3rd Deep-Argo Workshop

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Virtual meeting

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1. Introduction and objectives of the workshop

The objectives of the 3rd **Deep-Argo workshop** were to:

- assess progress of the Deep Argo mission, from scientific use of Deep Argo data to technological ability of floats and sensors;
- review end-users' needs,
- finalize the implementation plan of the global Deep Argo array of 1250 floats.

One question that remains open is the implementation of oxygen sensors on Deep-Argo floats. This question was addressed during the joint BGC-Deep Argo session. This session was also dedicated to interactions between Argo (Deep and BGC) and other networks and observing programs (DOOS, GO-SHIP, Oceansites, Gliders). The questions addressed during this session were (i) what can we do for each other, (ii) what can we do together.

2. Deep Argo: Scientific motivation, results and requirements

2.1 Status of the Deep Argo array (Nathalie Zilberman)

Four Deep Argo float models are currently in use, including the 6000-m capable Deep APEX and Deep SOLO both equipped with the SBE-61 CTD, and the 4000-m Deep NINJA and Deep Arvor with the extended-depth SBE-41 CTD. A new 6000-m RBR CTD is under testing. Some Deep APEX, Deep Arvor, and Deep NINJAs are equipped with oxygen sensors. Engineering development is needed to install oxygen sensors on Deep SOLOs floats. In addition to sensor development, new Deep Argo float designs are emerging. A new 4000-m capable Deep Argo float model was developed by Argo China called HM4000. This design under testing can either use RBR or SBE-61 CTD. Two additional 6000-m capable Deep Argo float models are under development, the HM600 from China with prototypes scheduled for 2022, and a 6000-m Deep Argo float from France with prototypes to be ready by 2025. Regional pilot arrays have been deployed in all ocean basins in regions that are deeper than 2000-m, where deep water mass observations indicate significant deep-ocean warming, where Argo partners can provide logistical support, and where reference data from shipboard repeat hydrography are available for validation of sensor accuracy. A total of 186 Deep Argo floats are currently active, 61 of them, about 1/3, measure oxygen. The estimated size of the Deep Argo array by the end of 2021 is 204 floats. This represents a 45% increase in the number of active floats compared to 2020. A total of 85 Deep Argo float deployments are planned for 2021. For comparison, the number of float deployment required for a global 1250 Deep Argo float array (assuming an averaged float lifetime of at least 4-5 years) is 300 floats per year. **The current Deep Argo float deployment rate is therefore only 1/4 of what is needed to implement and sustain the envisioned global Deep Argo array.**

2.2 Scientific highlights

◆ **Estimation of regional deep temperature trends from Deep Argo and historical hydrographic data** (Gregory C. Johnson)

In the Brazil Basin, a temperature trend of AABW was estimated from a comparison between Deep-Argo and WOCE data. The warming trend was about 2 m°C per year (Johnson et al., 2020 doi:10.1029/2020GL089191), which is similar to previously estimated trends in that basin from repeat hydrographic section analyses (Johnson et al. 2014, doi:10.1002/2014JC010367). However, uncertainties for the Deep Argo trend are 0.2 m°C per year half those from analysis of three repeat hydrographic section occupations of A16S in the Brazil Basin. Soon, estimating short term (Deep Argo era) trends should also be feasible.

- **Deep Argo observation and state estimation for deep ocean** - Shigeki Hosoda and Satoshi Osafune

The science motivation of deep Argo is to investigate variability in the deep ocean current and its roles on the long-term climate changes, focusing on heat/freshwater transport, diffusivity, and the global heat uptake. Since 2013, 59 deep Argo floats (deep NINJA and APEX deep) have been deployed. Cooperation with other groups and platforms (GO-SHIP, Ocean Sites, etc.) are crucial. JAMSTEC is preparing to develop new sensors (density, CDOM etc.), and to test the turbulent measurement with ALTO float (for the ArgoMix). A combination with assimilations for the deep ocean is important to realize the scientific motivation. ESTOC (Estimated State of Ocean for Climate Research by Using a 4 Dimensional Variational Approach) represents the comprehensive ocean state like recent decadal bottom-water warming. ESTOC is optimally estimated based on the Green's function method, including tidally effects and geothermal heat flux (ESTOCv04a). By those schemes, which makes the reproducibility of the horizontal distribution of bottom–water warming to be improved. From ESTOC data, positive T change extends from the Southern Ocean along its western part, with its amplitude decreasing to the north. To achieve reliable state estimate, we need more data from the deep Argo network.

- **From a pilot study to a Deep-Argo in the subpolar gyre of the North Atlantic ocean and beyond** - Virginie Thierry

A pilot array of Deep Argo floats was deployed in the subpolar gyre of the North-Atlantic Ocean since 2014. This array successfully demonstrated the feasibility of measuring high-quality temperature, salinity and dissolved-oxygen concentration data at depths greater than 2000 m (see presentations by X. André, V. Racapé, C. Cabanes and V. Thierry on those topics during the other sessions of this meeting). The data were then used to investigate ISOW (Iceland Scotland Overflow Water) and DSOW (Denmark Strait Overflow Water) pathways, mixing and interannual to decadal variability. Those first results yielded new insights into deep water mass circulation and mixing in a region essential for climate variability. We now aim at sustaining a regional array of 40 Deep-Arvor O_2 4000 m to continue monitoring deep physical and biogeochemical inventories in this region. Note that we also contribute to the Deep-Argo array in other regions. As part of the French PIANO and Argo-2030 projects (2021-2028), we will develop a Deep-Argo-6k float with oxygen sensors and deploy about 30 of them in the Atlantic and Southern Ocean.

