Euro-Argo
European Research Infrastructure
Consortium

Strategy for evolution of Argo in Europe

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Authors: Euro-Argo ERIC members and others

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Executive Summary

The “Strategy for the Evolution of Argo in Europe” presents a strategic plan for a European initiative for the future development of this international programme aiming for

- **strengthening** Europe’s role in and contribution to the global Argo Programme,
- **supporting** the implementation of the EU Marine Policy through the development and subsequent incorporation of biogeochemical sensors into the programme,
- **extending** spatially the observations into the European and Polar Seas, as well as into the abyssal parts of the oceans,
- **further developing** the existing data management system, and
- **maximising** the relevant knowledge of the Seas and Oceans, e.g. their role in a changing climate.

Argo is now the major and only systematic source of such data over the oceans interior. However, there is an essential need for more data, especially from polar regions and the abyssal ocean. Together with satellite observations Argo provides critical observations of the ocean that are required to constrain the Copernicus Marine and Climate Services modelling and forecasting systems.

A consistent policy for the European seas is a long-term objective of the European Union’s legislation, i.e. it’s Marine Policy. Jointly with the EU Marine Policy with its environmental pillars, the Water Framework Directive and the Marine Strategy Framework Directive several regional conventions demand a good state of the ecosystem. In addition, the Copernicus Marine Environment Monitoring Service (CMEMS) relies on quality controlled observations to provide regular and systematic reference information on the physical state, variability and dynamics of the ocean and marine ecosystems for the global ocean and the European regional seas.

Improved knowledge of the physical and biogeochemical processes of the European Seas is absolutely necessary for their management, protection, and for understanding their role in the climate system. Specific aspects are the oceanic circulation, the thermohaline stratification of the seas and control factors that govern the biogeochemical cycles. This demands a sufficient amount of monitoring data over the whole water column in the European marginal seas that in a sufficient spatial and temporal resolution only can be provided by Argo. The report thus defines targets for marginal seas like the Black Sea, the Mediterranean Sea, the Nordic Seas and the polar oceans. It describes the progress necessary in monitoring biogeochemical variables.

Polar regions, especially the continental ice sheets, show a higher vulnerability to global warming than other regions. The melting of the ice sheets affects the ocean and atmosphere systems, sea level changes, the global transport processes and heat and energy budgets. European interest in these areas has already led to the deployment of Argo floats in the Nordic Seas and the Southern Ocean which has dramatically increased the data availability in such regions. The report gives detailed information about the envisioned Argo monitoring system for these areas.

The deepest parts of the oceans play an important role in the evolution of the surface temperature on Earth through its capability to store and transport gases and heat. The technological developments in the recent years have made it possible to test Argo floats which probe the abyssal ocean. The report gives detailed information about the state of the technology and the next steps required to start an abyssal monitoring system.

Remote sensing from satellites provides an adequate tool for monitoring the sea surface height (SSH), sea surface temperature (SST) and salinity of the seas and oceans. Provision of background in-situ data is essential to the satellite community for that they can improve/validate their products. The report therefore specifies targets for temperature and salinity measurements of Argo floats near the surface.

Biogeochemical monitoring of key ecosystem indicators and chemical species allows tracing the flux of carbon, energy, and other elements at the base of the marine ecosystem. This is essential to improve the understanding of control factors and to realistically assess natural variability or climate change impacts (e.g., ocean deoxygenation) on important ecosystem services, e.g., the availability of food resources. The report details the foundations and required steps for a Biogeochemical-Argo array to monitor relevant ecosystem parameters.

All these suggested improvements in the existing Argo network also impact the data management system. New float technologies require data transmission modifications, too. The extension of the Argo mission requires adaptation measures in the data business. The data processing chain has to be adapted to new biogeochemical parameters. Measurements in high latitudes may suffer from missing precise locations and have to be post processed.

The initial version of this strategic plan was based on the original document entitled “Roadmap for evolution of Argo in Europe”, a deliverable (D2.2.1 published in November 2013) of the EC FP7 project “Strengthening international dimension of Euro-Argo Research Infrastructure (SIDERI)”.

1 CONTEXT

The need of understanding ocean processes driving climate variability and change is still a matter of great interest in the scientific community, in policy, in the economy and in the public. Promoting this research needs a reliable provision of quality controlled oceanic data. To meet this demand, different international ocean observing systems have been implemented in the last decades under the governance of the JCOMM (Joint technical Commission for Oceanography and Marine Meteorology).

At the European level, EuroGOOS is a pan-European ocean observing network operating within the context of the Global Ocean Observing System (GOOS) of the IOC that identifies priorities, enhances cooperation and promotes the benefits of operational oceanography to ensure sustained observations are made in Europe's seas. EuroGOOS has recently launch the European Ocean Observing System (EOOS), a flexible coordinating framework designed to align, integrate and promote Europe's ocean observing capacity. EOOS will link the dispersed community delivering and supporting European ocean observations with an overreaching vision and strategy, taking into account the specificities of each network (autonomous platforms, moorings, ships, etc.).

The international Argo program represents one of the major providers of in-situ data for the ocean interior. Together with satellite observations, Argo provides critical observations of the ocean that are required to constrain modelling and forecasting systems. The role of Euro-Argo is to coordinate, develop and consolidate the European contribution to the global network. The European contribution to Argo feeds the Copernicus Marine Service and helps addressing needs for oceanic data for specific European societal and scientific interests (e.g. in marginal seas, high latitudes). It is now timely to derive a roadmap for the future evolution of the Argo network and to specify the European interests in the network and define targets for the major regional interests. This will be done with close cooperation with Argo international and EuroGOOS, under the umbrella of EOOS.

2 EVOLUTION OF THE CORE ARGO SAMPLING STRATEGY

Argo is an international array of more than 3000 profiling floats that measure temperature and salinity every 10 days throughout the deep global ocean, down to 2,000 meters.

Many scientific achievements have been realized thanks to the availability of Argo data, e.g. Argo data have been used to better understand global sea level rise (e.g. Cazenave et. al., 2009) and to analyse large scale ocean circulation variations and deep convection areas (e.g. Väge et al., 2009). Argo provides a huge improvement in the estimation of heat stored by the oceans (e.g. von Schuckmann et al., 2009; Trenberth, 2010; von Schuckmann and Le Traon, 2011, Balmaseda et al 2013, Roemmich et al 2015). In relation to the historical record, Argo data have also shown salinity changes that suggest an amplification of the global hydrological cycle (Durack and Wijffels, 2010), and the salinity data from Argo are essential to constrain the halo-steric sea-level, especially in data assimilation systems that use altimeter derived sea surface height (Zuo et al 2015).

Operational predictions at seasonal and sub-seasonal time scales, as well as decadal predictions, rely on a sustained, stable and timely ocean observing system. The time evolution of the ocean in equatorial regions and the upper ocean is pivotal for monthly and seasonal predictions, while decadal predictions also need knowledge of the deep ocean. Modelling and initializing interactions between ocean, sea-ice and atmosphere in the polar regions are perceived to be important for increasing predictive skill at a variety of time scales (from days to decades). Argo has brought remarkable advances in ocean forecasting capability (e.g. Oke et al., 2009; Dombrowsky et al., 2009) and is essential for developing reliable seasonal to decadal climate predictions (e.g. Balmaseda and Anderson, 2009). The global Argo dataset is not yet of sufficient duration to derive robust global change signals and the greatest contributions of Argo for observing the global ocean are in the future.

All of these achievements require a high level of international cooperation, in which European agencies have played an important role from the beginning. In January 2008, a research consortium called Euro-Argo was established with 15 organizations from 12 countries. The European partners aim at providing about ¼ of the entire Argo array, which requires the capacity to procure and deploy about 350 floats per year, to monitor these floats properly and to ensure all data can be processed and delivered to users in a timely manner. On account of the strong interest of the European Community for the monitoring of marginal seas, Euro-Argo plans to contribute an additional 50 floats per year for strengthened monitoring in these areas through funding from the European commission. European contributions to the international Argo program are collected efficiently in the framework of Euro-Argo and communication and cooperation with the international program is thus strengthened. With the envisioned contribution of the European Commission, a stronger European contribution to international Argo will be achieved that will strengthen the leading European role in International Argo and its future evolution.

Euro-Argo needs to meet requirements from the research and operational oceanography community in Europe with a focus on European Seas. This requires adaption of the ‘Core Argo’ design to these needs and evolutions in array design float technology and data systems. In particular the European research community will need refinement of Argo strategy and technology in the following areas:

- Monitoring of marginal seas
- Monitoring of high latitudes
- Monitoring of the near surface oceans
- Monitoring of the abyssal oceans
- Monitoring of ecosystem parameters

The Atlantic Ocean is a region of great interest in the European research community, and float deployments will be continued in this ocean, with a specific attention on keeping the appropriate sampling in equatorial and boundaries regions.

The Gulf Stream Extension is one of the strongest Western Boundary Currents in the global ocean. It is part of the wind driven and thermohaline circulations (Gnanadesikan, 1999) and plays a critical role in transporting heat poleward. Heat is taken up at low latitudes and released to the atmosphere (Kown et al, 2010) while being transported northward (Ferrari & Ferreira, 2011). In mid-latitudes, it acts as a heat buffer (Kown & Riser, 2004; Kelly & Dong, 2004). The Gulf Stream is dynamically unstable and therefore permanently develops a strong turbulence that is characterised by eddies and meanders with typical diameters of about 100 km. This turbulence scale is smaller than the space/time covariance of Argo measurements that are typically mapped over scales of about 300 km. Many Argo data applications (e.g. heat and sea level variability budgets, water mass studies) thus require an increased sampling in the Gulf Stream Extension, and more generally in all turbulent Western Boundary Current regions. It is only in the Kuroshio/Oyashio area that an Argo sampling enhancement of at least 2 profiles per 3°x3°x10 days (i.e. twice the global Argo coverage) has been achieved (Kuragano et al, 2015). Euro-Argo will contribute to reach this enhancement for the Gulf Stream Extension region.

Euro-Argo partners have long-standing experience in float deployments in high latitudes. This interest is due to the fact that polar regions are especially vulnerable to climate change and play an important role on global scale for the heat balance and the circulation regime in northern Europe. Due to the harsh environmental conditions in these regions monitoring data are lacking or insufficient. At present, the use of floats in the polar oceans is seriously impeded by the presence of sea ice, since floats are prevented from transmitting their data and there is an increased risk of being damaged on the surface in the ice-covered regions. Nevertheless, the high latitudes are key regions of the global climate system and thus need to be monitored. Fortunately, during recent years, the ice-resilience of Argo floats has been increased. In particular, great progress has been achieved in Germany by the Alfred-Wegener-Institute (AWI) in cooperation with the German float manufacturer Optimare developing profiling floats to operate under seasonal ice.

Mediterranean Sea and Black Sea are two seas that are strongly affected by human activities and climate change. Since 2000, numerous Argo floats have been deployed in the Mediterranean and Black Sea within various national programs and by different institutions. Some European countries such as Italy, Greece and Bulgaria focus their Argo activities very strongly on these two seas and have developed necessary deployment capabilities and data management systems. Different cycling and sampling characteristics have been tested and selected for monitoring the thermohaline variability of these marginal seas. The settings include, among others, cycles of 5 to 10 days and parking depths between 350 and 650 m for Mediterranean and between 200 and 1550 m for the Black Sea. However, continuous assessments of the chosen float parameter are necessary. Argo data are required in different operational applications, e.g.

they are routinely assimilated in numerical forecasting model (MFS) of the Mediterranean and used in climate change studies.

In contrast to other oceanic areas, the Black Sea is the world's largest anoxic basin. Its deep waters are depleted in oxygen and most marine life. At present, the Black Sea is the least monitored and scientifically studied marginal sea among the European Seas. Bulgarian activities have focused on the Black Sea and let to the deployment of a number of floats in this sea. It is expected that the increased monitoring will lead to a better understanding of the circulation, the thermohaline stratification, and factors that control its biogeochemical cycles. The Black Sea is also an optimal laboratory for testing new sensors measuring biogeochemical parameters and developing new knowledge. Based on national initiatives some of the development is already underway. Floats with extended capabilities will be tested in projects such as NAOS (Novel Argo Ocean observing System) and Remocean (Remotely sensed biogeochemical cycles in the ocean) that aims at better understanding biogeochemical cycles and ecosystems.

