Report on the 2nd Deep Argo Implementation Workshop

Hobart, May 13-15th 2019

The Deep Argo workshop committee: Nathalie Zilberman, Brian King, Sarah Purkey, Virginie Thierry, and Dean Roemmich

Table of Contents

1. Introduction

As the earth system continues to accumulate heat from anthropogenic greenhouse gas emissions, the deep ocean will play a key role in determining the rate of ocean heat uptake. Understanding the rate of heat uptake and mechanisms controlling it, is vital to monitoring long term trends in the radiative global heat imbalance and sea level rise. The proposed Deep Argo Array, a global fleet of 1200 Argo floats measuring temperature, salinity, and pressure from the sea surface to near the ocean bottom, will expand Argo's current monitoring capabilities to the full ocean volume, allowing for assessment of year-to-year variability in the deep ocean's heat and freshwater content, circulation, and contribution to steric sea level rise (Johnson et al. 2015).

Currently, direct observations of deep-ocean heat and freshwater changes are based on spatially and temporally sparse ship-based repeat hydrographic sections, limiting our ability to monitor changes in deep-ocean temperature and salinity, in most places, to linear decadal trends on basin scales. Despite the limited data, a global pattern of deep ocean warming, Southern Ocean freshening, and fluctuations in deep ventilation at high latitudes has emerged. Below the 2000 m reach of the current Argo array, the deep ocean has accumulated heat at a rate of 0.071 +/-0.043 W/m2 (Johnson et al. 2018) between the 1990s and 2010s, with the strongest warming in the Southern Ocean (Purkey and Johnson, 2010; Kouketsu et al., 2011; Desbruyères et al., 2016). Some inter-decadal variability has been observed with the warming rate slowing in the western South Atlantic and accelerating in the South Pacific from the 2000s to 2010s compared to the 1990s to 2000s (Johnson et al 2014; 2019; Purkey et al. 2019). This variability may be driven by changes in deep ocean ventilation rates (Purkey and Johnson 2012). In addition, substantial deep ocean freshening has been observed in the Pacific and Indian sectors of the Southern Ocean (e.g. Aoki et al., 2005; Rintoul 2007; Purkey and Johnson 2013).

Recent technological advancements have led to the development of 4 new Argo models capable of reaching the deep and abyssal oceans: Deep Arvor and the Deep NINJA, with a pressure limit of 4000 dbar and the Deep SOLO and Deep APEX, with a pressure limit of 6000 dbar. Over the past 3 years, these new deep Argo floats have been tested in a number of regional pilot arrays. The international 2nd Deep Argo Workshop has been held at CSIRO in Hobart, Tasmania on May 13-15, 2019 in order to advance the global implementation of a Deep Argo array by:

- Presenting new Deep-Argo-based scientific results
- Reviewing the objectives of the Deep Argo Program
- Describing the Deep Argo float mission in support of Deep Argo's scientific objectives
- Confirming Deep Argo float and CTD readiness timetable for implementation of the global pilot array
- Reviewing plans for the deployments of Deep Argo pilot arrays

We summarize the workshop presentations, discussions, and key outcomes here. The workshop was organized to promote discussion between users and float providers, and speakers are indicated for each topic below.

2. New Deep Argo based scientific results in the context of the objectives of the Deep Argo Program

2.1. Deep Argo quantifies bottom water warming rates in the Southwest Pacific Basin

Speaker: Gregory Johnson

Data reported from mid-2014 through late-2018 by a regional pilot array of Deep Argo floats in the Southwest Pacific Basin are used to estimate regional temperature anomalies from a long-term climatology as well as regional trends over the 4.4 years of float data as a function of pressure. The data show warm anomalies that increase with increasing pressure from effectively 0 near 2000 dbar to over 10 (±1) m°C by 4800 dbar, uncertainties estimated at 95%. The 4.4-year trend estimate shows warming at an average rate of 3 (±1) m°C/yr from 5000-5600 dbar, in the near-homogeneous layer of cold, dense, bottom water of Antarctic origin. These results suggest acceleration of previously reported long-term warming trends in the abyssal waters in this region. They also demonstrate the ability of Deep Argo to quantify changes in the deep ocean in near-real-time over short periods, with high accuracy.

2.2. Deep-ocean circulation in the Southwest Pacific Ocean Interior: Estimates of the mean flow and variability using Deep Argo data

Speaker: Nathalie Zilberman

Deep Argo is a new source of ocean observations, complementary to GO-SHIP repeat hydrography and OceanSITES moored data, to characterize the large-scale ocean circulation from the sea surface to the sea floor. Here, Deep Argo profiles and float trajectories at parking depth, collected between 2016 and 2018, are used to describe the spatial structure, and to study the seasonal to interannual variability of the deep geostrophic flow in the Southwest Pacific Basin. Transport function (TF) estimates using Deep Argo data, show a broad southward flow in the 2200-3800-dbar layer, between the deep western boundary current (DWBC) region and the western flank of the East Pacific Rise (EPR); strong zonal TF gradients are indicative of flow intensification on the eastern flank of the Louisville Ridge (LR). The deep flow corresponds to a southward recirculation of a portion of the DWBC, which flows northward along the Tonga Kermadec Ridge. Time-mean absolute meridional transport, integrated vertically between 2000-4000 dbar and zonally between 172-160°W, is -1.9 Sv at 31°S, and -3.6 Sv at 37°S. Deep Argo-based transport estimates are consistent with previous moored observations at 32°S and 10°S. Monthly values of meridional transport show seasonal variability consistent with a deep expression of Ekman pumping. Measurements suggest a decrease in the deep transport at 37°S between 2016-2018, but no evident trend is observed at 31°S. Additional Deep Argo deployments are needed to extend the measurements of deep transport in the Southwest Pacific Basin from the DWBC to the EPR, and to assess the time variability of the transport on interannual to decadal time scales.

2.3. ISOW spreading and mixing from the Charlie Gibbs Fracture Zone as revealed by Deep Argo floats

Speaker: Virginie Thierry

To improve our understanding of the deep circulation, we deployed in 2015 and 2017 five Deep-Argo floats (0-4000m) in the Charlie Gibbs Fracture Zone (CGFZ) that channels the flow of Iceland-Scotland Overflow Water (ISOW), a dense water mass of the North-Atlantic Ocean. The floats, equipped with pressure, temperature, salinity and oxygen sensors, were programmed to drift at 2750 dbar in the ISOW layer. As expected, they first drifted westward within the CGFZ. Then, they followed different routes depending on northward intrusions of the North Atlantic Current (NAC) over the northern valley of the CGFZ. Although two of them recirculated eastward during a few cycles, the floats mainly moved westward within the ISOW layer. One float revealed a direct route for ISOW from CGFZ to the Deep Western Boundary Current at Flemish Cap. Oxygen data acquired in the CGFZ revealed that the ISOW layer, characterized by salinity higher than 34.94 and potential density greater than 1027.8 kg m^{-3}, was composed of the highly oxygenated ISOW and the less oxygenated North East Atlantic Deep Water (NEADW), a complex water mass from the eastern Atlantic. The relative proportion of the two water masses depends on the NAC or the float latitudinal position. The ISOW contribution is the largest in the northern valley of CGFZ and when the NAC is located further south. The interaction between the NAC and the deep vein favors mixing between ISOW and NEADW. Oxygen measurements from Deep Argo floats were essential for a better understanding and characterization of deep water masses mixing and spreading.

2.4. Rapid volume reduction in Antarctic bottom water off the Adélie/George V land coast observed by deep floats

Speaker: Taiyo Kobayashi

Recent changes in the Antarctic Bottom Water (AABW) off the Adélie/George V Land coast were examined using 20-months of observations with Deep NINJA floats and historical hydrographic surveys (Kobayashi, 2018). The salinity of the AABW along isopycnals was largely reduced by about 0.005 PSS-78 during the winter of 2011; since then, it changed little through the end of the float observation in August 2014. The thickness of the AABW layer decreased after 2011 by about 50 m yr^{-1}, which is four to five times the average rate since the 1990s. The change of density structure in the deep ocean is believed to have raised the local sea level by 5.0 mm yr^{-1} due to steric changes between depths of 1,900 and 4,000 dbar. This could explain the altimetric average increase of 5.8 (standard error; ±1.8) mm yr^{-1} for 2011–2014, coincident with a steric height change of 0.5 (±1.5) mm yr^{-1} for the upper ocean, 0–1,900 dbar, and mass-related change of about 2.0 mm yr^{-1}. The most likely reason for the large change in the AABW is the collapse of the Mertz Glacier Tongue in February 2010. The rapid contraction of the AABW could be due to a reduced supply of Adélie Land Bottom Water (ALBW) after the calving, and the associated decrease in sea ice production. The rapid contraction may continue for a long time because the drastic change of the icescape could prevent the ALBW supply from recovering to its pre-calving volume. The glacier collapse might prevent the AABW from freshening for a long time, even though the collapse would have initially resulted in a large isopycnal freshening of the AABW. Because it may take a decade or so for the supply of the ALBW to recover to pre-calving levels, the moderate freshening of recent decades could yield within 10 years an AABW that is fresher than the freshened AABW observed by the Deep NINJA floats.

2.5. Changes in bottom water of the Australian Antarctic Basin revealed by repeat hydrography and Deep Argo floats

Speaker: Steve Rintoul

Repeat hydrographic sections occupied between the late 1960s and 2018 are used to assess changes in the properties of Antarctic Bottom Water in the Australian Antarctic Basin (AAB). We focus on changes measured along the pathway of the two primary sources of bottom water to the basin, the Ross Sea Bottom Water (RSBW) and the Adélie Land Bottom Water (ALBW). The repeat sections reveal three phases in evolution of AABW properties in the Australian Antarctic Basin: a multi-decadal freshening/contraction trend; a sharp reduction in salinity and volume after calving of the Mertz Glacier Tongue; and a sharp rebound in salinity of dense shelf water and salinity/volume of RSBW (after 2014) and ALBW (after 2015). The increase in salinity, density and volume of RSBW and ALBW can be traced to changes in the shelf waters that supply bottom water to the basin. A new pilot array of Deep Argo floats is now mapping the evolving inventory of bottom water properties. Eleven floats were deployed in January 2018 (of which 9 are operational: 5 Deep SOLO, 3 Deep Arvor, 1 Deep NINJA). Three additional Deep SOLO floats were deployed in January 2019. To date, the USA, France, Japan and Australia have contributed floats to the pilot array. Floats in the sea ice zone survived the winter. A total of about 350 profiles to the bottom had been collected by May 2019. The Deep Argo data has been used to extend the time series derived by repeat hydrography and to map the bottom water properties in unprecedented detail. The causes of change in AABW and links to climate phenomena remain uncertain. The deep Argo pilot in the AAB will provide the continuous broad-scale measurements needed to better understand changes in AABW.