- **Deep Argo reveals bottom water properties and pathways in the Australian-Antarctic Basin** - Annie Foppert

A pilot array of Deep Argo floats was deployed in 2018 in the Australian-Antarctic Basin. The Deep Argo floats successfully map Antarctic Bottom Water properties throughout the basin in detail previously unobserved. The patterns of AABW temperature and salinity in the southern part of the basin, south of 60S, reflect the two sources of AABW. Warmer and more saline Ross Sea-sourced AABW is found in the southeast corner of the basin, and the coldest AABW is found near the Adelie Land source of Dense Shelf Water. AABW is density-compensated in the southern part of the basin, with no apparent along-slope evolution in density. There is a clear north-south divide around 60S, with a warmer and more buoyant variety of AABW found to the north. There is enhanced variability in AABW water-mass properties near 140E, where AABW from the two sources interact for the first time. For example, one float resolves near-daily variability on spatial scales of 10s of kms, and captures a pulse of ALBW flowing down the slope. Based on characteristics of water-mass properties, pathways of RSBW and ALBW are inferred. The main pathway of RSBW flows along the midslope, inshore of the 3700-m isobath, whereas the strongest signal of ALBW is found between the Hakurei Seamount and the continental slope at 140E.

◆ **Revisiting the 2003-2018 deep-ocean warming through multi-platform analysis of the global energy budget**. Andrea Storto

Several observing networks provide complementary information about the temporal evolution of the global energy budget. In this work, satellite observations of Earth's Energy Imbalance (EEI) and steric sea level and in-situ-derived estimates of ocean heat content anomalies, are combined in a variational analysis framework, with the goal of assessing the deep ocean warming. The optimized solution accounts for the uncertainty of the different observing networks. Furthermore, it provides fully consistent analyses of global ocean heat content, steric sea level and EEI, which show smaller uncertainty than the original observed timeseries. The deep ocean (below 2000m depth) exhibits a significant warming of 0.08 ± 0.04 W m −2 for the period 2003-2018, equal to the 13% of the total ocean warming.

2.3 Requirements from users

◆ **From the Sea level perspective** William Llovel

We evaluate the global mean sea level budget over 2005-2019 combining satellite altimetry, GRACE/GRACE-FollowOn and core-Argo-based gridded data. We show that the budget is closed over 2005-2015 within uncertainties. The budget is no longer closed after 2016 even when assessing the budget with the global mean thermosteric sea level contribution. Some possible candidate for explaining this non-closure would be an underestimation of the deep ocean contribution (below 2000m). One recommendation for closing the sea level budget would be to have a dense enough deep-Argo profile distribution to ascertain with good accuracy the deep ocean contribution to the global mean sea level budget. Regionally, deep steric sea level changes (below 2000m) can be estimated from the sea level budget approach. Over 2005-2019, we found large regional steric trends for the North Atlantic ocean and the south Indian/Pacific sectors. When converting these trends to deep temperature changes, we find values up to 6m°C/yr over 2005-2019. Good agreements are found for the deep steric sea level changes over 2018-2019 from platform #6901763 and the geodetic product. This approach might be valuable to detect any sensor drift/bias from deep-Argo float.

◆ **Deep Argo: Climate change and GOOS requirements** Karina von Schuckman

This talk discussed the importance of deep ocean measurements (> 2000m depth) for climate studies and discussed some stakeholder needs. There is an increasing sampling coverage in most areas of the global upper ocean, whereas in the deeper part below 2000m depth sampling is low, albeit this represents about half of the ocean volume and increase in sampling of the deep ocean below 2000m will increase our capabilities to further understand changes in the climate system, as well as to reduce uncertainties in climate monitoring. Several application areas have been discussed. For example, deep ocean changes for the evaluation of the Earth heat inventory amount to about 10%, and currently, a sequestration of heat into the deep ocean layer is reported (von Schuckmann et al., 2020). Increased sampling in the deep ocean below 2000m depth would help to reduce uncertainties in the Earth heat inventory and hence the Earth energy imbalance, and additionally help to unravel variations and processes of redistribution of heat into the deep ocean layers. Additionally, the understanding of regional heat and carbon budget inventories and ocean state estimates, deep ocean circulation change and variability could be improved. The importance of deep ocean measurements for operational oceanography have been discussed: Ocean reanalyses are an essential tool for analysing, monitoring and reporting on past and present ocean conditions and to further enravel the critical role of the ocean in Earth climate. Results based on observing system simulation experiments (OSSE) study suggests that a global deep Argo array of 1200 floats will significantly constrain the deep ocean by reducing temperature and salinity errors by around 50%. The presentation has informed about GOOS initiatives as part of the UN ocean decade for sustainable development. Driven by or with GOOS, Ocean Observing Co-Design, CoastPredict and Observing Together are the first programmes of many that will actively drive the Ocean Decade to “Ensure a sustainable ocean observing system across all ocean basins that delivers accessible, timely, and actionable data and information to all users." The planning processes of these programmes has already deepened partnerships with other organizations and endorsed Ocean Decade Programmes. Finally, the presentation has provided insight to the Deep Ocean Observing Strategy – a framework that brings together the broad range of expertise required to identify the challenges and seek solutions that will advance our understanding of and maintain the functioning and services of the deep ocean.