Strong interest of the European research community, the EU Marine Policy (e.g. Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD)) and Copernicus Marine Environmental Monitoring Service (CMEMS) exist for the extension to biogeochemical variables pH, oxygen, nitrate, chlorophyll, suspended particles, and measurements of the amount of the penetrating sunlight. It is expected that the use of biogeochemical sensors on Argo floats will revolutionize our understanding of the coupling between ocean physics and biology (e.g. Claustre et. al., 2010a, Johnson and Claustre, 2016) which will be important in terms of maintaining safe and healthy environmental conditions. Biogeochemical data could be used to initialise, constrain and validate operational real-time ecosystem models. Several pilot experiments are ongoing or in planning stages in different oceanic regions, which encompass several European Seas (Nordic Sea, Atlantic Sea, Mediterranean and Black Sea). It can be assumed that an intensification of *in situ* measurements by bio-optical profiling floats will strongly foster our understanding of ocean bio-optical and biogeochemical properties (Claustre et al., 2010a). Bio-optical floats will undoubtedly become the corner stone of future open-ocean observation systems dedicated to biogeochemistry and ecosystems that will largely be based on automated and remote techniques (Claustre et al., 2010b). Combined with satellite ocean-color radiometry (OCR), SSH and SST, bio-optical float arrays will permit, specifically, the creation of unique hydrographic and bio-optical 3D/4D climatologies, linking surface (remotely detected) properties to their vertical distribution (measured by autonomous platforms), and thus facilitating novel investigations. In particular, the eddy tracking from altimetry (Chelton et al., 2007) can be regularly applied to collocate Argo profiling floats within mesoscale features as recently demonstrated by Raj et al., (2016).

After years of regional efforts and great strides in sensor operation and calibration that demonstrated the feasibility of operating biogeochemical arrays of Argo floats, a workshop was held in Villefranche (France) in January 2016 to prepare the transition to a global-scale Biogeochemical-Argo program. The scientific and implementation plan was subsequently prepared that forms the basis of a new international Biogeochemical-Argo coordination framework (Johnson and Claustre, 2016) on which Euro-Argo will rely.

There is a strong interest in the satellite data community for in-situ surface temperature and salinity data access, e.g. for independent validation of various SST analysis products (GHRSST, Group for High Resolution Sea Surface Temperature). Observations of the ocean surface boundary layer is also of major interest in coupled ocean-atmosphere data assimilation systems. Thus, defining the strategy to bring Argo data up to the surface is a necessity.

Monitoring the deep ocean below 2000 meters is one of the main necessary evolutions of Argo. There is a strong requirement from the ocean and climate research community to develop floats which are able to go deeper than 2000 m (e.g. Freeland et al., 2010; Church et al., 2011). Abyssal warming has been recently documented (Purkey and Johnson, 2010) and there is a need to monitor these deep signals for studies of sea level rise and to be able to constrain climate models. Some development is already underway and a design for a future Deep-Argo array has been proposed by Johnson et al. (2015).

To meet the European requirements it is proposed to:

- Keep the Argo « Core mission » as the global +/-60° array (T&S)
- Define an Argo « extended mission » for marginal seas (T&S)
- Define an Argo « extended mission » for high latitudes (T&S)
- Define a strategy for O_2 and Biogeochemical Argo « extended mission » implementation
- Decide on targets for global area and European enhancements
- Continue pilot experiments for deep floats
- Share best practices, continuous evolution of data system and technologies
- Monitor the different components (through the AIC)

3 MONITORING MARGINAL SEAS

3.1 Mediterranean Sea

What exists

Since 2000, numerous Argo floats have been deployed in the Mediterranean within various programs and by different institutions/countries. Different cycling and sampling characteristics have been tested and selected to monitor this marginal sea, including cycles of 5 to 10 days. Parking depths are set between 300 and 400 m and maximum profiling depths vary between 700 and 2000 m. Between 2000 and 2016 more than 250 floats have been deployed in the basin (of all types: Apex, Provor, Arvor, Nova and Nemo) among which about 80 floats are still active today (October 2016). They produced more than 37000 CTD profiles during the last 16 years in the Mediterranean Sea.

Near the end of 2016, the number of active floats in the Mediterranean was in excess of 80 units. About two thirds of them had bidirectional Iridium data telemetry. 27 floats were equipped with biogeochemical and optical sensors (NAOS, HYMEX and other projects).

Use of Argo data

Argo data in the Mediterranean have been used to study the thermohaline variability in Mediterranean sub-basins. They have been combined with ship-based CTD data to check the consistency of the existing historical data base and to estimate long-term trends in the Mediterranean. For example, significant trends of increasing temperature and salinity are manifested in the Ionian Sea (see Figure 1).

Sparse information exists about the circulation scheme of the Mediterranean. The sub-surface circulation at 350 m (Figure 2) has been derived from float drift at the parking depth and has been used in scientific applications such as the study of the salt and mass transport of Levantine Intermediate Water (Menna and Poulain, 2010, Bosse et al. 2015).

Furthermore, float data are routinely assimilated in numerical forecasting model (Figure 3) of the Mediterranean, producing daily and weekly forecasting maps (Tonani et al, 2009). The assimilation of Argo salinity profiles increases the forecasting skill significantly.

Real-time and delayed mode quality control (QC) of float data

Real-time quality control (RTQC) is routinely done by the Coriolis GDAC. The NetCDFs files are created based on incoming data and real-time QC procedures are applied. OGS (Italian institute of Experimental Oceanography and Geophysics) is responsible for the DMQC for the Argo data (pressure, temperature and salinity) in the Mediterranean. Before the application of the DMQC, selected float profiles have been qualitatively compared (in time and space) with the historical data. Any possible surface pressure offsets were examined using the Metadata and Technical data files; different procedures have been applied to correct this pressure offset depending on the float type, following the standard method proposed by the Argo community.

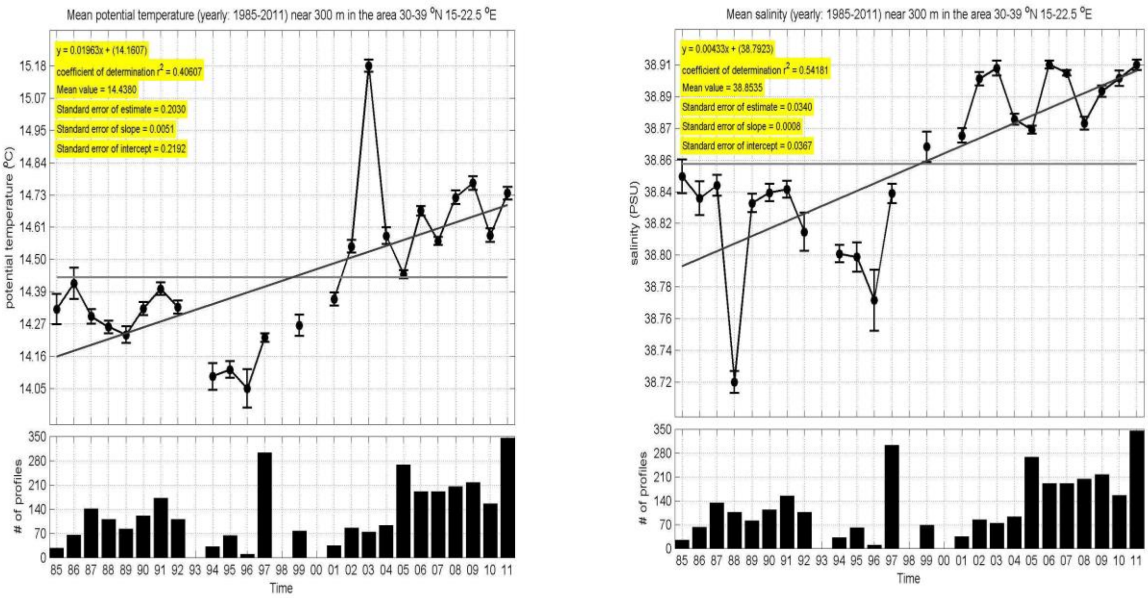


Figure 1. Trends in thermohaline properties in the deep Ionian Sea (1985-2011)

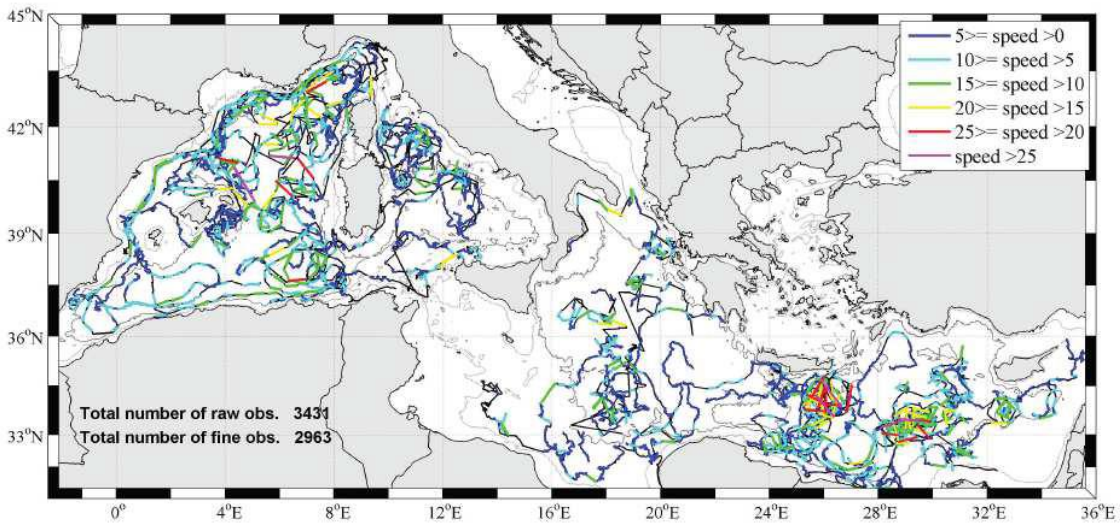


Figure 2. Sub-surface Mediterranean circulation at 350 m (from Menna and Poulain, 2010)

The goal for the future

The goal for the future is to maintain the current density of Argo observations in the Mediterranean (more than 60 active floats which corresponds to twice the standard global Argo density) for providing a better understanding of temporal and spatial variations in the different sub-basins. In order to achieve this goal, given the 5 days cycle sampling scheme in this area, about 30 floats should be deployed every year. Most floats should use Iridium or Argos-3 telemetry. Furthermore, about 8 instruments (25%) should be equipped with biogeochemical sensors.

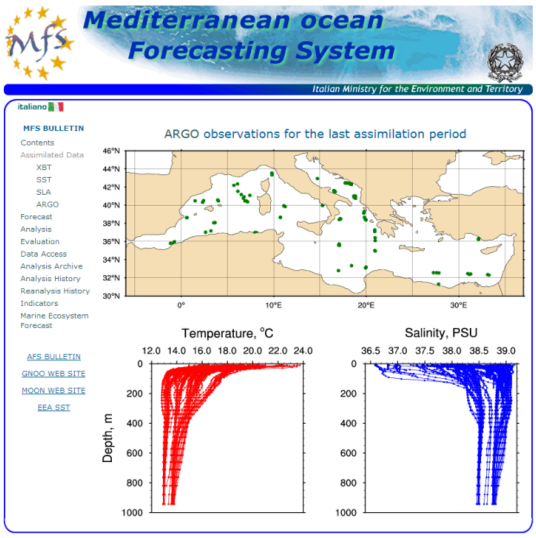


Figure 3. Example of Argo float data being assimilated in operational forecasting models of the Mediterranean.

European needs

The Mediterranean is an endangered Sea (Gibelin et al., 2003), because of the strong anthropogenic pressure on its coasts and because its relative small size could accentuate the impact of the global warming. A high-quality data set will be needed to identify such changes. It is hoped that the continuation of the Argo program with the modified standard parameters (cycles of 5 days, parking depth near 350 m) will provide more abundant data in the whole Mediterranean Sea in order to improve the data consistency, and eventually monitor long-term changes in the mean intermediate circulation related to climate change.

The Mediterranean ecosystem and all the related economical activities (i.e. fisheries, tourism etc) could be strongly perturbed by the climatic changes. Therefore, intensified monitoring could lead to a better understanding of aspects like circulation, thermohaline stratification, and control factors that govern the biogeochemical cycles. Biogeochemical data could be used to initialise, constrain and validate operational real-time ecosystem models.