3. Describe the present status of Deep Argo technology based on pilot arrays

3.1. Float user-and-provider presentation

- Deep Arvor

Speaker: Virginie Thierry (user)

Forty-six Deep Arvor floats are currently registered in the JCOMMOPS database and 18 of them are active. Most of the floats were bought by France, with an increasing number of other countries purchasing Deep Arvor in recent years (UK, Spain, Italy, Norway, Europe, China). Most of the floats were deployed in the North-Atlantic. Two Deep Arvor were deployed in the Tropical Atlantic and 4 in the Southern Ocean. Deployments in the Med Sea and Norway will be done in 2019. Two Deep Arvor floats realized more than 140 cycles and some floats failed prematurely. The main causes were identified and fixed. Among the 16 floats deployed in 2018, 14 are still active. Twelve floats were deployed in the subpolar gyre and faced multiple groundings. Feedbacks from these floats helped refine the grounding procedure of the Deep Arvor float. The ice-avoiding algorithm worked efficiently. The software was improved after this first deployment, which also revealed the need to increase float memory to store high resolution vertical profiles. The floats can be equipped with oxygen sensors. Requirements from the Deep Arvor users are that providers continue improving the float reliability, and increase float lifetime.

Speaker: Jerome Sagot, nke (provider)

The Deep Arvor float has been initially designed by IFREMER and has been industrialized by nke instrumentation in 2014. This float, based on Arvor technology (core 0-2000 m Argo float), is able to acquire up to 145 profiles with the CTD in continuous pumped mode, or up to 200 profiles with the CTD in spot-sampling mode, to a maximum pressure of 4000 dbar. Since 2014, the Deep Arvor float has been continuously improved to fix early-cycle issues (i.e. hydraulic improvement, grounding mode optimization, integration process). New functions, such as high-resolution sampling while profiling (with meter resolution), in-air measurements for dissolved oxygen, ice-avoidance, and the capability to sample at a different resolution compared to the rest of the profile on few tens of meter (typically 50 to 100 m) above the bottom after grounding detection, have been introduced into the latest Deep Arvor firmware. Latest deployments made in 2018, show a significant improvement of overall reliability.

- Deep SOLO

Speaker: Dean Roemmich and the SIO Argo team (float developers and users)

Deep SOLO is a light (27 kg) 6000 dbar float housed in a 33 cm glass sphere and carrying a SBE-61 CTD. There are presently 55 operational Deep SOLOs located in regional Deep Argo pilot arrays, delivering data to the Argo data system. Another 46 Deep SOLO's are planned for deployment in the coming year. Deep SOLO's buoyancy hydraulics are based on the highly reliable SOLO-II, with some strengthening for high pressure. The buoyancy system has worked well in every Deep SOLO deployed to date. Problems in communication between the float and the CTD have been identified in several floats and are being corrected. Early Deep SOLOs with 4 primary lithium battery packs have been supplanted by newer versions carrying 5 hybrid lithium battery packs. Deep SOLO expends 27 kJ of energy per cycle and the new model is expected to have a battery life of 6 – 7 years (210 to 250 cycles to 6000 dbar). A passive bottom detection device enables the Deep SOLO to profile within 3 m of the sea floor on most cycles. Successful recovery of Deep SOLO has been carried out by several vessels, as well as CTD replacement and firmware updating on board recovery vessels – opening possibilities for diagnostic troubleshooting, problem correction, and float recycling. The high scientific potential of Deep SOLO as a major contributor to a global Deep Argo array has already been demonstrated through several research publications.

Speaker: Neil Bogue and Ronnie Nigash, MRV (commercial provider)

We appreciate the invitation to the Workshop, and our inclusion in the full proceedings. We strongly believe that the Argo program benefits from the contributions of all participants. And we thank our hosts at CSHOR, CSIRO, and the City of Hobart, for welcoming us to their home. MRV Systems was founded in 2010 as a spin-out from the Scripps Institution of Oceanography Instrument Development Group. In late 2015, MRV licensed the Deep SOLO design from IDG-SIO-UCSD. Greg Johnson, PMEL-NOAA, secured funding from the Paul G. Allen Family Foundation to become our launch customer for the Deep SOLO. The first five floats were delivered in May 2018. Two were deployed near the HOTS site north of Oahu later that month. To date, MRV has delivered eight Deep SOLO floats: five to PMEL-NOAA, and three to CSIRO (Steve Rintoul). Six have been deployed, and are performing nominally to date. Two more should be deployed in late-May 2019. The next order of 28 Deep SOLOs will be delivered to PMEL-NOAA in July 2019 for eventual deployment in the Brazil Basin. The lead-time for Deep SOLOs is currently nine months, dominated by the seven-month lead-time for the SBE-61 CTD. We require two months for final assembly, ballasting (at SIO), packaging and shipping. MRV's production capacity is between five and ten units per month, once the original lead-time has passed. The primary limitation is our use of the SIO ballast tank. We have a quote in hand to acquire and install our own ballast and pressure test tank, and plan to have this facility operational by mid- to late-2020. The MRV Systems plan was to carefully mimic the IDG-SIO Deep SOLO build and test procedures, given their nearly perfect performance record over the past three years. We are also collaborating closely with IDG-SIO on enhancements to Deep SOLO, including optional Iridium® RUDICS, optional RBRargo³ CTD, improved handling and recovery aids, ability to park a specified pressure above the bottom, and addition of Bluetooth local communications. We also plan to improve the pre-deployment test procedure, and provide a physical indication of pass-fail. MRV is improving the user-facing experience with a variety of piloting tools. These include Xdecode, our float data decoder that works on all SOLO-family and MRV floats, and Float Commander, a syntax-checker and command quality-control utility to minimize piloting error. Xdecode produces ASCII or JSON output. MRV has enhanced our customer-service capability, by hiring additional staff, creating an email address for support (pilot@mrvsys.com), and we will soon launch a refresh of our website www.mrvsys.com that will contain FAQs, tips and tricks, and a blog. We also noted that all quotes issued in the past two years for Deep SOLOs in small quantities (one to five) have been less than $70,000 (USD). This does not include shipping, customs brokerage, warranty assignment, or other costs beyond the base cost of the float itself. The price will be lower for large-quantity orders, and those economies of scale will be better known upon completion of the build of 28 Deep SOLOs for PMEL-NOAA.

- Deep APEX

Speaker: Brian King (user)

The UK has procured 14 Deep APEX, 10 with Aanderaa optode. Of these 14, two floats failed testing at NOCS and were returned to TWR. One float had antenna damage in shipping, and one had an Iridium communication problem associated with connecting to RUDICS at CLS. Of the 12 deployed, 4 have been recovered. s/n 7 developed a hydraulic leak at high pressure, and was recovered in the Atlantic along 24°N after 60 deep cycles. It will be redeployed. s/n 12, 13, 15 all developed water leaks after a few cycles, and were recovered from Drake Passage thanks to the efforts of the UK James Clark Ross and US L.M Gould. Recovery meant that faulty components could be identified. The water leak was through the interior of the glass-penetrating connectors, rather than at the connector-glass join, or the glass-equator join, as might have been thought more likely. In each case the float design has been modified to use different components. All floats have been operated in 3-day cycles with 2-dbar continuous profiling over full depth, in order to exercise the floats and gain experience as rapidly as possible.

3 floats survived early mortality but had later failures:
s/n 7 had a hydraulic leak after 60 cycles and was recovered
s/n 8 performed 50 cycles and went offline with no indication of cause
s/n 21 reported 160 cycles and is now 30 days overdue, probably with batteries exhausted. It was stuck on the seabed at 3506dbar, but exercising its full buoyancy, with associated energy cost, for 20 of those 160 cycles. However, PSAL was bad from cycle 3 onwards, and the optode failed to return good data after cycle 88.

4 floats are active and profiling in 3-day cycles, and have achieved 171, 92, 60 and 59 cycles (s/n 19,18,22,23).

Managing near-bottom sampling has revealed some problems to be addressed.
s/n 22 in the deep western North Atlantic has not reached the bottom in depths around 5900 m. The float was probably ballasted slightly cautiously, and minimum buoyancy produced a maximum depth of 5650 dbar (5540m). Deep APEX floats have previously reached greater

depths, so revised ballasting would likely solve this problem.

In order to understand some of the problems encountered, note that during one float cycle, the apf11 advances through several “mission states”, reported in the system log file transmitted ashore:
SURFACE – on the surface
PARKDESCENT – descending from surface to park depth (ParkPressure)
PARK – drift at the programmed park depth
DEEPDESCENT – descent from park to maximum profiling depth (DeepDescentPressure)
ASCENT – The ascending profile is collected during the stored rise of float
SURFACE – back on the surface

There are stored buoyancy positions, which can be updated in a mission control file, but which the float can also update itself as it learns the correct buoyancy for the park and maximum profile depths. These are the ParkDescentCount, the buoyancy position that should get the float to the park depth at the end of the PARKDESCENT phase, and DeepDescentCount, which should get the float to the maximum profile depth at the end of the DEEPDESCENT phase

Operating floats in Drake Passage where there is variable topography has produced unexpected behavior when grounding. The apf11 in the UK Deep APEX in Drake Passage (Firmware|07/18/16 20:08:07 DEEP_APEX-v2.3.18) recognizes grounding during DEEPDESCENT but not during PARKDESCENT. If the float reaches the seabed during PARKDESCENT, then it does not recognize grounding and keeps pulling in ballast in an attempt to go deeper. The float learns a new buoyancy position for the next cycle and produces unplanned action on the next cycle. It is therefore necessary to park shallower than any possible topography. If the floats ground during DEEPDESCENT, that has not been a problem. The descent towards DeepDescentPressure is aborted and the ASCENT begins. Grounding during descent towards park at 1000 dbar was not very likely in 2000-m APEX floats when the apf11 was designed. TWR will review grounding recognition and action during PARKDESCENT. The adoption of the bottom-approach passive wire/chain is now available on Deep APEX and will be used on future UK Deep APEX floats (see future plans). s/n 21 grounded and stuck on the seabed for about 20 cycles between 106 and 125, but then broke free and resumed normal cycling. Other firmware issues occurred (Firmware|07/18/16 20:08:07 DEEP_APEX-v2.3.18). Initially the Drake Passage floats were configured with both ParkPressure and DeepDescentPressure set to 3500 dbar. The fact that Park and DeepDescent pressures were the same prevented the float from learning the correct buoyancy counts for 3500dbar. The problem was resolved by setting ParkPressure shallower then DeepDescentPressure. s/n 18 had a problem on the first cycle on 17 Dec 2017. The float was programmed to park at 3500 dbar, but ParkDescentCount was set too shallow, at 1500 counts, and the float stopped descending at 2980 dbar. The PARKDESCENT state should have timed out after 911 minutes and progressed to the next mission state, but the timeout failed and the float remained in the PARKDESCENT state. At this stage it was presumed lost. An apf11 on-board monitoring program, referred to as a watchdog, created an event on 7 July 2018 and progressed the float to PARK and then DEEPDESCENT of cycle 1. The float system log reports a timeout after 29546 minutes (20 days). In fact, the elapsed time before timeout was 202 days. Float operation has become normal since. The reason why the float mission did not timeout properly, and a watchdog event did not progress to the next mission state, is unexplained at present.