◆ **How is ocean circulation being studied using Deep Float data** Brian King

Based on the four different studies that used Deep-Argo floats data to investigate the ocean circulation, it was possible to draw some conclusions and raise some unresolved questions.

- No-one has enough data yet to produce quantified maps of ocean circulation directly from float displacements. The mapping efforts of core Argo floats (YoMaHa, Andro) typically use 5 or 10 years of data for one time-averaged map.
- Some analyses reveal pathways using either water mass properties (profiles) or float trajectories. This has been schematic rather than quantitative.
- Quantitative analysis of abyssal circulation used dynamic height from deep profiles relative to a shallower reference level.
- The descriptions of deep and abyssal circulation from Argo data will depend on all of: CTD density profiles, good quality water mass properties, and float displacements. The impact of float displacement during ascent and descent of deep floats has not been widely assessed.
- The One Argo vision anticipates that Deep Argo floats will be full contributors to the core mission, in terms of sampling. This is OK for profiles, but potentially the fit is less good for park depth and trajectories.
- Circulation pathways: **Deep float operators may wish to park at particular depths to reveal circulation pathways**. This was a discussion point early in Argo when parking depth was expected to be 2000 dbar, but the nominal depth of 1000 dbar has been almost universally followed.
- Float dispersal: **Deep float operators may have a strong preference to park floats deep in a basin to minimise float dispersal**. Particularly when coverage is by basins and not yet global.
- The Deep SOLO could be upgraded to deliver a real-time profile from the park depth to the surface. The depth requirement for this profile has not yet been agreed.
- **If Deep floats do not park at 1000 dbar, the number of 1000 dbar trajectories for direct mapping will be reduced.** Perhaps this can be partially filled by deep trajectories and dynamic height calculations.

- **User Requirements for Deep Argo: modelling community and operational oceanography** Peter Oke

There are still very few modelling studies that have attempted to demonstrate impacts of Deep Argo data on assimilating models.
Ocean models and reanalyses are biased in the deep ocean.
Different models produce quite different properties and circulation – particularly in the deep ocean.
Assimilating models that use Deep Argo show promising results … models can ingest and retain information from deep measurements.
Deep Argo will likely serve two purposes for the modelling community:

1. Constraining deep ocean properties to deliver useful reanalyses
2. Promoting understanding of the causes of model bias, and helping to identify solutions

- **General Bathymetric Chart of the Oceans (GEBCO)** Mathias Jonas

Future Collaboration of GEBCO and ARGO would meet the best intentions of the Ocean Decade. Planned grounding and a dedicated ARGO bathy data product would help to fill the gaps in ocean mapping, having still 80% of the global sea area unsurveyed.

- **Discussion on the compatibility between the current Deep-Argo mission and the requirements expressed by the users (Discussion Leader: Gregory C. Johnson)**

The question of parking depth was raised and discussed. The question was whether the Deep-Argo floats should be parked at 1000 dbar to contribute to the mean circulation estimate at this level or at deeper levels. One argument for having the parking depth deeper for Deep floats than for Core and BGC floats is to keep them in deep water. This argument seems more compelling than the idea of mapping the deeper velocity, as the deeper-than-1000dbar displacements will have even more uncertainty due to the rise time and even smaller velocities at deeper depths.
The issue of pressure sensor accuracy was also discussed. The need for independent tests for deep sensors was put forward.
Finally, there was a question on the impact of the deep floats type (6000m versus 4000m) for the modeling community. While such studies are expensive, they are currently carried on at Mercator Ocean.

3. Interactions: BGC/Deep Argo and cross networks

3.1 Implementing O2 sensor on Deep-Argo

- **Scientific motivation and users need (sampling, accuracy) (biological community, water mass identification).** Laurent Coppola

There is a need to extend oxygen observation to the deep ocean to: 1) observe the expansion of OMZs and its impact on biodiversity (habitats, species adaptation, and vertical migration), 2) improve IPPC models, 3) estimate the impact of ventilation on deep waters and 4) study the impact of hydrothermal vents on the O2 solubility. The methods to correct the deep Argo-O2 data are not yet defined but the cross-networks approach would be interesting, especially with fixed moorings able to measure O2 in deep waters (e.g. the MedSea NW). The WOA plans to integrate O2 Argo data and lacks deep water data for the deep ocean variability. One of the objectives will be to combine both data from in situ measurements (Winkler) and CTDO2 profiles close to the Argo profiles. Finally, the GO2DAT initiative (Global Ocean Oxygen Database and ATlas) aims to assess and predict deoxygenation and ocean health in the open and coastal ocean (Grégoire et al., 2021). This is an international effort to combine all O2 data following the FAIR principles with open access. It also highlights the need for the community to cover deep ocean variability to better understand global O2 dynamics.