Requirements

The following recommendations for the sampling strategy of the Argo program in the Mediterranean Sea have been derived in the Euro-Argo PP program. They have been revised and include:

1. Maximum profiling depth of 2000 m at every cycle or every two cycles, with a short 700 m profiles in between;
2. Deployment in deep waters (depth > 2000 m);
3. Cycles of 5 days is a good compromise to capture more variability of the sub-surface velocity field and to obtain a robust estimate of the mean velocity at parking depth.
4. Parking depth between 300 and 400 m to track the Levantine Intermediate Water throughout the Mediterranean;
5. Use Argos-3 or Iridium telemetry to reduce surfacing time (from about 6 h to less than one hour) and probability of hazards (stranding, theft by seafarers, etc.);
6. Deploy the floats inside and outside the significant circulation structures (with sub-basin scale of about 100 km) such as the instability eddies of the Algerian and Libyan-Egyptian Currents, in order to obtain unbiased statistics.
7. In terms of coverage floats have to be deployed in specific areas as it is shown that the Aegean, Algerian Current, the southern and eastern Ionian and the southern Levantine Basin are less/scarcely sampled.
8. There is a strong need to set up a link with ship agencies that operate R/Vs in the Mediterranean and seek ships of opportunity for more effective deployments.
9. A good fraction of the floats should be equipped with optical sensors to monitor dissolved oxygen and other biogeochemical parameters (typically 20-25% of the array, see also section 7).

Technical advances needed

Given the high traffic and limited dimensions of the Mediterranean basins it is important to use 2-way communication satellites (Iridium and Argos-3) to reduce the surfacing time and change the cycling and sampling characteristics of the floats when needed using the downlink. Many floats are also bound to be stranding, so a good international collaboration with all the Mediterranean countries is crucial in order to recover and redeploy the floats. A more efficient use of Ship-of-Opportunity (SOOP) is needed to guarantee frequent deployments in most sub-basins.

In terms of data validation (T and S but also biogeochemical parameters) there is a crucial need to obtain an increased reference dataset for the DMQC covering most areas of the Mediterranean Sea.

3.2 Black Sea

What exists

The first Argo floats were deployed in the Black Sea in 2002-2006 by US scientists (see Korotaev et al., 2006). Since then more than 20 Argo floats were deployed there. In addition to the standard CTD measurements, some floats were equipped with sensors to measure dissolved oxygen concentration, chlorophyll and CDOM fluorescence, backscattering and attenuation coefficients, nitrogen and hydrogen sulphide concentrations, and irradiance. In October 2016, 10 floats were still active in the Black Sea, including 4 with biogeochemical sensors.

Use of Argo data

The Argo data allow the detailed studies of the thermohaline characteristics in the Black Sea. Figure 4 shows the evolution of temperature and salinity measured from the float with WMO-ID 1901200 deployed in December 2009 in the eastern part of the Black Sea, off the coast of Bulgaria. These measurements allow a detailed insight into physical processes such as a cold water transformation during winter and the establishment of a seasonal thermocline during summer.

Two NEMO floats have been deployed in the Black Sea during the first leg of R/V Maria S. Merian Cruise MSM15 (07.04.2010 - 29.07.2010) equipped with Aanderaa optode in order to provide oxygen measurements in addition to temperature and salinity measurements. Figure 5 shows some significant results regarding biogeochemical processes. Both floats show an oxygen maximum occurring in the upper 50m-depth, just above a thin suboxic zone at the base. A persistent cold intermediate layer (CIL) is extending during the entire year, at depth between 50 to 150m-depth depending on the measurement region. Important vertical gradients in salinity appear especially in summer around 100 m-depth.

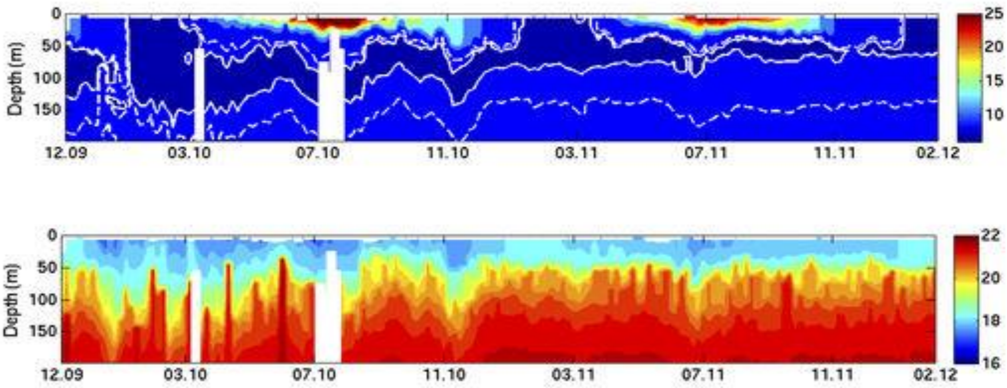


Figure 4. Evolution of temperature [°C] (top panel) and salinity [psu] (bottom panel) with time for the PROVOR Float WMO 1901200 in the Black Sea. Tick marks at the bottom indicate months and years.

Real-time and delayed mode quality control (QC) of float data

Over the last years, several methods have been used for validation of Argo data, including comparison with nearby measurements from other Argo floats, comparison of Argo measurement with nearby shipboard CTD data, comparison with reference climatology etc. Due to the specific hydrological regime in the Black Sea, the standard delayed mode quality control procedures of Argo data have been adapted to the Black Sea regional peculiarities. The Argo dataset has been validated using comparison with SeaDataNet climatology and reference CTD data. The method allows detection of significant errors and deviations in the Argo dataset that can't be recognized by standard Real-Time Quality Control procedures. The quality controlled float data have been integrated in the Bulgarian National Oceanographic Database.

The goal for the future

For the future, it would be necessary to increase the active number of floats in the Black Sea to more than 10 units (including about 5 floats equipped with biogeochemical sensors) to resolve spatial and temporal scales. This number corresponds to about double the number of floats with respect to the global Argo density, as for the Mediterranean Sea and requires annual deployments of 5 floats.

European needs

At present, the Black Sea is the least monitored and scientifically studied marginal sea among the European Seas. More intensive monitoring could lead to a better understanding of aspects like circulation, thermohaline stratification, and control factors that govern the biogeochemical cycles. In contrast to other oceanic areas, the Black Sea is the world's largest anoxic basin. Its deep waters are depleted regarding oxygen and most marine life. Argo floats are capable to measure not only the thermohaline characteristics, but also the dissolved oxygen concentration and water quality properties. These biogeochemical data could be used in the future, to initialise, constrain and validate operational real-time ecosystem models. The regular measurements from Argo floats present a unique tool on the way towards operational oceanography in the region.

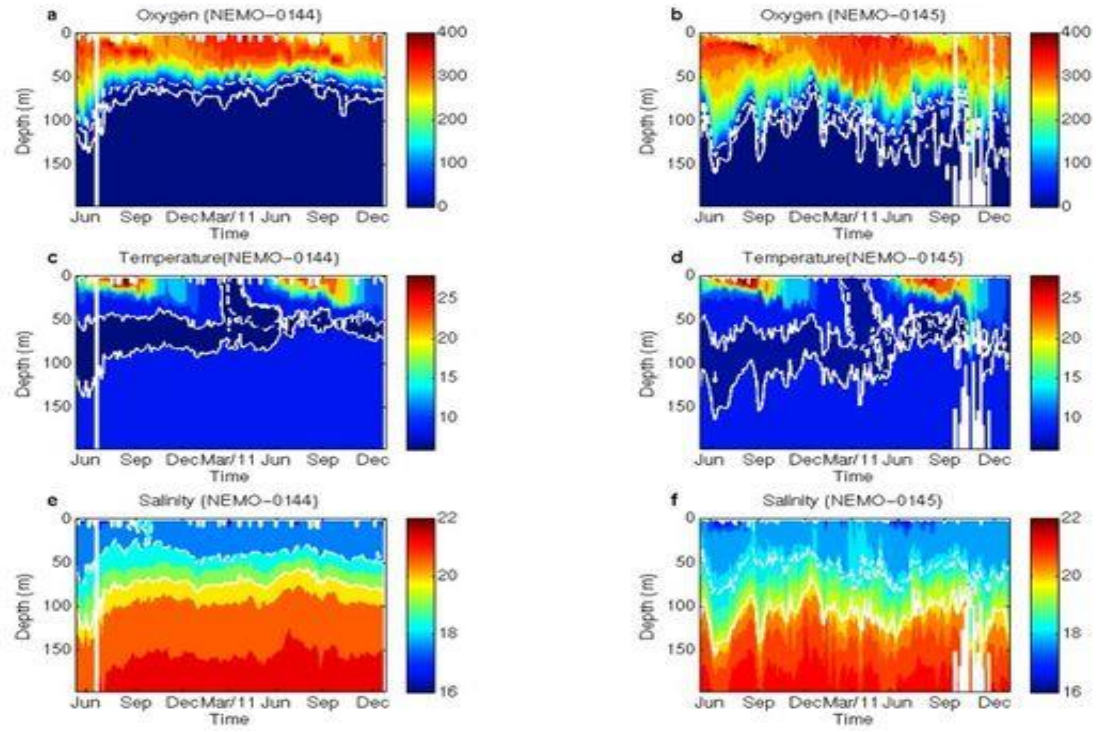


Figure 5. Oxygen [umol/l] (top), temperature [°C] (middle) and salinity [psu] (bottom) as a function of depth and time for NEMO Float #0144 (left column) and #0145 (right column), see Stanev et al. (2013) for the specification of these floats.

Requirements

Specific requirements of higher concentration of float density for adequate monitoring of T/S and biochemical parameters (smaller scales with respect to the world ocean):

- Develop sampling strategies that avoid unnecessary grounding and beaching of floats through short surface times for data transmission and use of bottom topography maps onboard the floats,
- Develop cooperation with neighbouring countries to recover beached floats and redeploy them,
- Develop cooperation with the fishing community to deal with floats picked up by seafarers
- Establish protocols with neighbouring countries to deal with floats passing through territorial waters and EEZs. IOC resolution needed, or concerted action to give permission for Argo from all coastal states.

The following recommendations for the continuation of the Argo program in the Black Sea have been obtained from the studies performed in Euro-Argo:

1. Maximum profiling depth of 2000 m at every cycle or every two cycles, with a short 700 m profiles in between;
2. Deployment in deep waters (depth > 1000 m);

3. Cycles of 5 days is a good compromise to capture more variability of the sub-surface velocity field and to obtain a robust estimate of the mean velocity at parking depth.
4. Use Argos-3 or Iridium telemetry to reduce surfacing time (from about 6 h to less than one hour) and probability of hazards (stranding, theft by seafarers, etc.);
5. A minimum array of 10 floats for the Black Sea.

Technical advances needed

Given the high traffic and limited dimensions of the Black Sea it is important to use 2-way communication satellites (Iridium and Argos-3) to reduce the surfacing time and change the cycling and sampling characteristics of the floats when needed using the downlink. Many floats are also bound to be stranding, so a good international collaboration with all the Black Sea countries (e.g. Romania, Turkey) is crucial in order to recover and redeploy the floats. A more efficient use of Ship-of-Opportunity (SOOP) is needed to guarantee frequent deployments in most sub-basins. In terms of data validation (T and S but also biogeochemical parameters) there is a crucial need to obtain an increased reference dataset for the DMQC covering most areas of the Black Sea.

3.3 Baltic Sea

The Finnish Meteorological Institute (FMI) has utilized Argo floats in the Baltic Sea research since 2011. Activities are motivated by the need to find economical solutions to obtain data from regions in the Baltic which are not visited so often by research vessels or monitored by buoys.

In general, Argo floats have been designed to be used in deep oceans where there is no danger of hitting the bottom or being hit by the ship while at the surface. Normally, there is also no need to change the diving parameters during the mission. However, in the Baltic Sea the operating environment is completely different, with bottom depths of few 100 m or shallower. Therefore, to be able to change the diving parameters of the float, a two-way satellite communication is an absolute requirement.

What exists

The Finnish Meteorological Institute has deployed 11 floats in the Baltic so far. Five of them have a bio-optical sensor suite. Deployment areas are the Gotland Basin in the Central Baltic and the Eastern part of the Bothnian Sea (Figure 6, Purokoski et al., 2013).