Speaker: Shigeki Hosoda (user)

JAMSTEC has deployed 12 deep APEXs and suffered some experiences on hardware/ firmware troubles of deep APEXs. Salinity and oxygen profiles are largely biased and drifted with time (S/N:29). Oxygen profiles are too shallow above 1000 dbar depth (S/N:26). Sampled levels are sparse less than 10 (S/N:27). The problem was fixed releasing improved firmware, but the earlier instances are still under discussion with the manufacturer TWR. Recently buoyancy engine failures were found from several deep APEXs after deployment. Two of the floats went into emergency mode and drifted on the sea surface. TWR has implemented a potentiometer change with a microcontroller to interface between the potentiometer and APF 11 expansion board to provide more reliable positioning readings. Also, software modifications are applied replacing the potentiometer and releasing new firmware 2.12.2.4. Although many problems occurred in earlier deployments, the deep APEXs seem improved due to much hard work by TWR and users. Preliminary investigations of SBE61 CTD data were shown in this talk. Regarding salinity data on SBE61 of deep APEXs, small noise is detected in almost all profiles, whose amplitude is ~0.005 for salinity. Although we chose 4-dbar spot sampling (discrete mode) from the bottom to the surface, the noise amplitude is large relative to climate signals. Further, the sampling interval is variable between 1~ 7 dbar although spot sampling every 4 dbar was chosen on some deep APEXs. We are now discussing with manufacturers to resolve these problems for improvement of deep APEXs.

Speaker: Dan Ryan, TWR (provider)

Teledyne provides 6000-m Deep APEX profiling floats that were first deployed in 2012. After a solid initial design by Douglas Webb in 2010, the Deep APEX has matured with updates to materials and firmware for improved reliability. The Deep APEX profiling float is positioned to become an economical workhorse that meets the requirements of the Deep Argo Program. It is capable of running over 200 mission cycles. It includes features such as passive bottom detection, ice avoidance, hyper-retraction and long term profile storage. Ordinarily, to leave the surface, the float will adjust the buoyancy position to the value expected to take the float to the park depth (ParkDescentCount). Hyper-retraction allows the float to get off the surface quickly (perhaps in ice conditions) or move the float through a mixed layer more easily. The float can be configured to pull in extra oil at the surface (HyperRetractCount), and remain that way until a configured depth is reached (HyperRetractPressure). The float then returns the buoyancy setting to the count used for park (ParkDescentCount) and descends normally to the park depth. Profiles are collected during ascent and transmitted when the float surfaces. Profiles are also archived and can be retrieved again at any time. Mission and sampling behavior can be easily modified after deployment. Teledyne is a global organization of 23 product brands and

24/7 support to customers. Teledyne has delivered over 8000 APEX profiling floats. The Deep APEX is based on Teledyne's experience and design of other products that we provide. The Deep APEX supports the Sea Bird SBE-61CP CTD and is capable of supporting the RBR CTD. The Deep APEX also supports the Aanderaa 4831-MP Optode or JFE Advantech AROD-FT RINKO Optode. The Deep APEX profiling float implements dissolved oxygen in-air measurements using Scientific Committee on Oceanic Research (SCOR) Working Group 142 recommendations. The Deep APEX immediately descends and performs the normal Park and Profile mission with sampling during ascent. The Deep APEX is also capable of sampling during descent and Park. The Deep APEX float and subcomponents are tested multiple times during the manufacturing assembly process. Utilities are provided to customers for continued testing of the buoyancy engine, air engine, communications, GPS, CTD and sensors before deployment. When deployed, the Deep APEX reports vital information during each mission cycle. Vitals include internal vacuum, humidity, leak detection, coulomb counter, battery voltage and battery current. Teledyne values customer input and looks forward to helping the Deep Argo Program reach its goals.

- Deep NINJA

Speaker: Taiyo Kobayashi (user)

Deep NINJA is a Deep Argo float that can observe temperature and salinity up to the depth of 4,000 dbar. It is available in the global ocean; in the Antarctic region seasonally covered by sea-ice, it can operate safely with a function to detect/avoid sea ice. The salinity measurements have fresh bias with pressure dependency, the details of which are referred to in the description of the CPcor session. Recently, the manufacturer, TSK, released a new model with an oxygen sensor (AROD-FT: RINKO type oxygen sensor provided by JFE Advantech, Japan), and the measurements are fairly accurate in general. The details of the oxygen measurements are referred to in the description of the RINKO oxygen sensor.

Speaker: Anthony Escarcega, TSK (provider)

The Deep NINJA is a 4000 m profiling float jointly developed with TSK and JAMSTEC in 2012. First deployed in 2012, the Deep NINJA was the first Deep Argo style float commercially available. Since then, a total of 24 Deep NINJAs have been deployed, mostly in the Southern Ocean.

The Deep NINJA has several attributes that make it adaptable to the needs of the scientific community:

- Ice Avoidance - Based on temperature and pressure, while ascending, the Deep NINJA can anticipate if there is surface ice and it is not able to come to the surface.

- Bottom avoidance - The Deep NINJA is flexible in regards to the bottom parking, or maintaining a level above the bottom.

- Highly programmable by the user to make changes in many parameters. These can be made via direct programming, or via Iridium satellite. Some recent examples: The Deep NINJA has been primarily deployed in the Southern Ocean, and in doing so, has experienced sea ice. The longest that a Deep NINJA has been underneath the sea ice is 8 months. And during this time, the Deep NINJA has performed "ice avoidance is 14 times" For Bottom Avoidance, the Deep NINJA float with the most "bottoming" has been 40 times. Currently, there are 6 active Deep NINJA floats. TSK is collaborating with Rockland Scientific and Tokyo University in the development of a turbulence sensor on a profiling float. Recently, a Deep NINJA has been deployed off the Japanese coast in December of 2018. The float was deployed for 6 months, and recently retrieved in April of 2019. The data has been collected, but it is currently being analyzed. The mission has been a success. TSK is currently improving the Deep NINJA in three phases:

- Improved buoyancy engine - The improvements in the efficiency should increase the current design to 100 cycles with the current design. This will occur during years 2020-2021

- Decreased size and weight - The current Deep NINJA is too large. In order to meet the standards of 150 cycles, a large weight reduction is necessary. This will occur during the same time period.

- Total package integration: 2021-2022

- A 6000 m float is being considered. TSK recognizes that the standard for the Deep Argo program is a 4-5-year float, meaning 200 cycles, reliably. We are working with our engineers to meet these standards.

3.2. CTD user-and-provider presentation

- SBE-61 CTD and extended-depth SBE-41 CTD

Speaker: Nathalie Zilberman (user; SBE-61 CTD)

The SBE-61 CTD has been developed by Sea-Bird Scientific for use on 6000-m capable Deep Argo floats, including the Deep SOLO and Deep APEX models. Out of 30 Deep SOLOs deployed between 2016 and 2018 in the Southwest Pacific Basin, 17 CTDs (~57%) show salinity within 0.004 PSS-78 of nearby reference data, on potential temperature surfaces corresponding to pressure higher than 5000 dbar. These estimates are based on SBE-61 data corrected for compressibility of the conductivity cell, as recommended by Murphy and Martini (2018). A salty drift is typically observed in SBE-61 data about 1-2 years after deployment. Measurements show three types of drift, including linear correctable drift, hybrid linear/oscillating semi-correctable drift, and "catastrophic" uncorrectable drift. Out of 11 Deep SOLO floats deployed in 2016, 6 CTDs (~54%) drift salty, including 2 CTDs showing linear drift, 1 CTD showing semi-correctable drift, and 3 CTDs showing uncorrectable drift. SBE-41 CTDs mounted on regular 0-2000 m Argo floats, show similar salinity failures. The cause for SBE-41 and SBE-61 salty drift is not well understood. Static pressure measurements from dead-weight testing indicate SBE-61 initial pressure accuracy is within the target of 3 dbar, but the pressure sensor stability is not yet well defined in the field. A collaborative NOPP proposal between Scripps Institution of Oceanography, Sea-Bird Scientific, PMEL, and WHOI, has been funded to improve the accuracy and stability of the SBE-61 CTD. A 14-day cruise, part of the NOPP project, is scheduled in 2020-2021. Objectives are (i) to define the SBE-61 pressure and salinity errors through comparison with synchronized shipboard data from CTD casts, and (ii) to validate the stability of SBE-61 pressure using 6 Deep SOLO floats equipped with a second stand-alone pressure sensor.

Three Deep SOLO floats deployed in the South Australian Basin and Southern Ocean have shown communication issues through the cable that connects the float to the CTD. A suitable solution — with minor trade-off in energy consumption of 1 profile over a 250-cycle float lifetime — would be to use RS-232 protocol instead of the logic-level communication system.

Speaker: Virginie Thierry (user; extended-depth SBE-41 CTD)

France deployed 20 Deep Arvor floats equipped with an oxygen sensor in the subpolar gyre of the North-Atlantic Ocean. For 18 of those floats, a reference profile was acquired at float deployment. The quality of the salinity measurements was assessed by running the OWC method and by comparing the first float profiles to the reference profile when possible. Results of the OWC generally agree with the comparison with the reference profile when considering the deep layers. For most of the floats a fresh offset is found (positive correction). The offset varies between -0.003 PSS-78 and -0.017 PSS-78. Two floats experienced permanent or temporary jumps towards larger fresh bias and one float experienced a linear salty drift.

We investigated the pressure dependency of the fresh offset in computing the salinity difference between the float and the reference profile on float theta levels. Salinity differences on theta levels (ΔPSAL) are then plotted against float pressure. Moving averages of ΔPSAL over 1000 db are computed at different levels and a weighted linear fit is calculated. The fit provides the intercept at surface (y0) and the slope (r). In most cases y0 was negative and generally varies between -0.004 PSS-78 and +0.001 PSS-78. For three floats, y0 was found to be less or equal to - 0.012. Considering now the slope, except for three floats for which the slope estimate was not significantly different from zero, we found values in the range of [-0.001 -0.002] /1000db. Those negative slope values reveal a pressure dependency of the fresh bias and are consistent with new CPcor values provided by other groups (Taiyo Kobayashi, Sarah Purkey and Greg Johnson). Salinity data of our Deep Arvor floats were corrected based on the results of the OWC method that considers a constant offset over the water column. Considering the differences between correction proposed by OWC and y0, we estimated that the surface salinity of the floats might be overcorrected by 0.007, which is still in the target accuracy of core Argo salinity (+/- 0.01). The correction will be revised based on new findings about CPcor. Before running the OWC, we investigated the quality of the reference data base in the North-Atlantic ocean and found more than 500 suspicious profiles. These profiles have been reported to the Coriolis Team and are now excluded from the Argo CTD reference database (2018v02). As part of the European project EA-RISE, an inter-comparison exercise will be conducted by France and Spain. France will deploy two 3-head deep Argo float equipped with an SBE41 on the head and an RBR and an SBE61 on the flanks. Spain will deploy two 2-head deep Argo floats (RBR on the head / SBE61 on the flank). The deployment will be done in the North-East Atlantic and in the Canary Island where the deep waters are stable.