- **Scientific results**
  - **ISOW spreading and mixing as revealed by deep-Argo floats with O2 sensor launched in the Charlie Gibbs Fracture Zone.** Virginie Racape

While knowledge in deep circulation is required to understand long term changes in acidification or ventilation of the deep ocean, large uncertainties remain on deep circulation pathways. To improve our understanding of deep circulation, five Deep-Argo floats equipped with oxygen sensors were deployed in the Charlie-Gibbs Fracture Zone (CGFZ), a gap in the Mid-Atlantic Ridge that constrains the pathway of deep water masses. Those autonomous platforms freely drifted at 2,750 dbar in the core of the Iceland-Scotland Overflow Water (ISOW), a young water mass, rich in O2, originating from the Nordic Seas. Oxygen data acquired by the floats coupled to surface velocity analysis revealed that the interaction between the North Atlantic Current and the deep flow in the CGFZ favors the mixing of ISOW with the North East Atlantic Deep Water, an old water mass characterized by low O2. These results advocate for equipping Deep-Argo floats with oxygen sensors to improve understanding of deep circulation and water mass mixing.

  - **Multiplatform investigations of oxygen in the subpolar North Atlantic** David Nicholson

The North Atlantic is a critical region driving the Atlantic meridional overturning circulation (AMOC), including the uptake/ventilation of carbon dioxide and oxygen. The region ‘recharges’ oxygen that is subsequently respired in the interior of the rest of the Atlantic basin. To quantify these processes of the oxygen cycle, a multidisciplinary collection of observing systems are now characterizing target regions on the Labrador and Irminger Sea. This includes ~70 moored oxygen optodes deployed in 2020 on infrastructure from the OSNAP AMOC mooring array. A range of processes within the Labrador, including deep convection, exchange between the gyre and boundary currents and seasonal photosynthesis and respiration result in a highly seasonal and dynamic oxygen cycle.

By combining oxygen measurements from BGC and Deep Argo with moored and ship-board measurements we aim to fully characterize the annual cycle of ventilation and transport for the Labrador Sea.

◆ Sensors readiness (performance versus needed accuracy from the users) and QC

- **Aanderaa and SBE63** Henry Bittig

Sensor accuracy is a mixed bag – historically! Prospects aren't as grim. Floats that go into the water have both multi-point calibrated optodes and in air observation capabilities -> Primed to give accurate results if QCed according to BGC-Argo specs.

Unaddressed issue: Operational Implementation of time response correction is an unaddressed issue: 1) Errors increased in gradient regions. 2) Ascent as default profile -> systematic effect!

Deep Argo: 1) Optode pressure dependence is only roughly characterized with ca. 0.3% / 1000 dbar uncertainty. 2) Calibration against deep, "stable" water mass ?? -> Creates hen-egg problem if looking for deep O2 trends!

- **SBE83** Steve Riser and Seabird

SeaBird-83 is more precise than Aanderaa for air gains.

- After air-calibration, SeaBird-83 and Aanderaa 4330 agree to better ~1 μmol/kg (~0.5% at surface).
- It appears to be better to use Aanderaa temperature for Aanderaa air calibration. The difference in temperature (SB-83 vs Aanderaa) likely reflects real microenvironments.
- The daytime bias is likely caused by biofouling or light interference. This idea needs more study.
- SeaBird-83 appears to work equally well on Apex and Navis floats.

- **AROD-FT(RINKO)** Hiroshi Uchida / Kanako Sato and Hua LI (JFE)

Optode-based oxygen sensors (RINKO series) have been developed by JFE Advantech Co., Ltd., for over 15 years. RINKO has the originally developed sensing foil and optimally designed electronics and is calibrated with a high accuracy multi-points calibration method. RINKO is used in a variety of observations: the GO-SHIP hydrography in Japan, continuous surface water measurement along these cruise tracks, and an OceanSITES mooring observation (station K2). RINKO for float (ARO-FT/AROD-FT) has also been installed into BGC- and Deep-Argo floats since 2014 (MRV-S3A, BGC-Apex, Deep-Ninja and Deep-Apex). RINKO has the advantage especially in the fast-profiling shipboard CTD measurement due to its fast response. Although RINKO with a brand-new sensing foil usually shows time drift (~10 μmol/kg) due to degradation of the sensing foil, RINKO with a well-used sensing foil is satisfactorily stable in time. The electronics of ARO-FT/AROD-FT is updated to suppress degradation of the sensing foil. RINKO shows time-dependent pressure-induced hysteresis (about −4 μmol/kg) like the electrode oxygen sensor (SBE 43). A practical method to correct the hysteresis might be required, especially for the Deep-Argo measurement.

◆ Discussion (Discussion Lead: Brian King)

The diurnal cycle was discussed, as optical measurements are optimum at noon (?) and optode measurements are better during the night. The issue of oxygen measurements accuracy and more especially sensor responses were also discussed.

3.2 Cross networks interactions

In order to help identify how Deep & BGC Argo could better collaborate with other observing neworks, representatives of the main ocean observing networks were invited to present their programme with an emphasis on what they can do for and expect from (i) Deep Argo and (ii) BGC Argo.