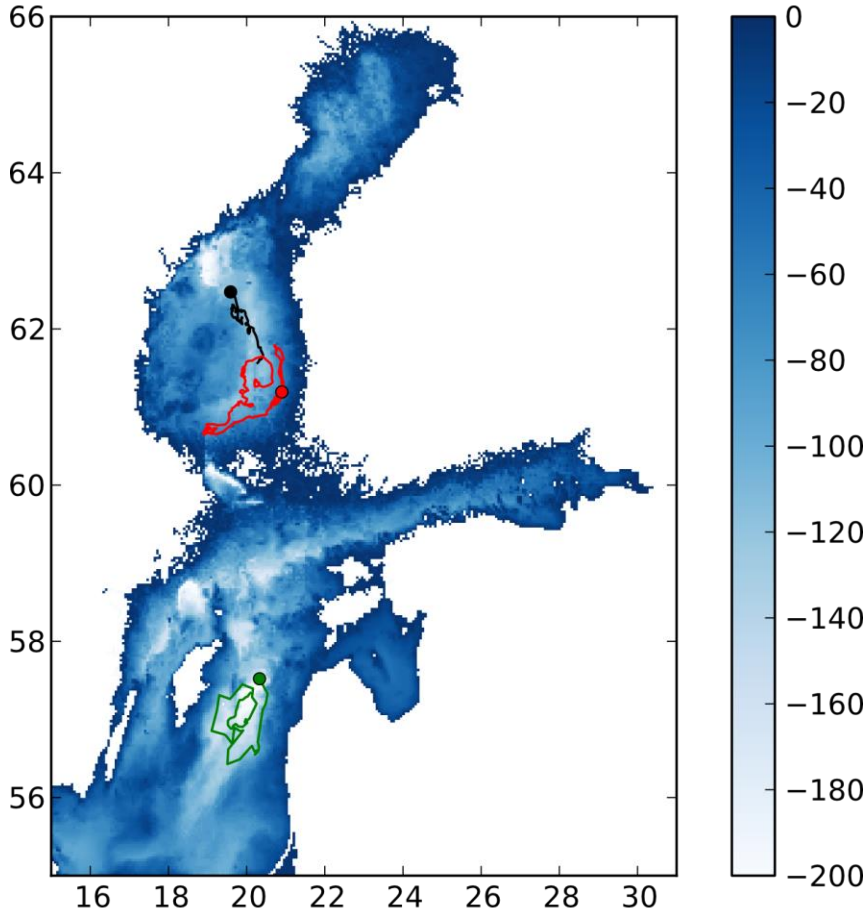


Figure 6. Drift patterns of Argo measurements in the Central Baltic Sea (green) and in the Bothnian Sea (red and blue).

During the first Baltic Sea mission with Argo floats in 2012 the float transmitted over 200 daily vertical CTD-profiles in good quality. Figure 7 depicts time series of individual profiles, showing seasonal changes in the water masses – warming of the surface layer during the summer time and mixing of the water column in fall can be easily detected. These data, as well as the drift of the float have been used in development of a regional circulation model (Westerlund and Tuomi, 2015).

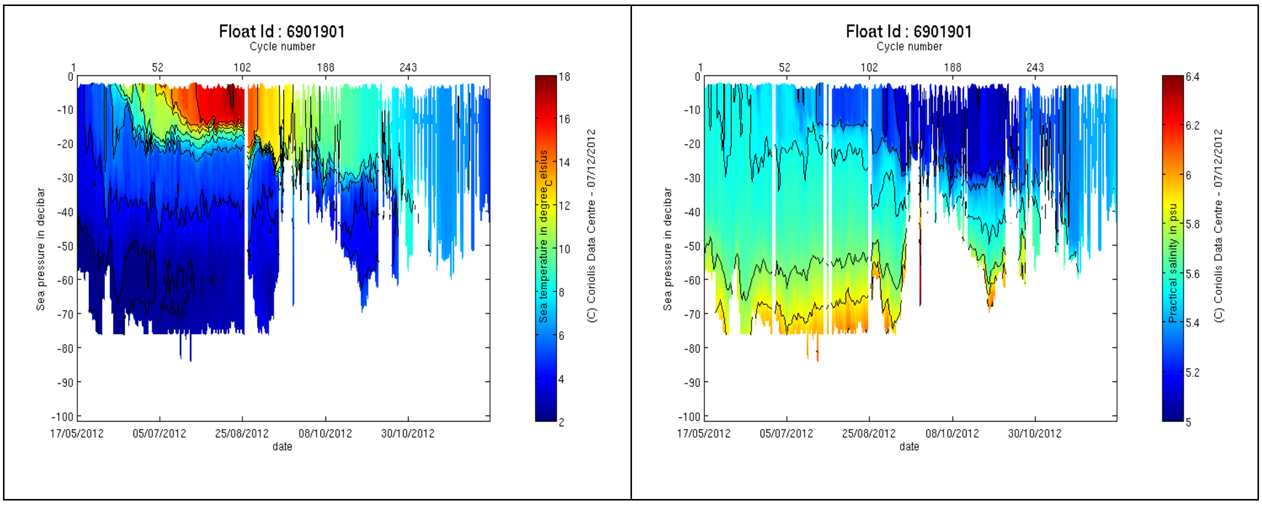


Figure 7. Time series of temperature and salinity at the Bothnian Sea from May to November 2012.

The goal for the future

In the beginning the Argo activity in the Baltic Sea have been limited to scientific interests of FMI. Since the early results showed that Argo floats are extremely good instruments in the Baltic Sea conditions too, the Euro-Argo goal has been to engage more Baltic Sea countries to Argo activity in order to cover all major basins of the Baltic.

IO PAN (Institute of Oceanology of the Polish Academy of Sciences) will begin to use Argo floats in the Baltic starting in 2016. Their interest is to investigate inflow of saline oxygen rich water from Southern Baltic to the Central Baltic and water mass exchanges between the Baltic Sea sub-basins. The first Polish Baltic Argo float has been deployed in December 2016 in the southern Bornholm Basin. Next float will be deployed in beginning of 2017 in the Gdansk Deep. Two-way Iridium communication will be applied.

European needs

As in other sea areas, general need in the Baltic Sea monitoring and research is to conduct real-time measurements in better resolution, both temporally and spatially. Argo-floats have been demonstrated to be a very cost-effective method to fill this gap.

Particular needs for the Baltic Sea are to use floats in examination of deep water circulation, vertical mixing and oxygen depletion. For Copernicus Marine Services, real-time observations assimilated to models are very important in order to improve forecasting capabilities of hydrography, circulation and drift of pollutants.

A more extensive array of Argo floats is expected to be very valuable for the entire Baltic Sea community. In addition to the traditional temperature and salinity measurements, Argo floats equipped with biochemical sensor should also be used. Those floats will revolutionize Baltic Sea monitoring programme of HELCOM (Baltic Marine Environment Protection Commission - Helsinki Commission).

The Baltic Sea with its seasonal sea ice cover could also serve as a test bed for the development of Argo floats operating in sea ice environments. The gained expertize could then be exploited in the development of floats for the Arctic Ocean. In particular, experiences from the Baltic Sea are valuable for designing of the monitoring activities in the Arctic shelf regions and other ice-covered seas.

Requirements

Ideally, the Baltic Sea Argo network should cover all major basins of the Baltic Sea (Figure 8), but in practice a sufficient network would include 7 active floats: one float in the Bothnian Bay, two floats in the Bothnian Sea and four floats in the Baltic Proper. This target could be achieved by deploying 4 floats per year in the Baltic. Since it is planned to recover the floats on an annual basis, the floats could be reused after laboratory calibration and would not need to be replaced by newly purchased ones.

a

Figure 8. Regions and basins of the Baltic Sea: 1 = Bothnian Bay 2 = Bothnian Sea 1 + 2 = Gulf of Bothnia, partly also 3 & 4 3 = Archipelago Sea 4 = Åland Sea 5 = Gulf of Finland 6 = Gulf of Riga 7 = North Gotland Basin 8 = West Gotland Basin 9 = East Gotland Basin 10 = Bay of Gdańsk 11 = Bornholm Basin & Hanö Bight 12 = Arkona Basin 7 – 12 = Baltic Proper, partly also 3, 4, 14 13 = Öresund 14 = Belt Sea, divided among Baltic Sea & Kattegat 15 = Kattegat, not an integral part of the Baltic Sea[21] 16 = Skagerrak, no part of the Baltic Sea.

Technical advances needed

One obvious technological development need is to increase the buoyancy range of Argo floats. Density differences, both in vertical and horizontal dimensions, are large in the Baltic. Due to this feature, floats used in the Southern, Central and Northern Baltic Sea have to be ballasted differently. In case of float drifting from South to North, the float becomes too heavy to be able to drift at the desired parking depth. On other situation, the float could be too light for diving throughout the pycnocline.

To better monitor the different sub-basins in the Baltic, it would be beneficial if the drift of the floats could be controlled and the float would remain in a tight area. This could potentially be achieved by parking them at the bottom in a deep basin or by ‘claws’ at the bottom of the float to anchor it in place. A new type of coastal float which uses claws to anchor the float has successfully been tested in the Bay of Biscay and could maybe be adapted to the Baltic, if the sea floor is not too soft and the float would get stuck. Experiences from the Finnish deployments have also shown that changing of mission parameters could be used to contain the drift of the floats if parked in deep holes. For the upcoming deployments from Poland, a drift at the bottom is envisaged to keep the floats more stationary, but would require changes in firmware to monitor the drift parameters more frequently.

4 MONITORING HIGH LATITUDES

The core Argo mission was defined for the ice-free global ocean between latitudes of 60 °S and 60 °N. The Southern Ocean as well as the Nordic Seas and the Arctic Ocean were originally not included in the design of the Argo array. But meanwhile technical developments have been allowing operation of Argo floats in the seasonally ice-covered environment of the Southern Ocean. Development of appropriate deployment and sampling strategies has also enabled operation of Argo floats in the ice-free areas of the Nordic Seas (e.g. the deep central basins). But for the Arctic Ocean, the seasonally ice-covered regions of the Baffin Bay and the other areas of the Nordic Seas, work still has to be done on the development of appropriate ice-sensing algorithms, based on the respective hydrographic conditions. Presently, other direct methods of ice-sensing, especially based on optical measurements, are being tested for the ice-covered high latitudes in the Baffin Bay.

4.1 Northern High Latitudes

The northern High Latitudes consist of regions with seasonal to multi-year ice-coverage, such as the Arctic Ocean north of the Fram Strait or Baffin Bay, as well as regions which are only partially and seasonally covered with ice, such as larger parts of the Nordic Seas (e.g. the Norwegian, Greenland, Iceland and Barents Sea). Observations from hydrographic surveys are sparse in these regions and did not resolve the intrinsic variability of the systems. The technical development of autonomous profiling floats within the international Argo programme allowed hydrographic observations with a time resolution of 10 days at least in the ice-free regions of the Northern High Latitudes.

In the following sections we concentrate on the Nordic Seas (4.1.1), which are rarely ice-covered, and on the ice-covered Arctic Ocean (4.1.2).

4.1.1 Nordic Seas

The Arctic Mediterranean, comprising the Arctic Ocean and the Nordic Seas, is a major site for high latitude water mass transformation that is driven by intense buoyancy fluxes at the air-sea interface. These buoyancy fluxes act on the subtropical warm and saline Atlantic Water that enters the Nordic Seas from the south and is transformed into two major components: the light, low salinity Polar Water and the dense Overflow waters. The dense waters exit into the Subpolar North Atlantic via the overflows over the Greenland-Scotland Ridge. This vertical circulation loop is the northern limb of the Atlantic Meridional Overturning Circulation.

What exists

Deployment of Argo floats in the Nordic Seas began in 2001. More than 16000 profiles were collected from March 2001 to date by 190 floats. While the life expectancy of floats in the open ocean is estimated to be 4 years or more, the conditions in the Nordic Seas reduce these lifetimes. Floats in the interior Nordic Seas have an average life time of 2.4 years.

