mean and low frequency variability of the deep stratification and shear;
- ❖ Improve estimates of heat and freshwater transports, by constraining the interior flow and tracer fields;
- ❖ Identify water mass pathways (hence circulation) with much greater detail than is possible with existing sparse deep hydrographic sections;
- ❖ Provide insight into interactions between the circulation and topography;
- ❖ Allow changes in inventory to be linked to changes in dense water formation or flow through passages;
- ❖ Greatly improve estimates of the deep circulation from inversions and state estimates.

## 9. General Discussion

Deep Argo has the potential to achieve the GOSHIP survey every year for T and S. In this way, it will be incredibly transformative in our information on both the spatial detail and variability of the deep stratification and circulation field. At present little is known about the deep seasonal and interannual variability. Deep Argo will deliver new information on this in the first few years.

We can anticipate that, as the Deep Argo database builds, we will better measure the mean and low frequency variability of circulation and shear. Water mass pathways will be detectable at a much great level of spatial detail and time resolution. We will learn more about flow – topography interactions.

Can we link inventory changes to water-mass formation rates and delivery into deep basins (e.g. heat inventories to deduce mixing rates)? This is harder as it will require full transport variability estimates that Argo cannot deliver. Other choke point or Western Boundary Current arrays are needed for this.

We can anticipate the use of deep Argo data in inversions and state estimates, and thus improved circulation estimates indirectly, with the caveats on the current limitations of these systems to resolve and preserve deep property fields.

The question of whether floats should be maintained in “lines” – pseudo sections of dynamic height stations, or in clouds, and randomly map out the mean structure and inventory changes was discussed.

The key areas we can anticipate major progress in are:

- ❖ Change detection – building a well sampled unbiased and detailed modern ocean climatology – against which older data can be compared for past change detection

- Detailed stratification and shear climatology – we will learn a great deal about the deep circulation, its relationship to topography and source regions.

- Deep Argo will have relevance to several CLIVAR (Climate Variability and Predictability) research panels and the WCRP (World Climate Research Programme) Grand Challenges on sea level, and on the planetary radiation budget.

- Decadal variability – this is very important for sea level variability and regional climate projections. Deep Argo will be important for initializing these systems and helping to underpin the theory and basis of decadal predictability.

- Mixing – what can we measure and learn? If full resolution 2 dbar profiles are achievable, what could this do to advance our understanding of mixing processes and their spatial/temporal distribution?

- Oxygen – some deep floats can carry these sensors. It has a large dynamic range and thus the signal to noise might be larger compared to T and S. What science questions could be addressed with Deep oxygen? Are the sensors adequate for this? Is oxygen a possible future extension?

The meeting agreed that the straw-plan described in Johnson et al., (2015) (Figure 5) was achievable and met nearly all of the science goals with a realistic budget. The need for a global array was agreed, with a pathway to it via some regional pilots and other sparse deployments. Ongoing sensor development is needed.

How do we ensure interaction with other parts of the Global Ocean Observing System (GOOS)? The GAIC2015 Galway meeting (http://www.gaic2015.org) is one opportunity to meet with GOSHIP and OceanSITES. Other forums need to be explored (e.g. GODAE OceanView Science Team meeting in Sydney – November 2015) and the GOOS Steering Committee (SC) briefed.