- **EOV shared by various platforms: T, S, O2 (Deep) and Chla, bbp, pH, O2, UVP (BGC) (including data management)** Hervé Claustre, Virginie Thierry

As an introduction to this cross network session, the common EOV were presented, as well as the importance of collaboration between networks for an optimized ocean observing system. Several opportunities for enhanced collaboration were listed, for instance in technological development, observing system design, data management, or communication and outreach.

- **DOOS presentation** Lisa Levin

DOOS, the Deep Ocean Observations Strategy, is a network of observing, modeling and policy-user platforms aimed at maximizing the potential of available observations and models to gain insight into deep-ocean physics, biogeochemistry and ecology, and to translate this into science-informed policy making. DOOS will work to develop best practices to observe the deep ocean, including advancing the measurement of essential ocean variables (EOVs). This will involve both site-specific observations needed for ecosystem exploration or for managing particular human activities (e.g. deep-ocean mining or fishing) as well as the global-scale network of observations needed to have an in-depth knowledge of the present and future state of the deep ocean circulation and biogeochemistry. The interactions between DOOS and the BGC/Deep Argo programs are several: (i) The DOOS focus is strongly interdisciplinary and it connects BGC/Deep Argo observations with a broader scientific community. (ii) DOOS brings together multiple stakeholders (scientists, policy and society) and can be the vessel to translate BGC/Deep Argo data and knowledge to science-based decision-making, regulation and governance. (iii) The Argo programs provide an extremely successful example of scaling up an observational platform to global scale. DOOS will take advantage of the key characteristics of such success (e.g. EOVs observed, cost-efficient, etc.) in the design of a sustainable, long-term, integrated observing system for the deep ocean. (iv) Existing and new floats will be used in DOOS demonstration projects. (v) DOOS will promote BGC/Deep Argo data access (e.g,. for Deep Ocean Early-career Researchers, DOERs).

- **OceanGlider presentation** Pierre Testor

OceanGliders is a developing but still emerging GOOS observing network. It develops its own scientific objectives with Boundary currents, Storms, Water Transformation, Ocean Health but there are scientific and technological commonalities with Argo, Deep Argo and BGC Argo that must be taken into account to optimize the global efforts. OceanGliders Data Management has progressed well. Ok for real time but still work in progress for delayed mode. There is a lack of personnel resources to develop that more rapidly. OceanGliders Best Practices are developing well. Relatively few glider endurance lines are really sustained but the number is growing with many ‘candidates’. None yet with a 6000 m depth objective, but it will come soon.

What can Ocean Gliders do for Argo, Deep Argo and BGC-Argo ?

Core-Argo: Develop services (climate, ocean health, operational) for the public and the industrial sectors. Avoid the launch of numbers of floats in “divergence” areas, and reduce the models' forecasting errors by sampling required areas, thanks to glider maneuverability (Observing System co-design exercises). Provide our two-way communication expertise for handling sampling. Co-develop/assess scientific payloads. Provide high quality data for inter-comparison purposes and delayed mode data management (applies to OceanSites and GO-SHIP as well). Corrections could be propagated → better data consistency.

Deep-Argo: Provide estimates of the drift of the float during dive/ascent to 6000 m depth, with glider depth-average currents. Provide reference profile data for inter-comparison (with pre/post-calibrated sensors)+ smaller scale variability estimates at regional scale and uncertainties quantification

BGC-Argo: Provide reference profile data for inter-comparison (with pre/post-calibrated sensors) + smaller scale variability estimates at regional scale and uncertainties quantification

What can Argo, Deep Argo and BGC-Argo do for Ocean Gliders ?

Core argo: Gliders are very similar to profiling floats. We expect to benefit from Argo examples/resources in order to improve our scientific payloads with a GOOS perspective, improve our real time and delayed mode data management (adding gliders data in existing systems is really about almost nothing?), procure with new gliders? and develop a shared vision/design for a more integrated GOOS, that would be more focused on the various oceanic (phys/bgc/bio) phenomena that we need to observe, and better public outreach

Deep-Argo: Work together on 6000 m sensors. Better ocean state estimates helping glider mission planning and implementation

BGC-Argo: Work together on new BGC sensor integration and complement with different BGC variables collection. Develop data management and best practices for the collection of BGC variables. Provide large scale and high quality BGC data to provide a context

- **GO-SHIP presentation** Yvonne Firing

The Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) coordinates and facilitates ship-based climate-quality hydrographic sections to achieve a decadal-resolution, full-depth, global survey of heat, freshwater, oxygen, carbon, nutrients and transient tracers as part of the global ocean and climate observing systems, with the objective of tracking and predicting the interrelated changes in ocean circulation, nutrient budgets and acidity, heat and carbon storage, and the water cycle. GO-SHIP also contributes to high-quality measurements by the community as a whole through development and maintenance of expertise and best practices for sampling, measurement, calibration, and data availability. GO-SHIP and Argo have overlapping goals and complementary approaches. GO-SHIP cruises provide opportunities to deploy Argo floats in infrequently-visited regions. GO-SHIP makes an outsize contribution to the calibration of Deep and BGC Argo data because of its coverage of different watermasses and regions over the full depth, and the high standard of measurements of both physical and biogeochemical parameters. Deployment cast data from GO-SHIP cruises have proved valuable for validating assumptions about pressure-dependence of the calibration function for BGC parameters, and GO-SHIP data will contribute to evaluating pressure and salinity biases and drifts as well as checking calibration of newer BGC variables and sensors in different regions. GO-SHIP's best practices and training also contribute indirectly to the set of data available for Argo calibration and validation. Argo's higher temporal resolution and spatial coverage, meanwhile, has added value to GO-SHIP's global decadal survey by allowing investigators to contextualise and understand the uncertainties in section-based estimates of ocean property inventories. As this is extended to the deep ocean we will be able to better quantify changes in deep water mass distributions and full-depth heat content; and as it is extended to BGC variables we will be able to investigate more questions about the potentially changing roles of circulation and biogeochemical processes in the carbon cycle.