The Nordic Seas consist of 4 major basins with weak cyclonic circulation in the interior, which are surrounded by a swift boundary current, that circumnavigates the whole Nordic Seas cyclonically. The inner basins, the Greenland Sea Basin, Norwegian Basin and Lofoten Basin and the somewhat shallower Icelandic Plateau, are separated by submarine ridges and surrounded by the continental shelves (Figure 9). They are most important for the water mass transformation during winter, whereas the boundary currents manage the transport of transformed water masses from the inner basins to adjacent oceans. In the past the majority of floats were deployed in the centres of the basins, they were operating in the Argo standard mode of 10 day working cycles with a parking depth of 1000 m and a profile depth of 2000 m. Two exceptions were made: (1) for the Icelandic Plateau a profile depth of 1300 m was chosen because mean water depths in the region are around 1500 m, (2) for floats additionally equipped with biological sensors the profiling depth is 1200 m and the measurements are refined in the upper layers.

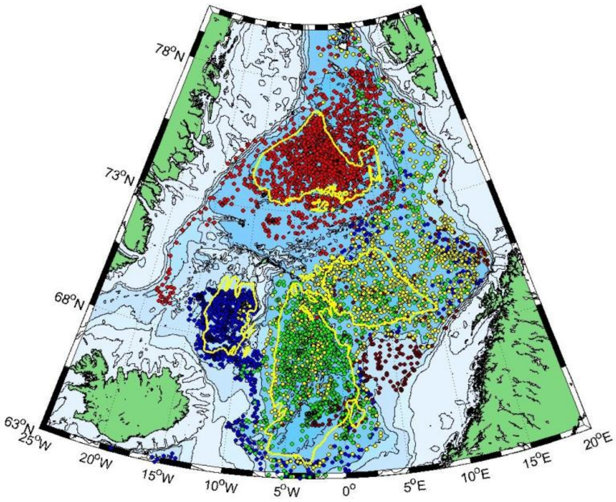


Figure 9. Position of all Argo profiles in the Nordic Seas in the time span 2001 to 2011; the colour indicates the deployment basin: green – Norwegian Basin, yellow – Lofoten Basin, red - Greenland Sea, blue – Icelandic Plateau. The yellow contour-lines define the areas of the individual basins.

In recent years additional measurements were carried in the boundary currents using floats, because these are of great interest in the exchange between the Nordic Seas and adjacent ocean basins. A parking depth of 500 m and a profiling depth of 2000 m are chosen for the boundary current deployments. Because of large displacements by the relative strong currents and the proximity to coasts and shallow waters there, and thereupon shorter life expectancy than in the interior basins, a five day working cycle has been chosen to guarantee an adequate spatial sampling in these areas. These measurements concentrate on the eastern boundary currents only (especially the West Spitsbergen Current), because too much ice-coverage is expected in the west.

Establishing a circulation scheme

Voet et al. (2010) analysed trajectories of Argo floats, drifting at mid-depth (1000 and 1500m) to determine the pattern, strength and variability of the regional circulation. They found that the mid-depth circulation is strongly coupled to the structure of the bottom topography of the four major basins (Figure 10) and of the Nordic Seas as a whole. It is cyclonic, both on the large scale and on the basin scale, with weak flow (< 1cm/s) in the interior of the basins and somewhat stronger flow (up to 5 cm/s) at their rims. Within the large-scale mean circulation, no exchange is observed amongst the basins and between basins and the boundary current. Such exchange takes place by mesoscale eddies, which are not observable by the floats with a sampling interval of 10 days. Mesoscale eddies and transfrontal exchange between Atlantic and Arctic domain were visible by floats deployed in the West Spitsbergen Current (1000 m parking depth, 5 days sampling interval).

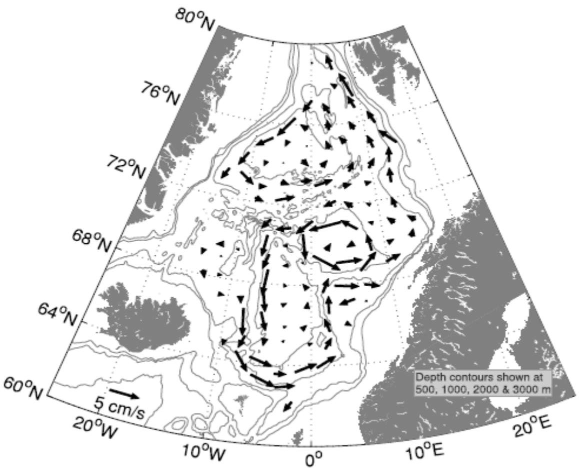


Figure 10. Average circulation in the Nordic Seas at depth of 1500m on a rectangular grid with a size of 110 km. Only mean values calculated from more than five observations are shown.

Hydrography variability

Latarius and Quadfasel (2010) and Latarius (2013) had analysed hydrographic data from profiling Argo-floats. To gain insight in the variability on seasonal to longer time scales measurements within each of the four deep basins time series of hydrography variability for the deep basins were established. The hydrography of the four major basins of the Nordic Seas was observed in this analysis nearly continuously during the time span 2001 to 2012 (Greenland Sea Basin) respectively 2002 to 2012 (Norwegian Basin) and 2005 to 2012 (Lofoten Basin and Icelandic Plateau). Gaps in the time series diminish in late part of their study period were due to drop in yearly deployments by the German, Norwegian and Finnish Argo programmes.

The analyses showed that time series of temperature and salinity for the basins are dominated by the seasonal signal in the upper 500 to 750 m. The detailed knowledge of the seasonal signal, derived from harmonic analyses, can be used for the analysis of longer-term variability on the basis of historical data. Without a seasonal correction, there is a risk of misinterpretation of the trends due to aliasing. The separation of interannual and decadal variability will be possible in the future on the basis of longer time series.

Based on the time series of hydrography derived from float data and in combination with surface flux data from meteorological data sets, heat and fresh water budgets are established for the basins of the Nordic Seas. They give insight into the interplay of lateral exchange between the basins and the boundary currents, the sea-surface heat and freshwater fluxes and the development of heat and freshwater content inside the basins. The results demonstrate the importance of lateral fluxes of heat and freshwater in the near-surface layer and enable to estimate the contribution of the basins for the whole water mass transformation in the Arctic Mediterranean.

Recently, Raj et al., (2016) provided an automated colocation of Argo profiling floats trapped inside the altimeter-based eddies to corroborate the vertical hydrographic structure of the anticyclonic and cyclonic eddies in the Lofoten Basin located in the Norwegian Sea. This combination of altimetry and Argo floats is therefore considered to be a promising observation-based approach for further studies of the role of eddies in trapping and transport of heat and biomass in the Nordic Seas.

Real-time and delayed mode quality control (QC) of float data

The real-time data processing of float data is performed at the Coriolis Centre in France, while the delayed mode quality control (DMQC) for most Nordic Seas floats has been performed at the BSH (German Federal Maritime and Hydrographic Agency). The delayed-mode procedures rely on statistical methods, which require an adequate reference database and an appropriate choice of spatial and temporal scales, as well as input of adjusted float pressure, temperature, position, and date of sampling. Because of expected interannual to decadal changes of water mass properties in the Nordic Seas, the historical reference dataset was extended to include recent CTD profiles. In the period from 2001 to 2009 the method detected sensor drifts and offsets in salinity data from 14 out of 56 floats in the Nordic Seas.

Goal for the future

Given the higher vulnerability of high latitudes to global warming and the potential impacts of global warming and an enhanced hydrological cycle on the water mass transformation in the Arctic Mediterranean and on the AMOC (Atlantic Meridional Overturning Cell), the fundamental research questions to be addressed by a climate observation system such as Argo are:

- What are the key regions for the water mass transformation in the Nordic Seas?

- What are the key processes?

- What variability is observed?

- What is the impact of climate change on these processes?

- What is the impact of climate change on the ecosystem?

The future sampling strategy should ensure to continue the observations in the ice-free regions of the Nordic Seas on seasonal to longer time scales. The number of measurements should match the core Argo requirements.

The continuation of float measurements in combination with satellite SSH, SST and ocean color observations, and capable assimilation systems, will allow to monitor the whole system with the intrinsic variability on seasonal to multi-decadal time scales. It will also allow to determine the impact of the Nordic Seas in climate, and the time frame at which these changes are predictable. This includes observations of the circulation pattern and hydrography of the deep basins as well as the boundary currents, the 3-dimensional properties of mesoscale eddies and the ecosystem. In the past, float deployments have been achieved mainly with contributions from European countries (Germany, Norway, Finland, UK, Denmark, Poland) and demonstrate the European interest in the area. Increased float numbers, to match the core Argo requirements, have to be sustained by the European community.

With the ongoing technological development, a further extension of the global Argo array in to the ice-covered areas of the Northern High Latitudes in envisioned (at about 5 years) and also coverage of the more several ice covered areas in the Nordic Seas (e.g. the East Greenland Current).

European needs

Observational data are needed in this sensitive area for assimilation in forecast models, to initialize, constrain and validate ecosystem and ocean models. It is also needed to initialize and validate coupled earth system models used in weather, seasonal and climate predictions. The Nordic Seas are also the habitat for several large fish stocks and plankton species, and biogeochemical measurements by bio-optical floats will strongly increase our understanding of the coupling between the ocean physics and biology in this area.

Although European marine ecosystems are influenced by many other factors, such as nutrient enrichment and overfishing, every region has shown at least some changes that were most likely attributable to recent climate change. Global climate modelling studies consistently show the High Latitudes to be one of the most sensitive regions to climate change. The ensemble of climate models used in the Intergovernmental Panel on Climate Change (IPCC AR4) predicted a global mean temperature increase between 1-6 °C by the end of this century with twice as high warming in the Arctic region compared to the global average. A result is a rapid decline in the sea ice extent simulated by most models. Not surprisingly, many Arctic life forms, including humans, are directly or indirectly dependent on productivity from the sea. Various marine ecosystems will respond differently to climate change. It is expected that there will generally be (further) northward movement of species, leading to a switch from polar to more temperate species in the northern seas such as the Arctic, Barents Sea and the Nordic Seas.

Requirements

Measurements with Argo floats are at presently only performed outside from the shallow shelf areas and outside from the seasonally ice-covered north-western boundary current area. The core Argo uses a target of one float per month in each 3° x 3° horizontal grid box to calculate the number of floats to be deployed. Using the same target (although a bit skewed by the convergence of longitudes) and considering the area in the Nordic Seas with water depth below 1000 m (Figure 11) a total of 39 should be active in the Nordic Seas. 29 of the floats should be active within the deep basins and 10 floats within the boundary currents. With an approximate life time of floats of 3 years in the deep basins and 2 years in the boundary currents 9-10 deployments per year are needed in the deep basins and 5 deployments in the boundary current (the different deployment areas are marked in Figure 11).

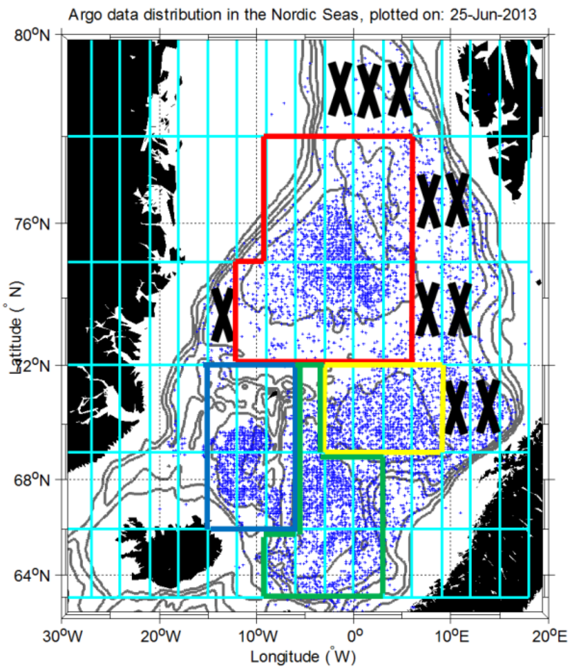


Figure 11. 3° x 3° boxes for deployments: 10 – boundary currents, 29 – deep basins, red – Greenland Sea, blue – Icelandic Plateau, yellow – Lofoten Basin, green – Norwegian Basin.

Floats deployed in the boundary currents should have a parking depth of 500 m, profiling depth of 2000 m and a working cycle of 3 days. Floats deployed in the deep basins should have a parking depth of 1000 m, profiling depth of 2000 m and a working cycle of 10 days. Additionally, floats deployed in the boundary current need improved strategies for ice protection and strengthened design.