Speaker: Dave Murphy, Sea-Bird (provider)

Dave Murphy presented work in progress to improve the accuracy, drift and dynamic performance of the SBE-61 pressure measurement and efforts to understand and improve drift performance of the conductivity sensor. Currently the SBE-61 is deployed with a 7000 dbar full range Kistler sensor. Pressure sensors from four other manufacturers are being integrated into the SBE-61 as prototypes. Results are presented from initial testing of bench top accuracy, performance in a dynamic temperature environment and noise evaluation. Improvements are noted in dynamic response and noise level. In-situ drift of the conductivity sensor deployed on the SBE-61 is discussed using examples of drift observed in the Deep Argo pilot array. Two SBE-61s that were drifting rapidly in the field were recovered and returned to Sea-Bird after an extended time in storage. These sensors showed small and typical drift in post deployment calibration rather than the exponential uncorrectable drift seen in the field. These observations are discussed as well as some results from deployments of experimental conductivity cells on a mooring near the Hawaiian island of Oahu. These results show the effect of changes in the physical properties of the conductivity cell materials.

- RBR CTD

Speaker: Virginie Thierry (user)

In the aim of equipping part of the Deep Argo fleet with RBR CTD, we tested the CTD during two cruises (RREX2017 and OVIDE2018). During the cruises, the RBR CTD was mounted following RBR recommendations, that is, face to the flow during descent and away from magnetic disturbances. The RBR replaced one bottle on the carrousel. It was placed very close to the SBE911 for inter-comparison, that is at a distance < ~20cm, but far enough to avoid proximity effects. During RREX2017 and OVIDE2018, 125 and 42 RBR profiles were acquired, respectively. The deepest profiles were at about 4500db in 2017 and 5500db in 2018. The RBR data were first pre-processed to align conductivity with temperature in time, to adjust conductivity for static pressure effect, to apply pressure compensation, to adjust conductivity for static temperature effect, to apply conductivity cell temperature correction and finally to adjust conductivity for dynamic temperature effect. We first compared the RBR pressure with the SBE911 pressure on bottle levels. Although the pressure difference between the two sensors lies within initial accuracy of ±3 dbar (0.05% FS of 6000 dbar) and within core Argo accuracy ±2.4db, there is a systematic pressure dependence that RBR attributed to a static pressure correction model issue. The pressure difference between the two sensors has been significantly reduced when considering the updated RBR static pressure correction model (updated in March 2019). When considering the temperature difference, a small linear pressure dependence was observed for the RREX17 stations. This linear pressure dependency was corrected and RBR temperature data collected during OVIDE18 exhibit temperature difference within initial and core Argo accuracy (±0.002°C). Regarding conductivity, RREX17 data indicate that improvements in modelling the response of the conductivity sensor to pressure was required. However, the bias had a systematic pattern meaning that it is correctable. During OVIDE2018, the conductivity sensor failed and drifted significantly. To conclude, we had very good interactions with the RBR team. The pressure and temperature sensors are suitable for Deep-Argo. Some work is still necessary on the conductivity sensor. In the future, we will continue to interact with RBR in testing the RBR CTD during cruises (next: RAPID-2020). We will also work within EuroArgo-RISE project on two deep Arvor three-CTD (SBE-41, SBE-61, RBR) and two-CTD testing prototypes (SBE-61, RBR).

Speaker: Greg Johnson, RBR (provider)

RBR has developed their deep CTD (RBRargo|deep6k) over the past few years. There are four main results obtained through the work done in collaboration with IFREMER, JAMSTEC, and DFO Canada: (i) conductivity cells currently require individual pressure characterization due to manufacturing inhomogeneities, (ii) the best model for pressure correction is a power law, (iii) anomalous manufacturing gives anomalous results - more attention is required to ensure consistent quality, and (iv) salt water pressure tank testing is a useful technique for cell characterization and to complement rosette comparisons.

3.3. Discussion on Deep Argo CTD standards (lead: Sarah Purkey)

At present, all 4 models of Deep Argo floats are using CTD sensors from Sea-Bird Scientific. The two 6000-m floats are using the SBE-61 and the two 4000-m floats are using an extended version of the core Argo CTD, the SBE-41CP. There have been no reported systematic issues with the temperature sensor, the primary focus was on addressing accuracy and stability of the conductivity and pressure sensor.

Both a time-dependent salinity drift and pressure-dependent salinity bias were discussed. All groups reported observing a slight pressure dependence in the conductivity cell that led to up to 0.007 fresh bias by 6000 dbar. This was discussed in detail on day three (see DMQC discussion on CPcor). During this discussion, we focused on observed salinity drift with time. Two primary modes of salinity drift have been observed (1) a slow linear drift and (2) a sudden catastrophic exponential increase in salinity. Both modes of failure are observed in Core Argo and Deep Argo CTDs. Two of the deep SOLOs that experienced the catastrophic salinity drift where recovered and sent back to Sea-Bird Scientific, but the issue reversed by the time it arrived back in Seattle and no conclusion has been made about the cause of the sudden catastrophic exponential drift. It was pointed out that this drift was similar to what is observed in Core Argo. Sea-Bird Scientific said they are continuing to look into it. RBR emphasized that this is a good reason to diversify the array and use multiple vendors for the CTD.

The pressure sensors accuracy and the possibility of using a different type of pressure sensor on the SBE-61 was briefly discussed. Sea-Bird Scientific is working with N. Zilberman to explore different pressure sensor options through a current NOPP project.

Finally, requirements to move forward with global implementation were discussed. The consensus was that while issues still remain to reach the target accuracy of 0.001°C, 0.002 PSS-78 and 3 dbar for temperature, salinity, and pressure respectively, the current SBE deep CTD sensors are performing well. None of the currently known issues should slow progress towards global implementation. However, causes of the conductivity cell failures should continue to be explored (as with Core Argo) and the Deep Argo group agreed that the deep fresh bias in the whole array (despite its relatively small magnitude), possibly attributable to conductivity cell compressibility, was concerning and needed to be further explored and addressed as soon as possible.

3.4. Oxygen sensor user-and-provider presentation

Speaker: Virginie Thierry (user)

Based on the work of many people, knowledge of the optode sensor greatly improved over the last years. This knowledge is summarized in Bittig et al., 2018 paper. The response of the optode sensor to temperature and dissolved oxygen concentration is well characterized. A foil multipoint calibration (T, O2) is recommended to convert raw measurements (PHASE) to the physical parameter (DOXY, PPOX). Based on the current knowledge, a two-step correction is required to take into account the pressure response of the sensor. First, a pressure dependent offset correction has to be applied to the phase data. A second pressure correction, that is also temperature dependent, has to be applied to O2. The sensor is known to exhibit both a storage and an *in situ* drift. The O2 sensitivity loss during storage (O(5 %) / year) is generally greater than the observed in situ drift O(0.5 % / year). When the sensor went through a lab multipoint O2-T calibration, the drift observed during storage can generally be adjusted with a slope only, which means that 1 point at high *p*O2 is enough for the adjustment. To correct the *in situ* drift, long-term deployments need a long-term way of referencing, such as regular in-air measurements. Most of the Deep Arvor floats were equipped with an Oxygen optode. The comparison with ship-based high-quality reference profiles revealed that an additional pressure correction was required on many of the floats. While a simple pressure correction model helps to remove this pressure dependent bias, its origin still needs to be determined.

Speaker: Taiyo Kobayashi (user)

A new RINKO optode type oxygen sensor of AROD-FT for deep floats was developed by JFE Advantech (Japan). The sensor has an advantage of the quicker response (< 1 second for 63%). JAMSTEC has deployed 4 Deep NINJA floats with this sensor in the ocean. The oxygen measurement by the sensor was very good; the first float DO profile was almost coincident with the shipboard CTD measurement at deployment, within (smaller than) 5 μmol kg^{-1}, except for the oxycline layer. In time, the bias of the slope component (against oxygen measurements) was decreased quickly from about 0 to about -0.03 within several cycles. The AROD-FT sensor was mounted on Deep APEX, and JAMSTEC has deployed 2 floats; their performance was not yet assessed.

Speaker: Brian King (user)

Brian King presented results from moored SBE-63 oxygen sensors on the 26°N mooring array.

- 36 sensors had been deployed for 18 months each.
- 18 of the sensors had been moored at depths between 1500 and 3500 dbar.

All sensors show identical behavior: oxygen concentration reported by the sensor drifted to lower values over the 18 month deployments. The effect was greater at greater pressure, and as large as 20 μmol kg^{-1} over 18 months at 3500 dbar, but more typically 5 μmol kg^{-1} at 1500 dbar. The sensor drift could be modelled with exponential decay with three timescales of 1, 10, 150 days. The behavior was similar for each sensor, but the amplitude of each exponential decay varied slightly from sensor to sensor. Similar behavior has been noted on other moored sensors including Aanderaa and Rinko. It appears to be a general property of the sensor foils used in each instrument type. The effect seems to be entirely reversible when the sensor is returned to surface pressure. Therefore, if the sensor is reporting low values at 2000 dbar after immersion, the vertical structure of that sensor anomaly, as pressure is reduced to surface pressure, is unknown at present. This is believed to be a pressure-dependent effect that is only present after prolonged immersion, not captured in the present recipes for oxygen processing. It is possible to see signs of this slow creep in floats parked at 1000 dbar for 10 days. Brian King has observed it on NAVIS/SBE63 floats in the SE Atlantic. The effect therefore needs to be characterized for both core and deep floats. The size of the effect will almost certainly be greater for floats parked at deep pressure compared with floats parked at 1000 dbar.

3.5. Discussion on the use of oxygen sensors on Deep Argo floats (lead: Virginie Thierry)

Virginie Thierry showed how oxygen data have been used in the North Atlantic to distinguish and trace two deep water masses that have similar T, S properties. Steve Rintoul mentioned that the Ross Sea experienced changes in T, S properties and volume of deep water masses. As there was no change in oxygen, it was possible to eliminate changes in ventilation as the cause of the T/S changes. Using oxygen data for such studies however requires accurate measurements. While large progress has been made over the recent years on the characterization of the optode sensor, especially for core Argo floats, some work still needs to be done for further understanding of the pressure response of the sensor. In addition, reference measurements are still required to adjust the data, which means that the sensor is not fully ready for global implementation. Besides the usefulness of oxygen measurements for regional studies (ventilation, water mass tracer), oxygen measurements should be done at global scale for estimating change in global oxygen inventory in order to follow global deoxygenation. A case study has to be performed to investigate whether monitoring the global oxygen inventory in the deep (2000-4000 dbar) and in the abyssal layer (>4000 dbar) should be done through the Deep Argo array or should be continued with GO-SHIP lines. To conclude, regional pilot arrays with oxygen measurements are encouraged to continue to better assess the quality of the sensor and to investigate how to do the DMQC of the data. In parallel, scientific motivation and corresponding missions for a global or regional Deep-Argo-O2 array should be established.