- **OceanSITES presentation** Raquel Somavilla

OceanSITES is the global network with the mission to coordinate the collection, delivery and promotion of high-quality data from long-term, high-frequency multidisciplinary observations at **fixed locations** in the open ocean. The time series observations cover the whole water column – from the seafloor to the atmosphere and address air/sea exchange processes such as heat and freshwater fluxes, and ocean carbon and oxygen update; ocean transport, but also other more biogeochemical and biological integrated in global ocean watch and finally deep ocean processes. OceanSITES presentation during the Deep and BGC Argo cross-network interaction session highlighted the idea that combining the truly Eulerian nature of moored observations affected only by temporal variability with the mixed Eulerian/Lagrangian float observations will not only improve our understanding of ocean variability and dynamics but of sensors characteristic helping to identify sources of drift ant behaviour of instruments in different platforms. Intercomparisons between moored and Argo sensors could also facilitate 2$^{\text{ndary}}$ QC, since OceanSITES high quality data is ensured by cross calibration with standardized instruments but also through water samples taking during ship visits to specific SITES. There is potential for this interaction between networks in all the places where OceanSITES have BGC instruments and/or deeper than 2000 or 5000 meters and several examples were presented to illustrate such potential interaction.

- **Discussion on the way forward** (Discussion Lead: George Petihakis)

It was stated that we need a multiplatform approach, but implementing the concept is not straightforward. Networks are in different stages of maturity which does not facilitate collaboration. One way to progress would be to interact more between networks, for example by having representatives of other networks in one network committee. There are various levels of collaborations possible, and the opportunities to collaborate on sensors, for instance, were noted and discussions were already held on this subject by the workshop participants in the chat. Common working groups on specific issues shared between networks could also be set up, such as the SCOR WG on BGC parameters on floats and gliders in the past. OCG could be a good forum for such cross network activities.

4. Deep Argo: Implementation plan

4.1 Floats technology: performances (including actual and expected longevity), issues, and future plans

- **Deep-SOLO** Nathalie Zilberman

New technology developments were implemented on Deep SOLO floats in the past 2 years to increase the float performances: (1) **A switch from Electrochem to hybrid-Tadiran batteries** and an increase in the number of battery packs enables an estimated Deep SOLO float lifetime of 6.4 years, above the 4-5 life expectancy targeted for the Deep Argo Mission. Other improvements include: (2) **New (RS232) interface boards on SBE-61 CTDs** to avoid cable failure between the float and CTD, (3) **a new bottom detection software** based on the vertical speed of the float near the bottom to avoid snagging at the bottom when bottom depth is shallower than parking depth, and (4) **an option for the float to profile during ascent** from parking to the surface, in addition to profiling during descent, as to provide near-real time data. A total of 9 MRV Deep SOLOs (out of 45 since 2016) by PMEL and CSIRO, and 10 SIO Deep SOLOs (out of 78 since 2016) were deployed between 01-09/2021. The Deep SOLO float deployments of 2021 have been focused on extending the regional Deep Argo arrays of the Brazil and Argentine basins, western Pacific Ocean, and Australian Antarctic Basin.

- **Deep-APEX** Brian King, Shigeki Hosoda

The Deep APEX can cycle to 6000 dbar, ground and li;off, park and profile at any depth. The energy budget for the Deep APEX is OK, in the absence of other problems the float can do 150 cycles of 2-dbar continuous profile, with Aanderaa DO. Significant changes have been made a;er analysis of early failures, especially to the internal buoyancy system, the apf11 controller, and to address comms with SBE61.

An experimental APEX/RBR deployed Dec 2020 lost comms between float and CTD (reason unknown). A batch of 5 floats built in 2019 and deployed in Feb 2020 was disappointing: 2 failures associated with the SBE61, 2 failures associated with buoyancy, 1 working OK

A batch of 5 floats built in 2020 and deployed in Dec 2020/Mar 2021 is encouraging: 5 working OK out to 32 x 10-day cycles

- **Deep-NINJA** Taiyo Kobayashi

Deep NINJA is a deep float which was developed by TSK and JAMSTEC to measure the deep ocean up to 4,000 dbar in the ocean from the tropics to the high-latitudes with seasonal sea ice. The present standard model has a SBE 41CP CTD sensor and a RINKO-DO sensor. A model with Rockland's turbulent sensors was newly developed; the observed turbulent data are available after recovery. Deep NINJA has sufficient capacity to load additional sensors. The float can observe about 70 full CTD profiles, which will be extended with a new buoyancy engine in future.