A fraction of the floats should be equipped with optical sensors to monitor dissolved oxygen and other biogeochemical parameters. Two floats with biogeochemical sensors (oxygen+bio) in each of the deep basins, except for the Lofoten Basin where 3-4 floats are needed due to its large east-west differences in the physical properties (e.g., western Lofoten Basin is characertized by large eddy activity compared to the eastern Lofoten Basin). However, a pilot study of the Nordic Seas could provide a better estimate of the number of needed bio floats for the region.

Technical advances needed

Reduce loss of floats

- Reduce time at surface.
- Include an Ice Sensing Algorithm to avoid sea-ice.
- Increase ice protection through top-cages and strengthened antennas
- Avoid grounding in shallow areas by using preprogrammed bathymetry map which also allow monitoring deep water masses (as near as possible to the bottom).

Additional sensors

- Argo floats that measure the change in the ecosystem/primary production. Include sensors like e.g. oxygen, chlorophyll-a (fluorescence), backscattering, and light (radiance and irradiance).

Real-time and delayed mode data processing

Delayed Mode Quality Control (DMQC): As long- term changes of hydrography are expected for the Nordic Seas at least yearly updated CTD-reference data are needed for comparison with the float data.

Sampling requirements

A higher vertical resolution in sampling is needed (2 dbar) in order to observe the vertical structures better.

Two-way communication should be used to be able to change the sampling strategy of bio-optical floats seasonally: short cycles (3-5 days) should be chosen to capture the spring bloom, during winter periods with complete darkness bio-optical sensors can be switched off to save energy.

4.1.2 Arctic Ocean

Recent changes of the Arctic Ocean ice cover and hydrography calls for enhanced monitoring of ocean properties, both in terms of temporal and spatial resolution. However, utilization of the Argo-floats in harsh Arctic conditions needs a considerably different approach than in oceans in general.

What exists

For a basic Argo-float, sea ice cover is an obstacle which disables widespread use of drifting floats in the Arctic. However, the multi-year sea ice cover provides a platform for an anchoring of the profiling float. The drift of the sea ice follows rather predictable pattern, anti-cyclonic circulation of the Beaufort Sea and transpolar drift carrying pack ice from the Chukchi-Laptev Sea regions to the Fram Strait, enabling measurements across the Arctic basin. This concept has been used in the frame of iAOOS project (integrated Arctic Ocean Observing System, led by the Arctic Ocean Sciences Board (AOSB)).

The basic difference of the proposed Arctic Ocean automatic hydrographic measurements in iAOOS compared to standard Argo float is that the iAOOS system includes a surface buoy which handles satellite communication and that the float itself is tethered on the buoy. These systems are called ice-tethered profilers (ITP's, Toole et al., 2011) or Polar Ocean Profiling Systems (POPS, http://www.metocean.com/products/metocean-systems/polar-platforms/pops). During the early Argo years the JMASTEC had been testing a similar device called J-CAD (JAMSTEC Compact Arctic Drifter) in the Arctic with a few devices. Present systems are very costly compared to standard Argo-floats. In order to guarantee long life time of the measurements, ITP's or POPS are mainly deployed on the multi-year ice floes.

The ice-tethered profilers has also that advantage, that they are suitable to carry more sensors than ordinary Argo float – some of them are already equipped with the oxygen, pH, and CO_2 sensors. They can also provide data of sea ice and air temperature and air pressure which are important for the Arctic monitoring.

In the duration of the iAOOS project, 15 autonomous platforms (Figure 12) should be operating at any given time in the Arctic Ocean for a period of 7 years in total (the project started in October 2011 and will end in December 2019). The platforms will transmit physical characteristics from the upper ocean and the lower atmosphere to describe the current status and changes of the Arctic sea-ice in near real time to a receiving station (IPEV, Brest, France) via satellites. Each platform is composed of 3 elements for oceanographic, sea-ice and atmospheric vertical soundings. They measure vertical oceanic CTD profiles of temperature and salinity along 1000 m long cable from surface down and up and transmit the data to the surface with inductive modems. The equipment for sea-ice is based on a combination of satellites (AMSR-E, Cryosat etc.) and ground based measurements collecting sea-ice thickness, snow depth and temperature profiles across the air-sea-ice interfaces. The equipment for the atmosphere is based on a combination of satellite (Calipso) and ground based measurements using autonomous and unattended micro-lidars and optical depth sensors (Provost et al., 2012).

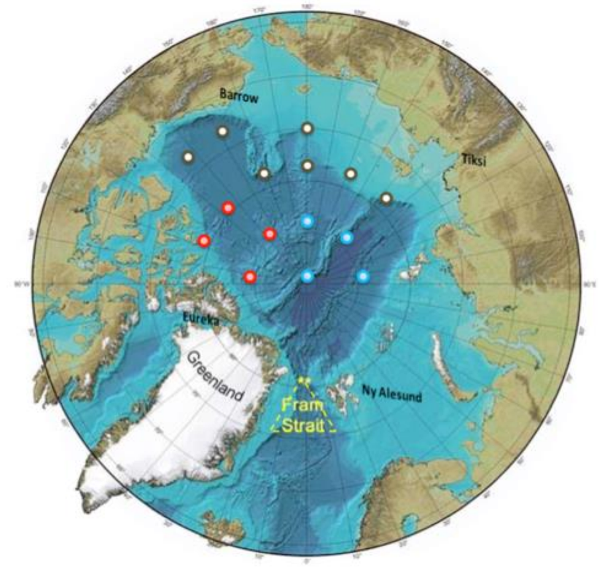


Figure 12. Ideal distribution of the 15 iAOOS platforms. Colour coding describes the origins of each deployment, white by Ship logistics, blue by Air logistics (Ny Alesund), red by Air logistics (EUREKA).

In areas with less severe ice conditions in the Arctic, standard Argo-float could be modified to work in such severe conditions but they need technical modifications such as adapted ice-avoidance algorithms or ice detection and ice-hardened antennas. These floats are programmed not to surface during ice covered situations and store data to an internal memory in such situations. They will send the observations when they are able to surface.

Technology for these ice floats has been developed already, and is tested under field conditions in the NAOS project in the Baffin Bay. The first deployments have been performed in September 2015 (2 floats) and have indicated some issues with the behaviour of the hydraulic oil at low temperatures. However, the issues could be solved by the float manufacturer NKE and floats have been redeployed. Sea-ice detection will also benefit from the enhanced features of the new generation of floats designed under the NAOS project. In addition to a regionally adapted Ice Sensing Algorithm based on temperature and salinity in the Baffin Bay, this new generation of float is able to carry an acoustic altimeter looking upward for thick ice, and a custom-built optical detector for thin ice. A top cage is added for the protection of the sensors. Profiles acquired under ice are stored internally on the float. In the coming years, a total number of 23 floats are planned to be deployed in the Baffin Bay. 13 floats funded by Equipex NAOS Arctic project and 10 floats funded by the CFI (Canadian Foundation for Innovation). All floats will be equipped with biogeochemical sensors.

Around the Alaskan and Siberian coasts the ice cover breaks up in summer. The MIZ intensive field program (http://www.apl.washington.edu/project/project.php?id=miz) has been designed to study such conditions in the Beaufort Sea and employs an array of cutting-edge autonomous platforms to characterize the processes that govern Beaufort Sea MIZ evolution from initial breakup and MIZ formation though the course of the summertime sea ice retreat. The program (Figure 13) is a research initiative funded by the Office of Naval Research in the US. The 5-year research project has started in 2012 and has conducted its first field phase in 2014. The profiling floats proposed in the MIZ are based on the ALAMO floats (Air-launched autonomous micro observer *http://alamo.whoi.edu*) used in hurricane research. The floats could use navigational support from the acoustic navigation sources deployed in the ice. Work in the marginal ice zone of the Beaufort Gyre has been continued in the SODA project using ALAMO floats and the has profited from the experiences gained in the previous years in the development of a regional ice-sensing algorithm. A total of 20 floats will be deployed during the coming years. Two floats are presently working successfully in the Chucki Sea and have sampled the shallow shelf collecting more than 200 profiles so far.

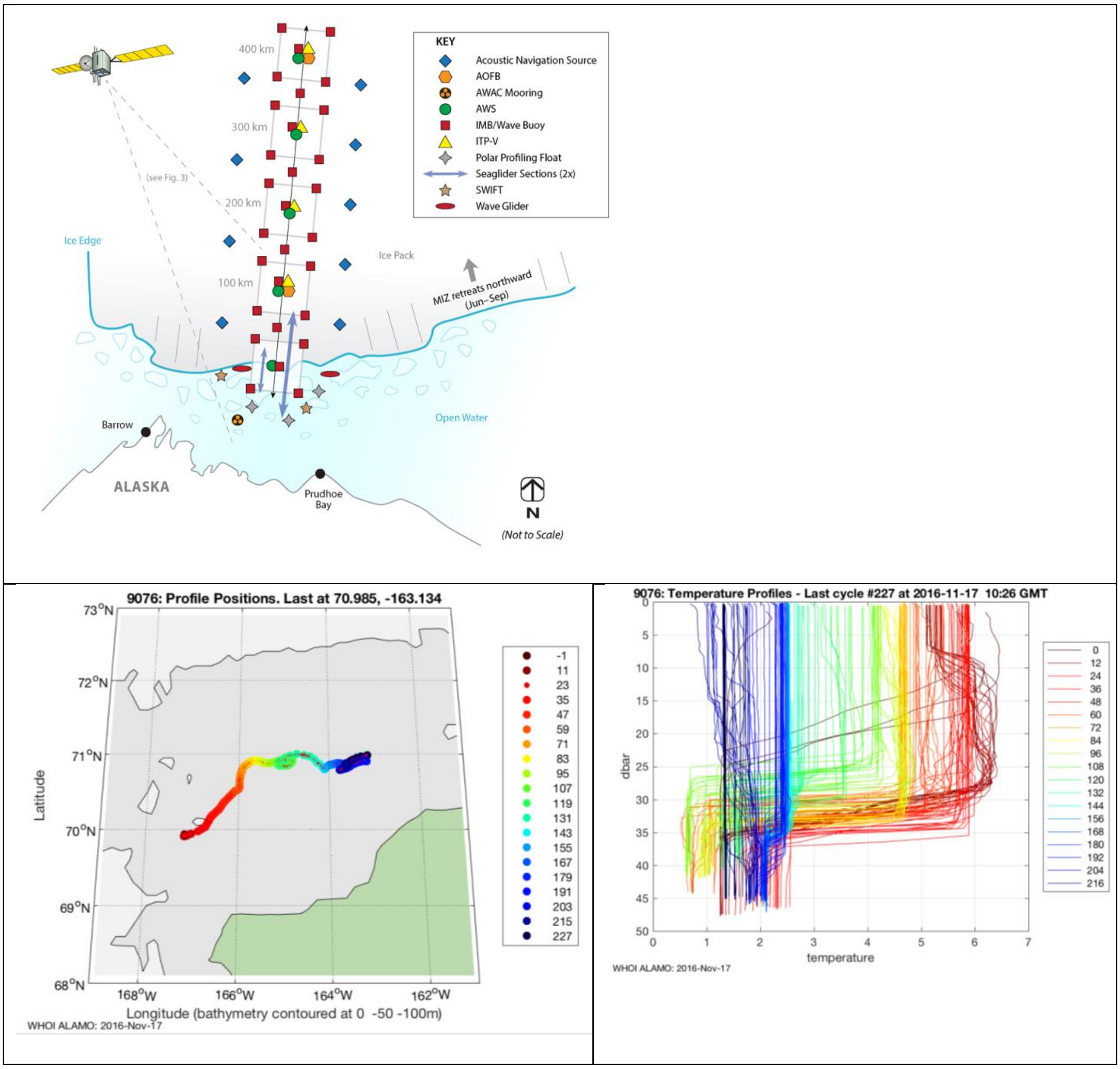


Figure 13. Platforms used in Marginal Ice Zone experiment. See legend for explanation (top). Temperature profiles from an active ALAMO Float in the Chucki Sea (http://argo.whoi.edu/alamo/9076/index.html) (bottom)

The MEOP consortium (Marine Mammals Exploring the Oceans Pole to Pole) brings together several national programs to produce a comprehensive quality-controlled database of oceanographic data obtained in Polar Regions from instrumented marine mammals. The CTD used on the mammals has been developed by the Sea Mammal Research Unit in St Andrews, Scotland, in collaboration with Valeport Ltd. A thorough description of CTD-SRDL tags is presented in *Boehme et al. (2009)*. The CTD-SRDL is the only miniaturized tag with high-quality CTD capabilities to date, so it is the only type of tag included in the MEOP-CTD database at this stage.