4. Describe the Deep Argo float mission and determine requirements to achieve Deep Argo's objectives

4.1. Input from the modeling community on the impacts of Deep Argo data on data assimilation and modeling activities

Speaker: Florent Gasparin

Most ocean reanalyses are consistent in representing the upper-ocean physical conditions at interannual and longer time scales, but can strongly differ in representing the deeper ocean. Due to a lack of frequent and global deep ocean observations, ocean reanalyses are hardly qualified in the deep ocean. Ensemble-based strategies demonstrate that large uncertainty exists in current global ocean reanalyses in representing temperature and salinity fields in the deep ocean (below 2,000m). Additionally, independent comparisons with the deep pilot array dataset suggest that reanalysis errors in the deep ocean are of the same size, or even stronger, than the deep ocean signal. The current deep ocean observing system appears to be not sufficient to properly constrain ocean reanalyses at regional and global scales.

A series of numerical experiments based on Observing System Simulation Experiments (OSSE) have been carried out within the H2020 AtlantOS project. In these OSSEs, ocean observing system data sets are extracted from a realistic simulation, to be subsequently assimilated in an experimental system.. Results suggest that a global deep Argo array composed of 1,200 floats will significantly constrain ocean reanalyses by improving the deep ocean representation of water masses, and will better capture large-scale variability. Such a deep global array will help ocean reanalyses to capture key signals in the deep ocean by significantly increasing the signal-to-error ratio of ocean heat gain below 2000m. Additionally, the comparison of numerical experiments has shown that information embedded in the abyssal layer (below 4000m) could not be completely captured by a global array only composed of deep floats going down to 4000-m.

Dedicated experiments so far have focused on the ability of the Mercator Ocean system to ingest information from Deep Argo floats. Other design issues could be further investigated, e.g., sampling accuracy and inhomogeneous sampling density. Most of the current global models have less than 100 vertical levels (e.g., 75 levels including 26 in the upper 200 m, from 1 m at the surface to 200 m at the bottom for the Mercator Ocean reanalysis), making OSSE a useless tool for investigating the vertical sampling of Deep Argo. However, this provides some guidance about the requirements for operational oceanography with regard to the required vertical sampling. Such work also aims to deepen the relationships between data assimilation/modeling/observational experts to refine assimilation procedures (e.g., correlation scales, observations errors) and process parameterization (e.g., in water mass formation) and adapt them to the deep ocean.

Speaker: Shigeki Hosoda

Deep Argo floats promise to provide unprecedented deep ocean information, especially on heat/freshwater budget, deep ocean currents, and their climate-related changes. Here we applied deep float data deployed by JAMSTEC to a deep ocean state estimation (ESTOC K7), mainly including Deep NINJAs deployed so far, by using a four-dimensional variational approach. The results demonstrate that the available deep NINJA float data enables some corrections of the modeled ocean state. The bottom water warming in the abyssal layer is improved to be more realistic comparing with previous version of the ESTOC data in which the Deep Argo float data were not included yet. Further, the slowdown of abyssal warming is detected in recent decades in the North Pacific, based on the ESTOC including Deep Argo data. Although the impact of the data on a basin-scale deep ocean state estimation was still limited in this study due to sparseness of available float data, changes in deep ocean state, including bottom-water warming, will be further revised by assimilating global deep float data.

4.2. Discussion on Deep Argo float mission and sampling requirements (lead: Brian King)

- We recall that deep floats should sample in a way that delivers cycles with resolution and timeliness that makes them a contribution to the ‘core’ 2000-m array.
- Deep Argo aims to sample the full ocean volume, to the seabed or to 6000 meters if the ocean is deeper than that.
- The ocean volume below 2000 m represents 51.2% of the total ocean volume, 39.5% for the 2000-4000m layer and 11.7% below 4000m. Of the area of ocean where the depth is greater than 2000m, approximately 35% is in the depth range 2000-4000 and 65% deeper than 4000m. If 4000-m capable floats are operating where the ocean depth is

more than 4000 m, there need to be sufficient 6000-m floats to resolve the signals of importance.

- The following points were agreed in discussion as being the default profiling mission for deep floats. From time to time there could be considerations that require changes to this mission. The sampling is a ‘minimum’ aspiration, that will meet the science goals of the array. Some floats may be capable of extra sampling.

Float Mission/programming summary

Floats will operate on a 10-day cycle.

Floats will sample to near-seabed. For Deep SOLO and Deep APEX, this means a couple of meters above the seabed, by use of the bottom-approach hanging wire/chain. Where the seabed is less than 4000m, Deep Arvors and Deep NINJAs can measure to the seabed by ‘grounding’. Mission controller software will then enable the float to rise from the seabed. Grounding in this way does not appear to harm float survival.

Parking: During pilot experiments, floats can park deep if they choose. This will reduce the number of floats flushed out of the pilot basins and make direct measurements of abyssal circulation. As we move to global we need to consider the pros and cons of parking at the core global array depth of 1000 m. In order to depart from the core parking depth of 1000 dbar, a compelling argument will need to be made.

Vertical sampling: Proposed at least 10dbar spot sampling deeper than a threshold, and 2 dbar continuous profile above the threshold. The threshold might be in a range of 2000 dbar to 500 dbar, dependent on local gradients and variability.

Upper-ocean near-real time (NRT). SOLOs measure their main profile on descent, and deliver it at the end of the cycle, typically 10 days later. This does not meet the core profile requirement of quick delivery for operational assimilation. In order to contribute to Core Argo, Deep SOLOs could measure an additional shorter profile on ascent. The requirements of this profile for vertical extent and resolution need to be determined.

Resolution: Some floats return data with 3 decimal places of T & S. Even if the absolute accuracy of the profile means that 3 decimal places seems appropriate, relative accuracy within the profile means that 4 decimal places are meaningful, e.g. for stratification. All floats should consider sending 4 decimal places of T and S.

Other comments on the mission

Enhanced near-bottom sampling – There was discussion of the possibility of higher vertical resolution sampling in a few hundred meters above seabed. This is not initially part of Deep Argo’s central science questions, but we should prepare to do this if a good case is made, perhaps in particular regions. Enhanced near-bottom sampling would have a small extra cost on the energy budget. Floats could probably increase resolution to 5-dbar near bottom without too much energy cost.

Other comments

Floats should aim to deliver a mean lifetime of at least 4 years of 10-day cycles (146 cycles). An average of 4-year lifetime will be achieved for example if 70% of floats reach 4 years and some last longer.

An average of 4-year lifetime requires 300 new floats per year to have a sustained array of 1200 floats.

Float types that reach the seabed should review their behavior on grounding detection and action taken when grounded, to minimize risk to the float.

The prospective cost of profiles is USD 500 per 6k profile. 75% capital purchase, 25% other lifetime costs. 4k profiles should cost less.

Float vendors and operators should review the action taken by floats when grounding during either descent to parking depth or descent to maximum profile depth (where this is meaningful for the float type). Grounding action should minimize risk to the floats. Grounding actions need to be described and recorded in metadata so that trajectories can be interpreted correctly.

Action items

#1: Undertake some studies on how core floats parked at 1000 m have been flushed out of the basins where deep pilot arrays operate. (Action not yet assigned)

#2: Undertake analysis to determine the value of trajectory data at 5000 dbar. (N. Zilberman)

#3: Determine the cost (energy or telemetry) of enhanced near-bottom. (V. Thierry)

#4: Float operators to determine the energy and telemetry cost of the recommended sampling of 10 dbar spot sampling and 2 dbar continuous either side of a threshold. (Action not yet assigned)

#5: Determine vertical extent and resolution of required extra NRT profile for SOLOs. (P. Oke)

#6: Determine the feasibility and cost of sending 4 decimal places of T&S. (Float vendors who don't already do this)

5. Strategies for implementing Deep Argo Quality Control

5.1. How can the core (0-2000 m) Argo methodology be modified for Deep Argo real-time mode quality control (RTMQC) and delayed-mode quality control (DMQC)?

Speaker: Brian King

CPcor – There is an ongoing task team on salinity calculation including CPcor.
One option would be to apply real-time adjustment to float salinity using a representative CPcor value, eg 13e-8. This may not be perfect for all floats, but might enable a real-time dataset with , eg, a deep uncertainty in S of 0.002 with small/zero mean bias, rather than the present real-time dataset which has a fresh bias of order 0.005. This is analogous to applying RT salinity adjustment to floats with known offsets, and results in PSAL_ADJUSTED, PSAL_ADJUSTED_ERROR, PSAL_ADJUSTED_QC all filled, and a data mode of A.

A value other than 13e-8 could be chosen, especially where it has been determined for a float cell by analysis of early profiles.

CPcor – we request that manufacturers make no change to the onboard value of CPcor at this stage, to ensure correct tracking of float salinity calculations. This request can be reviewed as understanding of CPcor increases.

CPcor – it is very important that data centres track the value of CPcor used in on board salinity calculation, especially if this is changed in the future.

CPcor – there remains analysis and investigation of CPcor in SBE41 and SBE61. Some of this analysis could carry over into core QC.

Uncorrectable salinity drifts – ongoing understanding and cataloguing of salinity drift pathologies, to inform DMQC.

Brian King drew attention to some aspects of DMQC for which practices developed for core Argo may need to be reviewed or revised. These passed largely without comment, but are included here for completeness. Comments for Core (C) and Deep (D) Argo

1) Pressure

C: Can't do much about pressure except note surface offset and adjust with single offset

D: Need to be aware that PRES errors might be depth dependent. Possibly the PRES_ADJUSTED_ERROR should be set to vary with depth, to reflect the larger uncertainty at the bottom of the profile, even when we think we have adjusted PRES correctly.

2) Do we assume the factory calibration of salinity has accuracy/uncertainty smaller than the uncertainty we want in our final calibrated observations, unless proven otherwise ?

C: Null hypothesis is that CTD is good, unless comparison with reference data provides strong enough evidence that this assumption is wrong and an adjustment must be made. This approach was adopted after a lot of experience and as SBE41 improved.

D: We need to get experience to support this approach. If we only make adjustments clearly above a threshold, but the raw data have a small bias, we could end up with a biased dataset.

3) Adjustment of PSAL may be depth-dependent

C: Assumption that when S needs to be adjusted, a single adjustment is adequate for the whole profile. This adjustment can be determined by comparison with reference data in one or more water masses, and is applied to the whole profile.

D: Strong evidence that this is not yet the case. Therefore, need to determine S offset at as many depths where ocean properties and reference data allow. Need to develop and share techniques and tools for doing this. Need to aggregate experience of vertical dependence of S error, and agree on application.

4) Should we make small adjustments to salinity ?

C: The minimum size of S adjustment that is determined with significance is determined from variability in the reference data. There is a commonly used threshold of 0.01. Adjustments smaller than this are not determined reliably by the statistical process.

D: We need to understand the uncertainty of any comparison methodology used in Deep, and be consistent about when we apply adjustments.