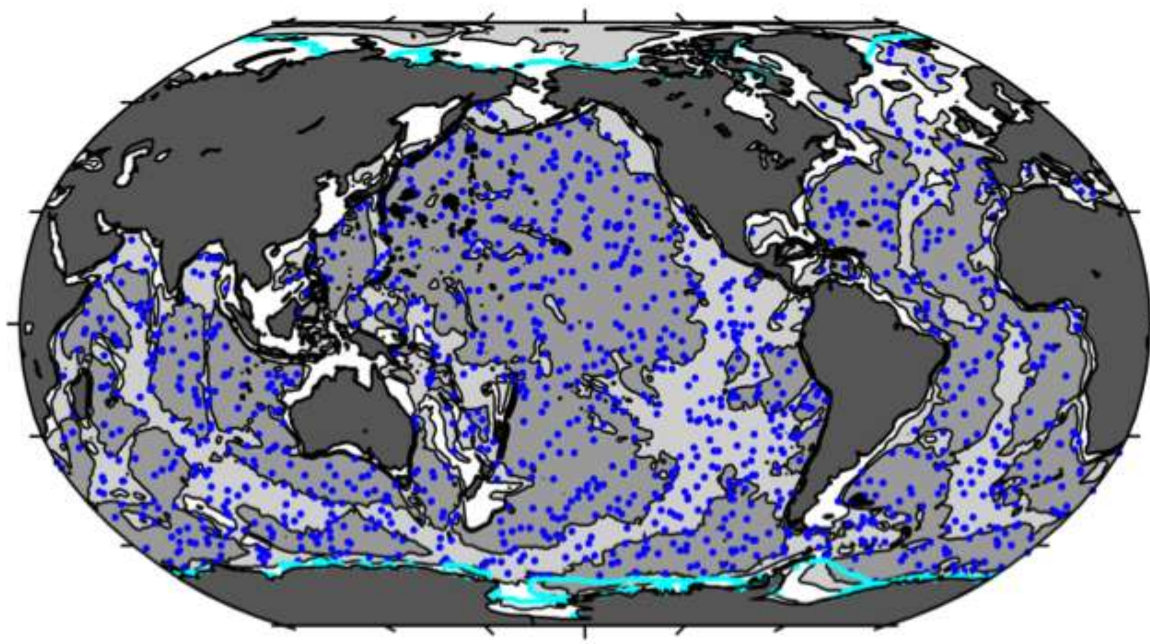

**Figure 5**: Straw-plan of a nominally 5° x 5° distribution of 1228 Deep Argo floats (blue dots) randomly populating the global ocean excluding areas shallower than 2000 m (white areas), and areas with mena 1981-2010 ice concentrations > 75% (poleward of thick cyan contours). Lightest gray areas indicate bottom depths between 2000 m and 4000 m, darker gray areas indicate bottom depths exceeding 4000 m, and darkest gray areas indicate land (Johnson et al., 2015).

## 10. Meeting outcomes

- EOS Article – a short meeting report. Leads are Nathalie Zilberman and Guillaume Maze.

- Workshop report edited by Nathalie Zilberman and Guillaume Maze, first and then SC to review/edit. A companion powerpoint on deep Argo would be helpful.

- The SC will work together on a 2-3 page "deep Argo prospectus", aimed at agency heads. Nathalie Zilberman and Guillaume Maze can draft an outline and assign SC members sections to write. Could be edited by some senior SC members. Prospectus can include: (1) Aims and expected outcome - societal and scientific; (2) What has been achieved to date, (3) the global straw-plan design and what it might cost, and (4) How we will get there – pilots and sensor development

- A Deep Argo "perspectives article" for Nature, Science, or PNAS (Proceedings of the National Academy of Sciences) - lead is Greg Johnson to approach editors.

- Outcomes to be presented at: NOAA Annual Climate Meeting in middle of June; BluePlanet (Argo-co chairs); Galway meeting; Argo Steering Team (AST) meeting -17 (Japan)

- Identified leads to help coordinate regional pilots: Atlantic – Guillaume Maze; Southwest Pacific – Dean Roemmich; Southern Ocean – Steve Rintoul. Leads need to coordinate and develop pilot plans; report back to AST and next Deep Argo meeting.

- We require input from other experts around other science application areas and report back to the SC (Mixing – Sarah Gille to contact Jen McKinnon; Oxygen – Steve Riser to liaise with Bio-Geo-Chemical community).

- Further refining sampling requirements and statistics using model systems: a small group will produce a set of useful calculations – leads are Sarah Gille and Matt Palmer.

- Next deep Argo meeting? Likely should be held within 12 months or so – once we have a target we could approach POGO (Partnership for Observation of the Global Ocean) for support.

## 11. List of participants

| Name | Email | Institution |
|---|---|---|
| **John Church** | John.Church@csiro.au | CSIRO |
| **Damien Desbruyeres** | dades@noc.ac.uk | NOC |
| **Denise Fernandez** | Denise.Fernandez@niwa.co.nz | NIWA |
| **Sarah Gille** | sgille@ucsd.edu | Scripps |
| **Alison Gray** | argray@princeton.edu | Princeton |
| **Steve Jayne** | sjayne@whoi.edu | WHOI |
| **Greg Johnson** | gregory.c.johnson@noaa.gov | PMEL |
| **Katsuro Katsumata** | k.katsumata@jamstec.go.jp | JAMSTEC |

| | | |
|---|---|---|
| **Brian King** | bak@noc.ac.uk | NOC |
| **Taiyo Kobayashi** | taiyok@jamstec.go.jp | JAMSTEC |
| **Norge Larson** | ngl@seabird.com | Sea-Bird Electronics Inc. |
| **Shuhei Masuda** | smasuda@jamstec.go.jp | JAMSTEC |
| **Guillaume Maze** | gmaze@ifremer.fr | IFREMER |
| **Peter Oke** | peter.oke@csiro.au | CSIRO |
| **Breck Owens** | bowens@whoi.edu | WHOI |
| **Matt Palmer** | Matt.Palmer@csiro.au | NOC |
| **Steve Piotrowicz** | steve.piotrowicz@noaa.gov | NOAA |
| **Sarah Purkey** | purkeysg@ldeo.columbia.edu | Lamont, Columbia |
| **Steve Rintoul** | Steve.Rintoul@csiro.au | CSIRO |
| **Steve Riser** | riser@ocean.washington.edu | UW |
| **Dean Roemmich** | droemmich@ucsd.edu | Scripps |
| **Andreas Schiller** | Andreas.Schiller@csiro.au | CSIRO |
| **Bernadette Sloyan** | Bernadette.Sloyan@csiro.au | CSIRO |
| **Phil Sutton** | Philip.Sutton@niwa.co.nz | NIWA |
| **Esmee Van Wijk** | Esmee.Vanwijk@csiro.au | CSIRO |
| **Susan Wijffels** | Susan.Wijffels@csiro.au | CSIRO |
| **Xuebing Zhang** | Xuebin.Zhang@csiro.au | CSIRO |
| **Nathalie Zilberman** | nzilberman@ucsd.edu | Scripps |

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