To date they have delivered more than 300000 profiles covering both poles (Figure 14). Data quality of the CTDs has been an issue, but the MEOP consortium has taken great efforts to calibrate the data following Argo procedures and all data are publicly available at *http://www.meop.net/.* Carse et al. (2015) have demonstrated that assimilating the temperature profile data into the Met Office's global ocean forecasting system (FOAM – Forecasting Ocean Assimilation Model) has a positive impact on the model temperature and salinity fields, and improves the model's RMS error statistics. However, assimilation of the temperature and salinity profiles together had adverse impacts on the model's salinity fields, due to the known problem of CTD-SRDL salinity readings being biased high, and the inability at present to correct for this in near real-time.

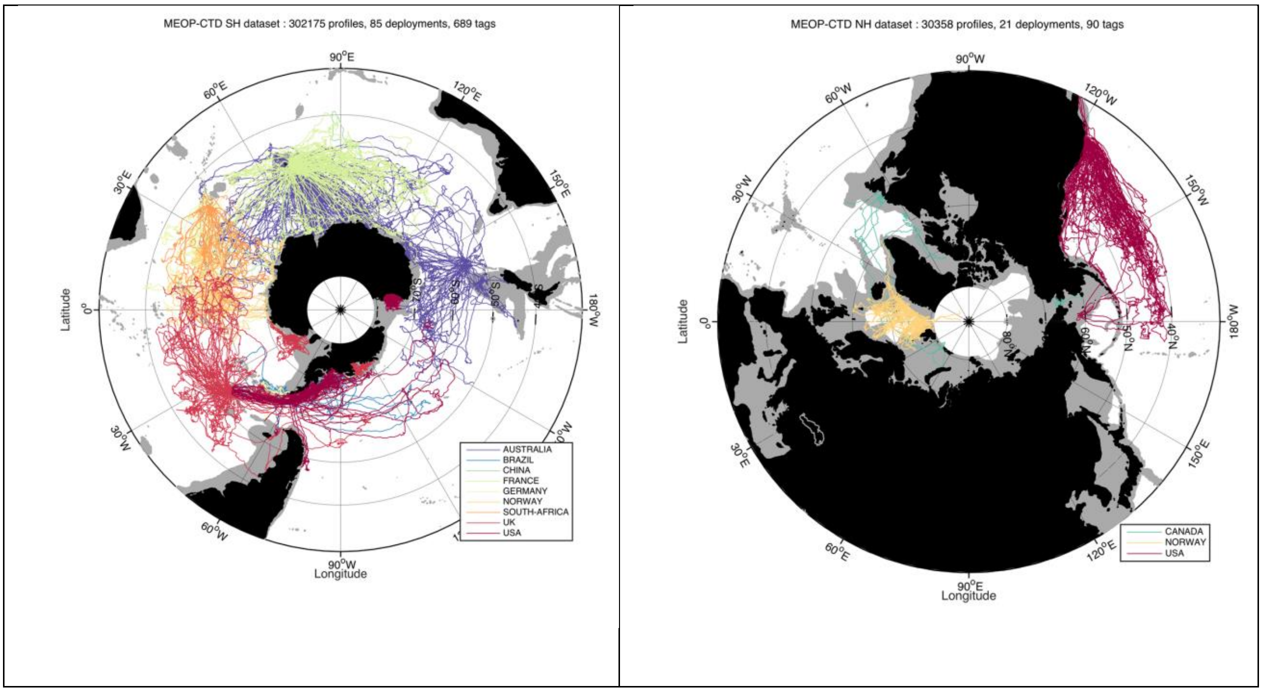


Figure 14. tracks of tagged marine mammals with CTD tags.

The goal for the future

The goal for the future is to enhance real-time monitoring of the Arctic Ocean. But serious concern exists if Argo floats are the appropriate sampling device for the Arctic with few exceptions as the eastern European Arctic. The difficulty of course is to adapt the floats to the ice conditions of the Arctic Ocean, enabling them to avoid surfacing in the ice or to transmit their data across the ice cover. High loss rates of Argo floats in the Arctic Ocean show that the ice-avoidance algorithms first developed for Southern Ocean floats still must undergo further development. It is therefore not possible to define a sampling target for Argo floats in the Arctic at this time. Pilot studies and other additional work should continue to be carried out to improve the technology and to devise the strategy how to sample the Arctic region best. It is planned to start such a pilot study in connection with the Year of Polar Prediction (YOPP) carried out under the auspices of the WMO. One of the aims of YOPP is to develop improved data assimilation systems that account for challenges in the Polar Regions such as sparseness of observational data, steep orography, model error and the importance of coupled processes. The intensive field phase of YOPP will be carried out in 2018 and it is planned to provide the coupled ocean/atmosphere models with float data from the marginal ice zone. The meteorologists have indicated the Laptev and Kara Sea as main areas to be targeted and within the ERIC Finland, Germany and Poland will be testing a small number of floats (2-3) to be deployed in the European Arctic during YOPP. Float tests should start in 2017, either in the area around Spitzbergen or the Baltic and float manufactures have been consulted to address the technological requirements for Arctic conditions.

An integrated Arctic observing system strategy should also consider the right balance between Argo floats and the existing monitoring activities based on ice-tethered profilers such as described above. It has however to be considered that large parts of the Arctic Ocean (Chukchi Sea, East Siberian Sea, Laptev Sea, Kara Sea and Barents Sea) are ice free during extended periods in the year (Figure 15) and need to be included in an integrated observing system. Especially, since the projected warming and ice loss in the coming decades is expected to produce large changes in these shallower shelf areas.

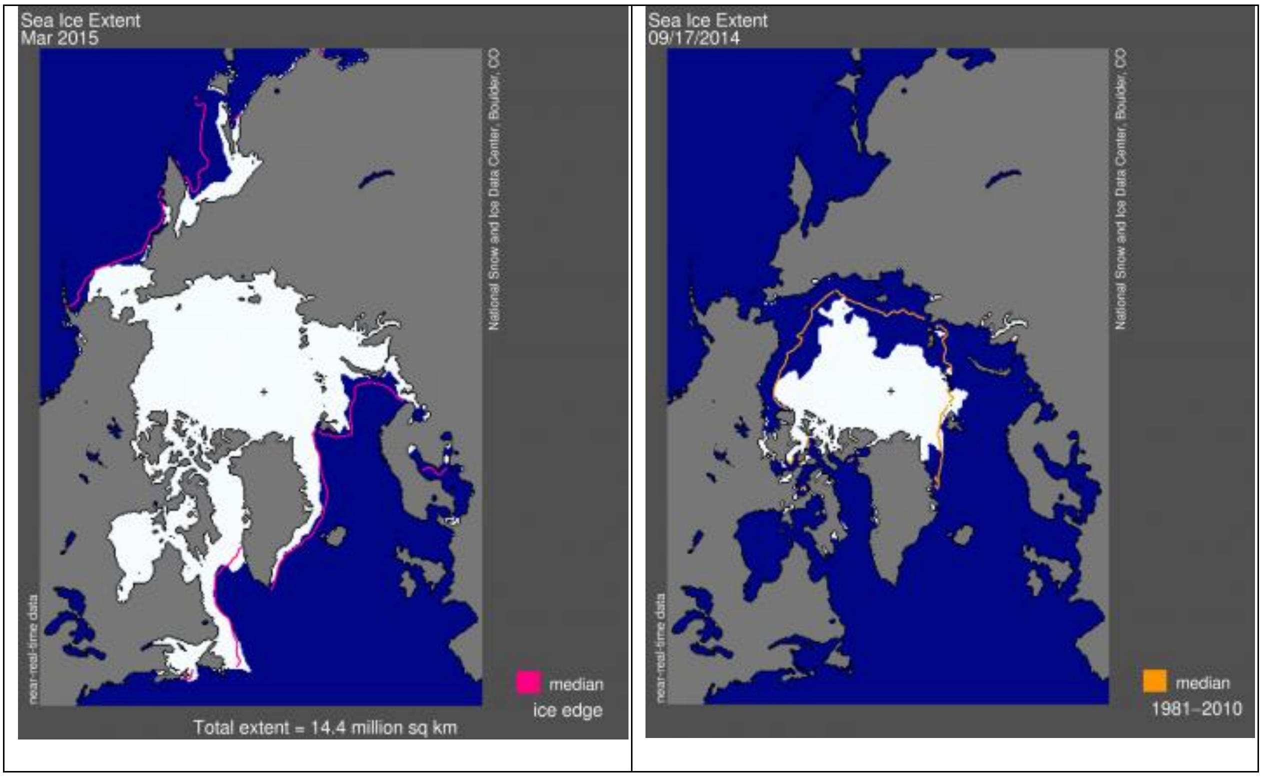


Figure 15. Ice conditions in the Arctic before and after the breakup of the seasonal ice cover

European needs

Understanding climate changes occurring in the high latitudes and their impact on the ecosystem requires better estimation of the heat and freshwater exchange between the Nordic Seas and the Arctic Ocean through Fram Strait on the one hand and the Barents Sea on the other hand. Likewise, a circulation scheme of the Arctic Ocean, especially in the Eurasian Basin is still under debate and needs direct observations. One major open question is that how much ocean heat, advected by the currents, is used for the melting of sea ice.

Furthermore, seasonal and long-term evolution of the mixed layer during the changing sea ice regime is also crucial for better understanding and prediction of changes which occur in the Arctic Ocean heat transfer and freshwater budget.

Shipping and off-shore activities in the Arctic Ocean has increased much during last ten years and this trend is expected to continue. The Maritime sector needs more real time observation and reliable short term and seasonal forecast. This issue will be addressed in the YOPP (Year of Polar Prediction Program). The measurement activities based on proposed operational systems such as iAOOs will not be able to cover the entire Arctic and leave gaps in the seasonally ice free areas. Shipbased CTD surveys, however, are seasonally and regionally peaked. Most of these activities occur during summer ice free period in the Arctic marginal seas. The recent HORIZON2020 call (Blue Growth-Demonstrating and Ocean of Opportunities) therefore invited proposals for an integrated Arctic observation system to close critical gaps with innovative solutions, as well as improve the integration and inter-operability of existing observation systems, also in view of data assimilation into models.

The Integrated Arctic observation system (INTAROS) project coordinated by the Nansen Environmental and Remote Sensing Center received funding and will start in 2017. The overall objective of the INTAROS is to build an efficient integrated Arctic Observation System (iAOS) by extending, improving and unifying existing systems in the different regions of the Arctic. INTAROS will extend the ITP network in the Eurasian sector of the Arctic Ocean in collaboration with US, Chinese, Korean and Japanese programs. IOPAN will be responsible for deployment of the novel Ice-tethered Platforms with CTD/O2 and bio-optical sensors. INTAROS will also contribute to EuroArgo initiative by supporting BioArgo floats in the Baffin Bay Observatory. 18 Bio-Argo floats adapted to polar environment will be deployed by the CNRS-TAKUVIK.

Most of the Arctic shelf seas where the sea ice is currently shrinking (besides the coast of Alaska and some areas in the Canadian Archipelago) are in the range of the Russian EEZ. It may be not a trivial issue to obtain permission to deploy any instruments that use satellite communication for the data transfer or for the navigational purposes. Floats (or other platforms) would need to be deployed from the Russian crafts. Collaboration in wider international programs such as YOPP or INTAROS could be a solution. It would be valuable to involve some partners from the Russian institutions, who already conduct research in these remote areas and may help in getting the suitable consents.

Furthermore, although the ice area shrinks, some areas of the northern Kara Sea, northern Laptev Sea and East Siberian Sea are still covered by compact sea ice (up to 2-3 years old) every melting season (but this is not easy to predict). This would demand a flexible deployment strategy, shifting designated resources between years and locations. Because of the fast changes and the highly dynamical region, ice and water related deployments will need to be considered in the marginal ice zones. Some of ITPs have been already deployed in the open water – their buoys eventually have frozen into the ice floes. Also, the meteorological buoys and other devices measuring the upper ocean layer (meteorological buoys, SVP, UpTempO buoys) have been successfully deployed both in water and on the ice (most of them have a spherical shape).