5) Is there an upper threshold for S adjustment, above which we think the data are uncorrectable ?

C: There is an upper threshold for adjustment. If S offset appears to be bigger than this, data are marked as bad. A strong consideration is that if the offset is very large, we have no confidence that it is depth-independent, so even if it appears well determined in one water mass, this may not fix a whole profile. Also, when the offset has become large, the cell often deteriorates quickly afterwards.

D: We need to understand the vertical variation of S drift at large drifts, and decide when to declare the profile as unrecoverable.

6) Reference data for DMQC

6) C: Initially, a large climatology of reference data was used. Variability in those data determined the uncertainty of any adjustment made, and also determined the uncertainty of any data not adjusted. Good nearby floats become a useful reference.

D: DMQC will depend on reference data selected for high quality – GO-SHIP is willing to help assemble this dataset. Deep Argo should interact and assist with this activity to ensure the product to meets the needs of Deep Argo.

We need to be very selective about reference data if we want to have confidence in unadjusted or adjusted deep data. The simple statistical approach from OWC may not always be the best way to evaluate Deep data.

7) PSAL_ADJUSTED_ERROR in Deep data

7) C: Uncertainty (PSAL_ADJUSTED_ERROR) is generally determined from the variability in the reference data as returned by the mapping error. If the adjustment is chosen to be zero, but the mapping error is large, i.e. lots of ocean variability, we in effect say "We believe the data are good without adjustment, but we still have a large uncertainty because we could not have detected a small error".

D: We need to develop and then apply consistent methods for assigning ADJUSTED_ERROR, whatever technique is used to estimate the adjustment. ADJUSTED_ERROR may be depth-dependent. For example, we might determine a deep adjustment very well, and have a small ADJUSTED_ERROR for deep data, but be uncertain about the pressure dependence and therefore have a larger ADJUST_ERROR in the upper ocean.

Action items

#1: Remind DACs at ADMT that on board salinity calculation parameters must be tracked, especially CPcor.

#2: Restate P, T, S _QC (RT) and _ERROR (DM) on SBE41 SBE61 at ADMT and AST.

#3: agree RT flags for oxygen and RBR CTD.

#4: Work with GO-SHIP/CCHDO on compiling/selecting highest-quality reference data for DMQC.

5.2. How to build a high-accuracy reference dataset for Deep Argo?

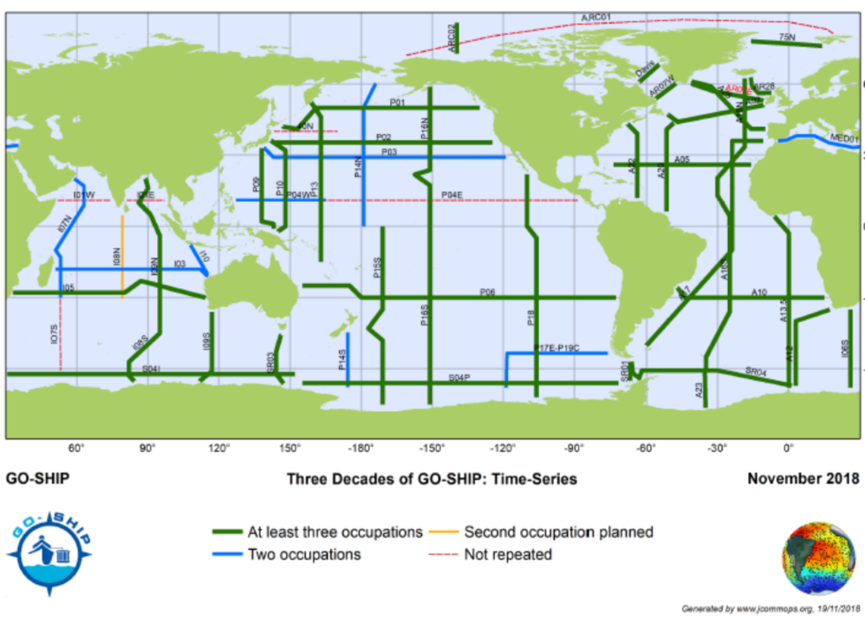
Speakers: Katsuro Katsumata & Bernadette Sloyan

Most deep salinity data with sufficient accuracy for calibrating the conductivity of Deep Argo floats have been and are being collected through the GO-SHIP (Global Ship-based Hydrographic Investigation Programme) cruises. With the discovery of deep salinity changes e.g. in the Southern Ocean, the use of these hydrographic data for calibration/validation may not be a direct extension of the core Argo technique. Streamlined access to the data from GO-SHIP and its predecessors, CLIVAR and WOCE, needs to be facilitated. A difficulty with these data[*1] comes from its rather raw format in the archive. A user must choose the right cruises, trim duplicate casts, apply Standard Sea Water batch correction, etc. before using the data for delayed mode quality control and salinity drift correction of the Deep Argo Data.

Here, we introduce a new format, "clean" sections[*2], which has spatial coordinates either on observed station location or a longitudinal/latitudinal grid, and to which the initial processing has uniformly been applied. The output is controlled by a master "station list" file. Users can choose which stations to be included in the final output in this master file. It is thus easy to produce both gridded section output (for plotting, differencing, comparing with simulation output) and output with all stations included (for float calibration). Thanks to the high precision/accuracy of the GO-SHIP output, the product serves as an initial minimal dataset for reference data for Deep Argo calibration, to be expanded by adding data after quality screening.

*1 https://cchdo.ucsd.edu/

*2 https://github.com/kkats/WOCE-GO-SHIP-clean-sections



5.3. Correction for compressibility error of the conductivity cell

- SBE-61 CTD

Speaker: Gregory Johnson (user)

Conservative temperature-absolute salinity curves for the first full-depth profiles from Deep SOLO floats 5905738 (cycle 7) and 5905739 (cycle 7) are compared with that for a carefully calibrated shipboard CTD profile from HOT cruise302. The salinity from the floats tends to get fresher with increasing pressure relative to that from the shipboard CTD. These differences reach 0.006 and 0.007 g/kg near the sea floor (around 4800 dbar). We assume that an error in the nominal value of the pressure correction coefficient (CPcor) is the cause of the difference. The Deep SOLO floats are equipped with SBE-61 CTDs and the HOT cruise was with a SBE-9plus CTD calibrated to bottle salinity samples standardized with IAPSO Standard Sea Water. The data were collected within 9 days and 30 km of each other in both instances. We interpolate the shipboard CTD potential conductivity values to the conservative temperature values measured by the floats at pressures greater than 1000 dbar. We then estimate a new CPcor for each float CTD that minimizes the differences between float and shipboard CTD potential conductivity on those surfaces. The newly estimated values are CPcor = -12.94e-08 for 5905738 and CPcor = -13.67e-08 for 5905739, both considerably larger amplitude than the SeaBird nominal correction coefficient of CPcor = -9.57e-08. Application of these new coefficients removes effectively all observed bias with no further correction required.

Speaker: Sarah Purkey (user)

An analysis of the offset and pressure dependent bias in the SBE-61 mounted on Scripps institution of oceanography's Deep SOLO floats is presented through a comparison of in situ float profiles falling within 0.5 degrees of a high quality, ship based, reference data profile. Only hydrographic stations taken through WOCE or GO-SHIP are considered here, with salinity, temperature and pressure accuracy of 0.002, 0.001 C and 2 dbars, respectively. Ship based CTD data has been calibrated to IAPSO Standard Sea Waters (SSW) and any batch-to-batch differences in SSW have been applied. Twenty-five floats had at least one profile falling within 0.5 degrees of a reference station, for a total of 2305 profile pairs. Note one float profile can have many profile pairs if it falls within 0.5 degrees of more than one reference station.

An optimized minimization is performed between each float-reference pair by allowing the CPcor and an offset term to vary following Johnson's method used at the HOT station. Examination of the optimized CPcor values showed stable values (at least within the large spread) up through the first 40 stations and slightly tighter agreement when the CTD reference data was taken post 2000, therefore only float-reference pairs where the float cycle number is less than 40 and the CTD reference data is more recent than 2000 are considered here. The mean CPcor calculated for each float is larger than the nominal CPcor value of -9.57×10^{-8} for all floats. The weighted mean of the CPcor, using the standard error from all profile-reference pairs for each float, was -12.955×10^{-8}. In addition, a small (0.00156) salinity offset was found.

- Extended-depth SBE-41 CTD

Speaker: Taiyo Kobayashi (user)

SBE41CP CTD sensor on Deep NINJA shows a fresh bias with negative pressure dependency, expressed as $\Delta S = \Delta S_{offset} + a_p \times pressure$. Statistics with 18 floats shows the averages of -1.5×10^{-6} dbar^{-1} for a_p and −0.011 for ΔS_{offset}. The salinity bias changed toward saline over time, mainly because of ΔS_{offset} changed toward saline. The negative pressure dependency of the fresh bias is likely caused by anisotropic deformations of the CTD measuring glass cell covered by a polyurethane jacket, due to its dual-cells structure, and the appropriate value for CP_{cor} is about -13.5 × 10^{-8} $dbar^{-1}$ based on the Deep NINJA observations. The fresh bias expected at the sea surface is mainly attributed to shrinkage of the jacket under high pressure. The fresh bias with negative pressure dependency could be eliminated by 1) pressure-ageing treatment for the measuring cell or 2) changing the jacket material into an elastomer.

Speaker: Kim Martini (provider)

The accuracy of Sea-Bird Scientific conductivity cells is sensitive to changes in the active sensing volume. At ocean depths greater than 1000 dbar, compression of the borosilicate glass leads to errors in the conductivity measurement and therefore the calculation of practical salinity. Sea-Bird has previously determined a correction to the pressure effect for conductivity cells made with an epoxy encapsulant. On Deep Argo Floats, a urethane encapsulant is used, changing the coefficient of compressibility. Using field data (i.e. conductivity measurements from the SBE-61 are compared against bottle salinities), the coefficient of compressibility is determined for conductivity cells with urethane encapsulant. Values obtained using two different methods agree with values obtained by other groups. However, they are physically unrealistic as they imply that the addition of a urethane encapsulant will increase the compressibility of the borosilicate glass cell. Results suggest that application of the empirically determined pressure correction may be appropriate, but the dependence may not only be an effect of conductivity cell compressibility.