- **Deep-ARVOR** Xavier André

The Deep-Arvor was designed by Ifremer and is commercialised by NKE instrumentation. It operates down to 4,000 m depth, and realizes its profiles during ascent. 22 Deep-Arvor have been deployed in 2021 by Ifremer, and 96 units in total. Regarding statistics, users must take into account the hardware characteristics (DO optode, etc.) and the sample strategy (spot sampling, continuous pumpins, etc.) in their calculations, as the impact on power consumption is important. The Deep-Arvor is also used as a cross-comparison platform for CTDs (SBE 41CP, SBE 61CP or RBR Concerto) or other sensors (Aanderaa 4334, JFE rinko AROD-FT). Ifremer announces its intention to develop its own 6,000 m depth float, that will be used as a complement to the existing 4,000 m version, that will continue to be deployed.

- **HM4000** Zhaoui Chen

The power supply module and the main control system of HM4000 have been updated. Currently, the measurement module can be compatible with SBE61 and RBRargo^3 CTD sensors. The power supply system and the battery capacity has also been increased by over two-thirds. The Deep floats for 6000 m (HM6000) are currently under development. 9 HM4000 floats were deployed in the Kuroshio/Oyashio Extension region in May/June, with 7 floats being alive as of October 18th. Float #14 was lost after 3 successful profiles, and float #18 was lost after 24 successful profiles. There will be 5 Deep Profiling floats to be deployed in 2022.

4.2 Performances and issues of CTD sensors (accuracy and stability)

◆ **SBE61 presentation** Nathalie Zilberman, Dave Murphy, Phil Sutton

As part of a NOPP project, Sea-Bird conducted collaborative research with Scripps and NIWA to identify new pressure sensors with performances higher than the Kistler model currently used on the SBE-61 Deep Argo CTD. Shipboard comparisons of experimental SBE-61 CTDs with SBE-9+ (equipped with Digiquartz) show Keller and Mensor pressure accuracies of ±1.5-2 dbar. Pressure comparisons between experimental SBE-61 CTDs and standalone Quartzdyne on Deep SOLO floats deployed in the Southwest Pacific Basin indicate Keller and Mensor pressure accuracies of ±1.5 dbar. **The Mensor and Keller models deliver higher accuracy than the target value (±3-dbar) envisioned for the Deep Argo Mission**. Deep SOLO float observations in the Southwest Pacific Basin indicate limited drift (< 0.5 dbar) 6 months after deployment. Collaborative engineering work will continue to reduce the risk of failure of Keller sensors due to parking at pressures higher than 5000 dbar, and to reduce noise and increase durability of the Mensor pressure sensor model.

◆ **SBE41 presentation** Taiyo Kobayashi

The comparison with shipboard CTD casts at deployment clarified that SBE 41CP CTD sensor (on Deep NINJA) yields fresher salinity with a negative pressure dependency, expressed as $\Delta S = \Delta S_{offset} + a_p \times pressure$ and $a_p < 0$: a_p and ΔS_{offset} were -1.80×10^{-6} dbar^{-1} and –0.012 on average, respectively. Sensors with a fresher ΔS_{offset} tended to have a smaller a_p. The fresh salinity bias changed toward saline over time. An analysis of Argo salinity —because the SBE 41/41CP CTD sensor is on most Argo floats— did not identify a statistically significant pressure dependency. Conclusively, the SBE 41CP CTD sensor on deep floats, in their present state, generally did not meet the target accuracy of Deep Argo for salinity. The present study suggests that the CTD sensor could almost achieve the target accuracy by aging with high pressure, accurate calibration of pressure-aged sensors, and a suitable canceling factor for pressure (*CPcor*: -12.6×10^{-8} dbar^{-1}).

◆ **3-head float experiment results** Virginie Thierry

Two Deep-Arvor floats equipped with three different CTD (SBE41CP, SBE61 and RBR concerto) were deployed in December 2020. One floats failed after 16 cycles and was recovered. It will be redeployed in 2022. The two floats revealed that the pressure difference between the sensors ranges from 0 at the sea surface to +/- 5db at 4000 dbar or even 9dbar when comparing the SBE61 and the RBR pressure sensors. The RBR sensor exhibits a pressure response below 2500 dbar that has been corrected since those deployments. The SBE temperature sensors agree within sensor accuracy (temperature differences are less than 1m°C). As known, the SBE conductivity sensor exhibits a pressure dependent response (referred to as Cpcor correction). Once corrected with an optimized Cpcor value, only one of the four SBE conductivity sensors present no offset compared to the reference CTD cast.

◆ **RBR presentation** Brian King and Mat Dever

The presentation includes a review of all Deep argo floats deployed with an RBR*argo*^{3}|deep CTD to date. It highlights the need for a unit-based characterization for the compressibility error on salinity during the calibration process. In fact, 6 of the 11 floats calibrated in a cold pressure tank demonstrated good salinity accuracy (± 0.01) to a depth of 4000 dbar. The remaining 5 floats could be corrected in post-processing to provide the target accuracy (±0.01) up to 6000 dbar. A consistent salinity error in the pressure response was observed in an experiment led by IFREMER where three different CTDs were mounted on one float. This feature has now been alleviated thanks to improvements in the production process. Finally, and despite the relatively short time series available, the stability of the

RBR*argo*^{3}|deep is discussed, showing encouraging results for 5 out of the 6 CTDs deployed. Longer time series will be necessary to draw definite conclusions.