5.3. Discussion on strategies for implementing Deep Argo Quality Control (lead: Sarah Purkey)

The discussion of Deep Argo quality control followed closely to the issues outlined in King's introductory talk outlined above. The pressure depended bias seen in the SBE-41 and SBE-61 is an important issue. At this point there is not sufficient evidence to attribute this entirely to CPcor or some other cause. In addition, further work needs to be done to determine the best value of CPcor and the extent to which it may vary from batch to batch or CTD to CTD. Sea-Bird Scientific asked if we wanted them to change the CPcor parameter for on board processing. There was a strong 'No' consensus from the group. Instead, it was recommended that, for now, each float deploying group should decide how best to deal with the pressure dependent salinity offset. A new CPcor value can be applied to the adjusted real time data if the float provider determines an adjustment is needed. A new CPcor value of -11.6 × 10^{-8} $dbar^{-1}$ was suggested by Murphy and Martini (2017), to be used until there is better understanding of the problem. More tests need to be done with SBE, including attaching SBE-61s to a SBE-911 rosette with bottle salinities, to determine the 'best' CPcor value or values. The CPcor issue will be further investigated by the AST task team (already set up) before the next AST meeting. Bernadette Sloyan and Katsuro Katsumata volunteered to work with GO-SHIP to help develop a Deep Argo reference database based on GO-SHIP data. They have already started working on this and will make it a GO-SHIP priority. They were also asking for any input of what additional information the Deep Argo community needed from the GO-SHIP data providers in terms of data availability and quality flags. Virginie Thierry has also worked on refining the Core Argo ship reference data base to include only good data, but has only done this for the North Atlantic. Finally, it was suggested the there be a session at the next ADMT meeting on Deep Argo DMQC.

6. Future plans for the expansion of pilot arrays, and strategy for transitioning to global deployment: National planning and funding status

6.1. U.S.

Speaker: Dean Roemmich, Emily Smith, and Gregory Johnson

The US Deep Argo Program presently has 55 operational Deep Argo floats in regional pilot arrays, with 46 more deployments planned in the coming year. The plans include deployment of 28 floats in the Brazil Basin, with support from the Paul G. Allen Family Foundation. Deep Argo float technologies (platforms and sensors) are maturing and will be ready to progress from regional/basin-scale deployment to global implementation in 2 years. Commercial partners will have the capacity to provide sufficient 6000 m floats and CTDs to meet the requirements of global Deep Argo implementation. The U.S. float deployment strategy balances sustaining and growing present regional arrays, prioritization of new regions, growth toward global coverage, leveraging international partner contributions, and use of reference datasets. The Core, Deep, and BGC elements of U.S. Argo will evolve into an integrated effort providing half of the floats required by the Argo Program. Argo is a high priority for NOAA, and the next 5-year cycle of U.S. Argo will include substantial growth toward global implementation of an integrated (Core, Deep, & BGC) Argo Program.

6.2. Japan

Speaker: Shigeki Hosoda

In FY2018, JAMSTEC Argo acquired 25 deep Argo floats (22 deep APEXs and 3 Deep NINJAs), 10 BGC Argo floats and 50 Core Argo floats. Deployments consisted of 12 deep APEXs, 2 Deep NINJAs, 1 BGC Navis and 20 APEXs mainly in the North Pacific, Southern Ocean and Indian Ocean, based on a special fund to expand Core, Deep, BGC Argo float observations following to the communique of 2016 G7 Ise-Shima Summit in Japan. In this FY, JAMSTEC is planning to deploy 15 deep APEXs, 1 Deep NINJA, 9 BGC Navis and 40 APEXs in the same basins. Also, one pilot study of Deep Argo will be carried out in the western North Pacific, constructing an observation array with 6 deep APEXs in the western North Pacific where operational CTD deep casts have been conducted for a long time, aiming to evaluate the SBE61 CTD and to detect changes in the deep ocean. Toward the next fiscal year, we are proposing for Deep Argo, BGC and Core Argo floats to sustain and expand the Argo float array. But due to decreasing amount of funding resource, the situation is not always optimistic.

6.3. France

Speaker: Virginie Thierry

33 Deep Arvor floats will be ready for deployment at the end of 2019. The floats will be deployed in the North-Atlantic Ocean to continue the on-going pilot experiment. Additional deployment in the Equatorial Atlantic (PIRATA) and in the Southern Ocean (in collaboration with JB Sallée and S. Rintoul) are envisioned. Over 2019-2021, we are funded for 15 deep floats/year (45 floats). These will be deployed over 2020-2022. We do not have sustained funding beyond 2021 yet; two possible funding sources will be pursued. Our objective is to buy 30 Core Argo, 20 Argo-O2, 15 Deep-Argo-O2 and 15 BGC-Argo floats per year.

6.4. Italy

Speaker: Virginie Thierry

2 Deep Arvor floats will be deployed in the Western Mediterranean Sea in 2019. In the future, Italy plans to deploy 2 Deep Arvor floats every 2 years with the goal to monitor the deepest areas of the Western Mediterranean Sea continuously.

6.5. Spain

Speaker: Virginie Thierry

2 dual-head Deep Arvor floats will be deployed in 2020 in the Canary Basin as part of the European EA-RISE project. There is no further funding for Deep Argo floats.

6.6. Norway

Speaker: Virginie Thierry

Norway received funding from the Norwegian Research Council (2018-2023) for purchase of BGC, Deep, and Core Argo floats. Probably 9 Deep Argo floats will be purchased. The objective is to maintain in operation a minimum of 2 Deep floats in each of the deep Basins in the Nordic Seas (Greenland Basin, Lofoten Basin and Norwegian Basin), thus 6 operative

Deep Argo floats. Three Deep Arvor floats were already purchased and one float in each basin will be deployed in May/June. All Deep floats will have oxygen sensors (Aanderaa optode). The floats will be deployed in areas were maximum depths are less than 4000 m (~3600 m), which means that the float must be able to measure down to the bottom and to cope with grounding.

6.7. U.K.

Speaker: Brian King

The UK has 6 Deep APEX floats being put in working order by TWR (4 recovered, 2 never deployed). Five of these have Aanderaa optodes. The intention is to deploy these along the Atlantic 24°N transect on a UK A05 GO-SHIP cruise departing from a US port around 20 January 2020 (PI Ale Sanchez-Franks, NOC; BAK will be on the cruise). These floats will include all the modifications resulting from TWR's investigations of past modes of failure. The hope is that one of the 6 floats will be converted to carry a RBR deep CTD as a trial on a two-headed float with RBR and SBE61. In that case the optode would be removed and mounted on a different float. A number of Deep APEX are due to NOC as warranty replacements for floats that did not achieve the warranty number of cycles of good data. This is under negotiation between NOC and TWR. At present, NOC will request up to 3 replacements. More may be due if some of the presently active floats fail before the they fulfil the terms of the warranty. Depending on lead time, including lead time for SBE61, these will be deployed in the South Atlantic, Drake Passage or elsewhere, at the earliest opportunity. For planning purposes, we anticipate 3 Deep APEX in Drake Passage in Feb 2020, but delays are possible. The UK does not presently have any active funding proposals. We need to get our existing floats in the water and working before seeking funding for more. The UK will need to consider how to evaluate tenders for any future procurements. The tender evaluation for the most recent UK procurement of 8 Deep Argo floats followed the advertised rules but resulted in an unsatisfactory procurement. However, funding was tied to FY and any attempt to revise or negotiate would have required a new tender exercise which could not have been completed before the FY year end, and would have resulted in loss of the funding and no procurement at all.

6.8. Australia

Speaker: Steve Rintoul/Peter Oke

Australia is coordinating the pilot array of Deep Argo floats in the Australian Antarctic Basin. Australia has also participated in a Deep Argo voyage to the Southwest Pacific Basin on RV Tangaroa. We plan to continue to maintain and enhance the pilot array in the Australian Antarctic Basin. To date, Australia has deployed three Deep SOLO floats manufactured by MRV. We have additional funding secured to deploy about another 12 floats in the basin in the coming years. Our priority is to extend the pilot array further west, to cover the full basin, and further east to sample the inflow of RSBW closer to its source (as well as to extend the sampling in time). Partners in this pilot array have also indicated interest in continuing to enhance the array. We will seek additional funding to expand the Australian contribution to Deep Argo, with the aspiration to contribute roughly 10% of the global array (as Australia does for Core Argo).

6.9. New Zealand

Speaker: Phil Sutton

New Zealand's main contributions to Deep Argo have been providing deployment opportunities and a vessel for the 2014 dedicated sensor validation voyage. NIWA's small research vessel, the 28-m R/V Kaharoa has deployed more Argo floats (> 1700) and Deep Argo floats (37) than any other vessel. Planning has begun to replace R/V Kaharoa, with the replacement vessel planned for 2022. The new vessel is planned to be larger, be able to go further south, be faster and only be incrementally more expensive. Of interest to Argo is that the replacement Kaharoa will have bigger deck space, with room for two 20' containers, more lab space/scientist accommodation and may have deep CTD capability. R/V Kaharoa will be maintained through past the delivery of the new vessel, with the intention that both vessels will operate for a period of overlap. Kaharoa's full capability will be maintained, so there should be no impact on Argo deployment voyages.

Future Float Deployment Opportunities: There will be continuing float deployment opportunities, in particular dedicated Argo deployment voyages as part of the continuing SIO/UW/CSIRO/NIWA Kaharoa collaboration. There are also Southern Ocean deployment opportunities from R/V Tangaroa during transits from New Zealand to Ross Sea, with the next Ross Sea voyage planned for Jan-Mar 2021 and Antarctic voyages intended at least every second year.

Future Float/Sensor development: R/V Tangaroa vessel time has been allocated for a second dedicated Deep Argo sensor validation voyage in 2020/2021. This will be led by Nathalie Zilberman (SIO) and Phil Sutton (NIWA) and will align with Nathalie's NOPP project on deep sensors. The provisional timing is April 2021, with the possibility of October 2020 if necessary and desired. The voyage length is currently 14 days, but could be extended if more funding is found. The intended location is in deep water east of the Kermadec Trench, similar to the location used in the 2014 voyage. There will be the opportunity to deploy floats in transit. The 2014 partners were NIWA, SIO, CSIRO, SBE and NOAA. All of these groups will hopefully participate and collaborate in this voyage and there is the opportunity for others to participate.

6.7. China

China began its development of 4000-m profiling float in 2016. The 'Wenhai' project was initiated and funded by Qingdao National Laboratory for Marine Science and Technology (QNLM) with over 3 million U.S. dollars. The 4000-m profiling floats prototypes developed by Ocean University of China, Tianjin University and Qingdao HiSun Ocean Equipment Co., LTD have been tested in South China Sea and Mariana Trench region in 2018 and 2019. More testing will be done in the Western Pacific Ocean during the second half year of 2019. In the next decade (2021-2030), 7 million US dollars will be funded by the China government to continue the development of 4000-m (and 6000-m) profiling floats. 20 Deep Argo floats will be deployed in the Southern Ocean and Western Pacific Ocean in 2020 and 60 in 2021 by Chinese research vessels. The 4000-m (6000-m) profiling floats are planned to be industrialized before 2025, and the data center will be built by QNLM and the second institute of oceanography (SIO). Hopefully the 4000-m (6000-m) profiling floats manufactured by China will be certified by the Argo Program. Before 2030, China will maintain at least 300 Deep Argo floats in the North Pacific (e.g., South China Sea, Kuroshio Extension regions and Mariana Trench regions) and the Southern Ocean, providing data down to 6000-m for the scientific community.

7. Summary of the 2nd Deep Argo Workshop: Outcomes and Deep Argo needs

7.1. Float performance

The viability of Deep Argo, with regard to cost per profile and the ability to re-seed the array, is dependent on developing floats and sensors with mean lifetime of at least 4 years. The prospects for this are good for some float models and possible for others.

7.2. CTD accuracy and stability

Deep Argo sensor accuracies of 0.001°C, 0.002 PSS-78, and 3 dbar, approaching GO-SHIP standards, are needed to provide adequate resolution of spatial and temporal changes in deep-ocean properties. The SBE-61's initial temperature target accuracy of 0.001°C is achieved. The initial pressure accuracy is good and is improving (presently 4-5 dbar; envisioned pressure accuracy is 3 dbar). Initial salinity accuracy is about 0.004 PSS-78, and approaching the envisioned value of 0.002 PSS-78, but still needing improvement and better consistency. A NOPP grant (Scripps Institution of Oceanography, Sea-Bird Scientific, NOAA/PMEL, and WHOI) will (i) enable additional testing of the initial accuracy and the stability of the Kistler pressure sensor mounted on the SBE-61 CTD, and of potential replacement pressure sensor candidates, (ii) reduce compressibility uncertainty of the SBE-61 conductivity cell, and (iii) decrease the occurrence of salinity drift failures. Recovery of Deep Argo floats having uncorrectable salinity drift, or other failure modes, is useful for diagnosis and correction. This is also true for Core and Deep Argo floats with SBE-41 CTDs. Performance of the extended-depth SBE-41 is improving, and Sea-Bird Scientific will continue working with JAMSTEC and IFREMER to increase salinity and pressure accuracies. A new Deep Argo CTD by RBR is under development; early comparisons with shipboard data in the North Atlantic have shown encouraging results.

7.3. Float and sensor production capacity and diversity of sources

Increasing capacity for production and deployment of Deep Argo floats and sensors will be demonstrated in 2019 - 2020. Alternative Core Argo platforms and sensors have been valuable for avoiding interruptions in Argo float production when platforms and sensors are unavailable (e.g. Druck pressure sensor in 2009), to promote healthy competition between providers, and to resolve technical issues. Based on Core Argo experience, it would be beneficial for Deep Argo to have more than one viable model of 6000-dbar and 4000-dbar floats and CTDs.

7.4. Cost effectiveness of Deep Argo

Cost effectiveness is a substantial issue for transitioning from the pilot to the global phase of Deep Argo. Larger orders, as required for global deployment, could help reduce the cost of Deep Argo floats and CTDs. The target cost (not yet achieved) per 0-6000 m profile, including production, data management, and deployment, is $500; and it is anticipated that 0-4000 m profiles would come at a proportionately lower cost.

7.5. Commitments from Argo National Programs

Argo National Programs with operational Deep Argo floats as well as plans for further deployments include the U.S., China, France, U.K., Australia, Japan, and the European Union. The national plans generally align in similar proportion to their Core Argo contributions, and additional deep Argo National Programs are likely to form. It is anticipated that once milestones are achieved for production and sensor accuracy, national programs will grow to provide the floats required to deploy and sustain the 1200-float Deep Argo array (about 300 floats per year if the mean lifetime is 4 years).

7.6. Timetable for progression towards a global array

The technical readiness of Deep Argo floats and CTDs for global deployment will be achieved in 2 years, as will demonstration of commercial capacity. Once the required global deployment rate is reached, it will take about 4 years to implement the global Deep Argo array. As it is difficult to anticipate the timing of available support, the Argo National Programs are prepared to adapt to a range of implementation rates, as long as growth is sustainable rather than transient. Completion of the global Deep Argo array may be in 7 – 11 years from now (2026 – 2030).

7.7. Outcomes of the 2nd Deep Argo Workshop

The primary objectives of the 2nd Deep Argo Workshop were to understand and demonstrate, for Deep Argo implementation teams, supporting agencies, and commercial partners:

- The technical readiness level of Deep Argo floats and sensors
- The level of engagement of Deep Argo National Programs
- The capability of Deep Argo to transition from the regional pilot phase to global implementation (technology readiness and production capacity).
- The scientific value of Deep Argo, and its complementary aspect with other existing observing systems, including GO-SHIP, and OceanSITES.

All of these Workshop objectives were met.

8. List of participants

Name	Email	Institution, Country
Neil Bogue	bogue@mrvsys.com	MRV, U.S.
Wenju Cai	wenju.cai@csiro.au	CSHOR, Australia/China
Zhaohui Chen	chenzhaohui@ouc.edu.cn	QNLM, China
Antony Escarcega	tony@tsk-jp.com	NKE, Japan
Annie Foppert	annie.foppert@csiro.au	CSIRO, Australia
Florent Gasparin	fgasparin@mercator-ocean.fr	MERCATOR, France
Tony Haymet	haymet@gmail.com	Scripps Inst. Ocean., U.S.
Shigeki Hosoda	hosodas@jamstec.go.jp	JAMSTEC, Japan
Tetsuro Ino	trade@tsk-jp.com	JAMSTEC, Japan
Greg Johnson — PMEL	gregory.c.johnson@noaa.gov	PMEL, U.S.
Greg Johnson — RBR	greg.johnson@rbr-global.com	RBR, U.S.
Katsuro Katsumata	k.katsumata@jamstec.go.jp	JAMSTEC, Japan
Brian King	bak@noc.ac.uk	NOC, U.K.
Taiyo Kobayashi	taiyok@jamstec.go.jp	JAMSTEC, Japan
Zhaoqin Li	lizhaoqin@sio.org.cn	Second Inst. Ocean., China
Kim Martini	kmartini@seabird.com	Sea-Bird, U.S.
David Murphy	dmurphy@seabird.com	Sea-Bird, U.S.
Ronnie Nigash	nigash.ronnie@gmail.com	MRV, U.S.
Peter Oke	peter.oke@csiro.au	CSIRO, Australia
Breck Owens	bowens@whoi.edu	WHOI, U.S.
Sarah Purkey	spurkey@ucsd.edu	Scripps Inst. Ocean., U.S.
Corentin Renaut	Corentin.Renaut@ifremer.fr	IFREMER, France
Steve Rintoul	steve.rintoul@csiro.au	CSIRO, Australia
Dan Ryan	daniel.ryan@teledyne.com	TWR, U.S.
Dean Roemmich	droemmich@ucsd.edu	Scripps Inst. Ocean., U.S.
Jerome Sagot	jsagot@nke.fr	NKE, France
Bernadette Sloyan	Bernadette.Sloyan@csiro.au	CSIRO, Australia
Emily Smith	emily.a.smith@noaa.gov	NOAA, U.S.
Phil Sutton	p.sutton@niwa.co.nz	NIWA, New Zealand
Virginie Thierry	vthierry@ifremer.fr	IFREMER, France
Xiaofen Wu	wuxiaofen83@163.com	Second Inst. Ocean., China
Zhongsheng Zhao	dfh2@ouc.edu.cn	QNLM, China
Nathalie Zilberman	nzilberman@ucsd.edu	Scripps Inst. Ocean., U.S.

9. References

A.

Aoki, S., S. R. Rintoul, S. Ushio, S. Watanabe, and N. L. Bindoff. (2005). Freshening of the Adélie Land Bottom water near 140 E. *Geophysical Research Letters*, *32*, L23601, doi:10.1029/2005GL024246.

B.

C.

D.

Desbruyères, D. G., S. G. Purkey, E. L. McDonagh, G. C. Johnson, and B. A. King. (2016). Deep and Abyssal Ocean Warming from 35 years of Repeat Hydrography. *Geophysical Research Letters*, 43, 10,356–10365, doi:10.1002/2016GL070413.

E.

F.

G.

H.

I.

J.

Johnson, G. C., McTaggart, K. E., and Wanninkhof, R. (2014). Antarctic Bottom Water temperature changes in the western South Atlantic from 1989 to 2014. *Journal of Geophysical Research: Oceans*, *119*(12), 8567–8577. http://doi.org/10.1002/2014JC010367

Johnson, G. C., J. M. Lyman, and S. G. Purkey. (2015). Informing Deep Argo array design using Argo and full-depth hydrographic section data. *Journal of Atmospheric and Oceanic Technology*, *3*2, 2178–2198, doi:10.1175/JTECH-D-15-0139.1.

Johnson, G.C., J.M. Lyman, T. Boyer, C.M. Domingues, J. Gilson, M. Ishii, R. Killick, D. Monselan, and S. Wijffels (2018): Ocean heat content. In *State of the Climate in 2017*, Global Oceans. Bull. Am. Meteorol. Soc., 99(8), S72–S77, doi: 10.1175/2018BAMSStateoftheClimate.1.

Johnson, G. C., Purkey, S. G., Zilberman, N. V., & Roemmich, D. (2019). Deep Argo quantifies bottom water warming rates in the Southwest Pacific Basin. Geophysical Research Letters, 46, 2662-2669. https://doi.org/10.1029/2018GL081685

K.

Kobayashi, T. (2018). Rapid volume reduction in Antarctic Bottom Water off the Adélie/George V land coast observed by deep floats. *Deep Sea Res.*, 140, 95-117, https://doi.org/10.1016/j.dsr.2018.07.014.

Kouketsu, S. et al. (2011). Deep ocean heat content changes estimated from observation and reanalysis product and their influence on sea level change. *Journal of Geophysical Research*, *116*(C3), C03012, doi:10.1029/2010JC006464.

L.

M.

Murphy, D. and K. Martini (2018). Determination of conductivity cell compressibility for Argo program CTDs and MicroCATs, Poster IS24E-2622, presented at 2018 Ocean Sciences Meeting, Portland, OR, 12-16 Feb.

N.

O.

P.

Purkey, S. G., and G. C. Johnson. (2010). Warming of Global Abyssal and Deep Southern Ocean Waters between the 1990s and 2000s: Contributions to Global Heat and Sea Level Rise

Budgets. *Journal of Climate*, *23*, 6336–6351, doi:10.1175/2010JCLI3682.1.

Purkey, S. G., and G. C. Johnson. (2012). Global Contraction of Antarctic Bottom Water between the 1980s and 2000s. *Journal of Climate*, *25*, 5830–5844, doi:10.1175/JCLI-D-11-00612.1.

Purkey, S. G., and G. C. Johnson. (2013). Antarctic Bottom Water Warming and Freshening: Contributions to Sea Level Rise, Ocean Freshwater Budgets, and Global Heat Gain, *Journal of Climate*, *26*, 6105–6122, doi:10.1175/JCLI-D-12-00834.1.

Purkey, S. G., Johnson, G. C., Talley, L. D., Sloyan, B. M., Wijffels, S. E., Smethie, W., et al. (2019). Unabated Bottom Water Warming and Freshening in the South Pacific Ocean. Journal of Geophysical Research: Oceans,124. https://doi.org/10.1029/2018JC014775

Q.

R.

Rintoul, S. R. (2007). Rapid freshening of Antarctic Bottom Water formed in the Indian and Pacific oceans, *Geophysical Research Letters*, *34*, L06606, doi:10.1029/2006GL028550.

S.

T.

U.

V.

W.

X.

Y.

Z.