➔ Discussion

Sea-Bird Scientific was asked to (1) estimate cost to provide to users individual CPcor values for SBE-61 and extended-depth SBE-41 CTDs, and (2) define plans to develop a new extended-depth SBE-41 CTD model with improved pressure sensor (with pressure accuracies similar to the NOPP SBE-61 CTD).

Deep Argo float providers were reminded that (1) Deep Argo float life expectancy should be longer than 4 years (>150 cycles) in order to successfully implement and sustain a 1250 global Deep Argo array, and (2) the targeted cost of Deep Argo profile (including float and CTD fabrication, float deployment, satellite communication, and data quality control) is $500 per 0-6000m profile, and <$500 per 0-4000m profile.

4.3 DMQC strategy (progress on CPcor)

◆ Presentation of the current strategy Cécile Cabanes

The current Delayed mode strategy for the salinity of deep Argo floats is based on:

the correction of a pressure dependency (CPcor issue) and the assessment of a pressure-independent offset/drift from OWC.The procedure is described in the Argo Quality Control Manual, section 3.10. The Cpcor is the correction term for the pressure effect on conductivity in the calibration equation of the SBE CTDs. The nominal Cpcor value from SeaBird is too large, resulting in a fresh salinity bias at high pressure. In delayed mode, the salinity should be recomputed using the recommended Ccpor values for SBE41CP or SBE61 or using a refined estimate obtained by comparing a deep argo profile to a reference profile. Once the Cpcor value is corrected the delayed mode operator should assess sensor drift and offset. Evaluation of sensor drift or offset should be done in accordance with the expected uncertainty for deep-Argo salinity (0.004).

◆ Feedback from DM operator about CPcor, long term stability and reference data

● Feedback from Ifremer Cécile Cabanes

54 French Deep-Arvor floats deployed in the North Atlantic and to date, 20 floats have been processed in delayed mode and data have been transmitted to Coriolis in August 2021. Recommended Cpcor value for SBE41 (-13.5 e-8) is adequate for most of our floats deployed in 2014-2018. However, this value seems too low (-11.5e-8 fits better) for floats deployed more recently (2020-2021). The combined use of OWC method and the comparison with the shipboard CTD made at launch allows the detection and correction of salinity bias as low as 0.002. We observed slightly more fresh offsets than salty offsets at launch, even after the CPcor correction.
Six floats (out of 20) show a salty drift. Some drifts are weak (0.005 psu/yr) but all started in the year of deployment.

● QC Status and long term stability of Japanese Deep Floats Kanako Sato

JAMSTEC succeeded in correcting the salt value of 60 Deep floats using the optimized CPcor and salinity offset for each float, calculated by using ship-board CTD data at its deployment. JAMSTEC investigated salinity temporal drift of Deep floats deployed in the northwestern Pacific Ocean by comparison between salinity profile about a year after deployment and ship-board salinity data of JMA within a radius of 120km and within 50 days from the profiles of Deep floats on isotherms. Only two floats are examined. As a result, the temporal drift of salinity is +- 0.001/yr, which is similar to the stability listed in the catalog of SBE61. In addition, It seems that pressure dependence of salinity is still small even about a year after deployment of each float in the deep layer. On the other hand, the temporal drift of pressure does not seem to be small.

- **Feedback from UW** Annie Wong

The current DMQC procedures for Deep-Argo salinity data are adequate in correcting the 3 Deep APEX floats at UW, to within the quoted uncertainty. Visual checks of temperature versus pressure can only discern gross errors.

- **Feedback from OGS** Antonella Gallo

We did DMQC analysis for two SBE41 floats using standard and optimized Cpcor. For WMO 6903268 float the optimized value didn't give good results, the original profile is the best. The positive deviation starts already from 200dbar. For WMO 6903203 float there is no CTD at deployment. The CTD nearest in time and space was used. Default Cpcor value gave better results. Review and improve the availability of high-quality ship-based CTD reference data for QC of deep Argo floats. A new Argo deep float was deployed in Rhodes trench few days ago with the help of HCMR.

◆ Existing status and future evolution of reference dataset Sarah Purkey

The Deep Argo program requires a highly accurate reference salinity database in order to meet the required 0.002 target salinity accuracy. The core Argo CTD reference data now includes a new quality flag (QCLevel=GSD) to indicate casts that were sourced from the GO-SHIP Easy Ocean database. These profiles, all collected through the WOCE or GO-SHIP programs, are the highest quality data and have undergone additional QC. Salinity data has additionally been adjusted to account for any batch-to-batch differences between standard seawater references used (Kawano et al. 2006). The GO-SHIP Easy ocean includes 16243 stations along 45 transects. This year, two new occupations along A20 and A22 in the North Atlantic were added.

◆ Discussion

There is a working group on Cpcor issues, which is open to anyone involved in the subject. Interested people should contact Cécile. The question of reference data to be used for deep DMQC was discussed and in particular the issue of using old data (i.e. WOCE data).

5. Conclusion

A paper on the Deep-Argo implementation plan will be written in 2022. It will be fed by the discussions held during the workshop.