Requirements

Continue European contribution to provide ice tethered platforms.

- Utilize standard/modified Argo-floats in ice free shelf areas. The floats need to include two-way communication system for guidance of parking depth.
- Ice sensing algorithms need to be developed and tested for the European Arctic
- Changes in float design (capacity for oil, strengthened antenna\top cages, claws for grounding on shelf areas, etc.)
- Integrate well with all other Artic observation systems
- Work on common data strategies

Technical advances needed

Improve ice avoidance algorithm and/or include ice sensing capabilities presently tested in the context of NAOS.

For floats using ice avoidance algorithm, a method to record positions under the ice-covered period is needed. One potential solution could be use the RAFOS system, but that would need to be installed and is expensive to maintain. Another possibility for underwater navigation is using the Inertial Navigation System (INS). First tests during EAIMS have shown that, the accuracy of these devices is still too low for the float positioning, but development of the inertial sensors and data processing methods is very fast. It is expected that cheaper and more accurate sensor will come on the markets within the next 5-10 years. “Underwater GPS” based on low-frequency acoustics is achievable at pan-arctic scale using a limited number of moored sound sources (see for instance http://anchor.apl.washington.edu). Such a facility can only be developed and maintained, however, by a multinational effort. Once available “underwater GPS” will allow the rapid development of an Arctic fleet of Argo floats.

For monitoring during ice free season in the coastal (shallow) seas, a special type of Argo float would be desirable. The shape of such floats should allow it to collide with the bottom without getting stuck and inflicting damages to the sensors.

4.2 Southern Ocean

What exists

Ice-avoidance algorithms for Southern Ocean, first developed by AWI for NEMO floats, have been successful in reducing damage to floats deployed in the seasonally ice-covered Southern Ocean and have helped to increase float lifetimes. This regional ice avoidance algorithm is based on the assumption that measured near-surface temperatures below a critical threshold (i.e. the surface freezing point) are a proxy for ice cover above. Temperature and pressure are measured during the float ascent and if temperatures are below this threshold then the float aborts its ascent and stores the profile before descending to the park depth and repeating the cycle. In early versions of the float design, the under ice profile data were lost, because interim storage on the float had not been developed at that time. In order to transmit the stored profiles in reasonable time after the ice melt the high data rate communication provided by Iridium is preferable. Stored profile data is telemetered to data centres when the float first surfaces after the ice melt in spring. The under ice positioning of floats requires deployment and maintenance of an array of sound sources that covers the float drift area. There is an existing array of RAFOS (Ranging and Fixing of Sound) sources in the Weddell Sea. Floats that are equipped with RAFOS receivers can have positions calculated for their under ice profiles in post-processing during DMQC. The Iridium telemetry system has become essential for floats deployed in the high latitudes because of the reduced communication and thus surface time when stored profiles have to be transmitted. Float deployments in the seasonally ice-covered Southern Ocean have therefore increased over time and resulted in an extended data set.

Real-time and delayed mode quality control (QC) of float data

The reference data base is sparse in the high latitudes and because long-term changes of the hydrography are expected, frequent updates of the CTD reference data are requested.

Under-ice profiles need to be assigned approximate locations during real-time QC. These approximate locations are determined by linear interpolation between the last two known locations. More precise locations from the RAFOS system can only be assigned during DMQC.

The goal for the future

The extension of the core Argo array beyond 60 degrees in southern hemisphere will ensure that it evolves into a truly global component of the ocean observing system. Based on pilot studies it is possible to use Argo floats equipped with ice-detection software in the seasonal ice zone.

To extend Argo to beyond 60˚S in the seasonal ice zone at the nominal core Argo design density would require 320 active floats in the Southern Ocean (see Figure 16). These calculations are based on the number of floats required to populate the area between 60° of latitude and the fast ice edge with an assumed profiling depth of 2000 m. Due to the strong research interest of European scientist in the Weddell Gyre and the already installed RAFOS array this area is one of the chosen places for a European enhancement of the global Argo. 50 floats should be active in the Weddell Gyre based on the nominal design density. In order to maintain an array of 50 floats and taking into account an increased failure rate of floats of 20%, 25 deployments per year are required to keep the population at a steady rate.

European needs

The high southern latitudes are important regions for deep water mass formation. Quantitatively the most important region is the Weddell Sea. The circulation in the Southern Ocean connects all ocean basins and regulates the meridional overturning circulation. It is expected to cause change in the circulation and in the exchange of water masses. This leads to changes in the transport of heat and fresh water with significant consequences on climate and sea level for the Western Europe. An established array of sound-sources (RAFOS) and acoustically-tracked floats provides already valuable information on ocean circulation and structure beneath the sea- ice.

Requirements

To make full use of the profiles under ice it is necessary to maintain RAFOS sound sources for the positioning. So far 15 sound sources are operated and financed by AWI in the Weddell Gyre. Sustainable financing of these activities as well as for the maintenance and extension the array of sound sources should be contributed by the Argo program.

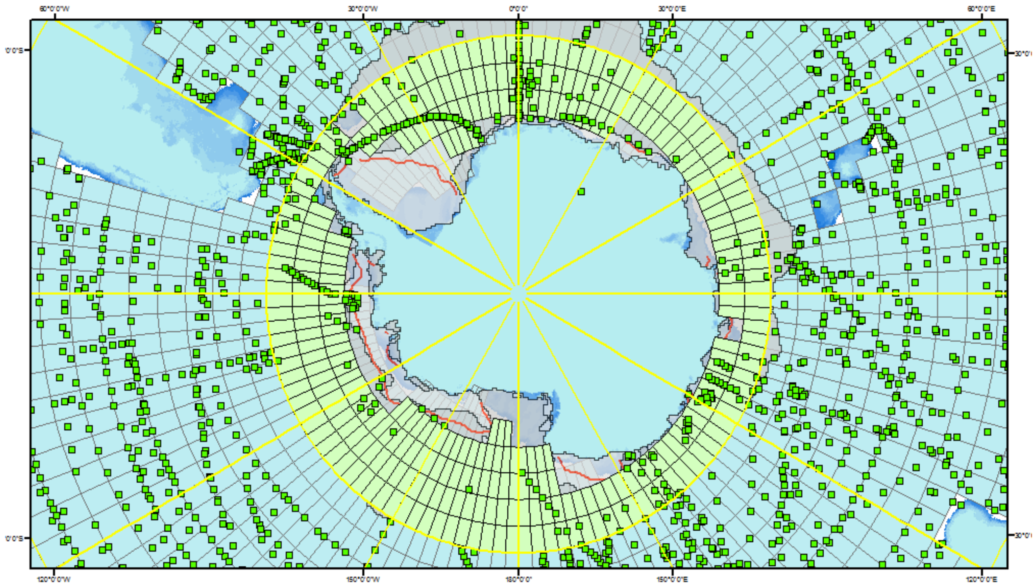


Figure 16. The historical deployment locations over the last decade (green squares) are indicated as well where we have been able to deploy floats and where not (M. Belbéoch)

Technical advances needed to reduce loss of floats

Recent failure rates (20 %) of ice-sensing floats, operating in the sea ice zone, are higher than for open ocean floats. Further reduction of loss rates should be achieved by reducing surface times with high data rate satellite communications and further improvements of the ice avoidance algorithms.

Additional sensors

Looking to the future, we envisage profiling floats that will carry a suite of additional sensors (biological and chemical) to measure primary productivity, nutrients, and perhaps even carbon - through the proxy measurements of pH and nitrate (about 10 of the 25 floats deployed).

5 MONITORING NEAR SURFACE OCEANS

Argo floats normally measure temperature, salinity and pressure from 2000 to 5 dbar, where a pump is used to circulate seawater over the sensors. Pumping of the CTD sensor is turned off at around 4 or 5 m depth before the float reaches the surface to avoid contamination (and hence degradation) of the salinity sensor by pollutants at the sea surface. This means that the uppermost temperature and salinity measurements made by floats are typically 4 or 5 m below the surface.

On the other hand, satellites provide measurements of temperature and salinity for surface layers, where for infra-red radiometers the skin layer is the uppermost ~10-20 µm and for microwave radiometers is of ~1-10 mm. For salinity from SMOS the penetration depth is ~1cm. Such skin SST (sea surface temperature) measurements are subject to diurnal variation, as illustrated in Figure 17.

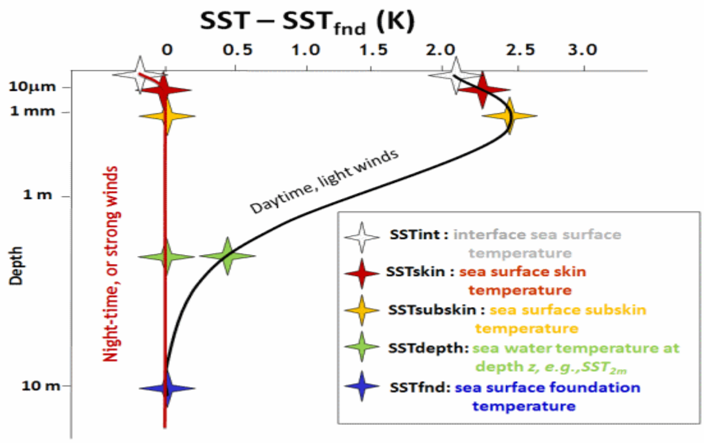


Figure 17. Hypothetical vertical profiles of temperature for the upper 10m of the ocean surface in high wind speed conditions or during the night (red) and for low wind speed during the day (black). Taken from https://www.ghrsst.org/ghrsst-science/sst-definitions/.

In 2005 the GHRSST (Group for High Resolution Sea Surface Temperature) community identified the potential of Argo to provide near-surface temperature measurements, as there was only a very limited data set of SST profiles through the upper 10 m of the ocean, with limited geographical coverage. GHRSST are now using Argo data for independent validation of various SST analysis products, as the uppermost (~5 m) Argo temperatures provide a good estimate of the 'foundation' SST (the SST free of diurnal warming) (Kaiser-Weiss, 2012; Martin et al., 2012) and for studying diurnal variation (Gille, 2012). Another application of the use of Argo data for GHRSST products, relevant for climate applications, is, for instance, the validation of OSTIA (Operational Sea Surface Temperature and sea-Ice Analysis) products of daily, high-resolution, global foundation SST and sea ice concentration fields (Roberts-Jones et al., 2012).

Near surface salinity changes in the upper 5 m of the ocean can occur as a result of precipitation events (giving a shallow fresh layer) and evaporation giving a shallow saltier layer, as observed by Soloviev and Lukas (1997). There can also be changes due to lateral advection in a stratified surface layer, for example by daily warming. These changes can have different vertical scales, typically metre-like, but in some instances can be cm-scale. These salinity-stratified conditions probably happen more than 10% of the time in large swathes of the world ocean.

What exists

Un-pumped measurements on Apex and Provor floats

In 2008 Webb Research provided an optional firmware change on Apex floats (that use Argos telecommunications) to enable temperature measurements to be recorded up to the sea surface, after the pump is switched off. At depths less than 5 dbar, 12 un-pumped PT samples are taken at 6 second intervals. This allows for sampling up to the sea surface at approximately 0.6 m intervals with samples continuing to be taken for a short period of time with the CTD out of the water after the float has surfaced. (Note that this Near Surface Temperature (NST) capability is not presently available on Apex floats that have ice-avoidance software and that salinity is not recorded on Apex floats after the pump is turned off). This was achieved through a firmware modification with no modification to the float hardware, hence it was cost neutral. The only other change required was for several extra ARGOS? messages to transmit the additional data. This has no impact on the resulting ARGOS? communication charges. The first of these floats were deployed in 2008 and it was shown (Turton and Pethica, 2010) they were able to observe near-surface temperature stratification that would otherwise remain undetected and so provide useful additional information. A more recent study (Carse et al., 2012) showed many profiles with significant temperature gradients of >0.5 ºC in the top 10 m of the water column, the majority were due to surface warming (up to 4 ºC), but there were a few profiles due to surface cooling (up to -1.0 ºC). An example is shown in Figure 18. Provor floats can also be configured so that CTD measurements of salinity and temperature are still recorded after the pump is switched off, and the optional firmware change is also available for Apex and Provor floats that communicate via iridium.

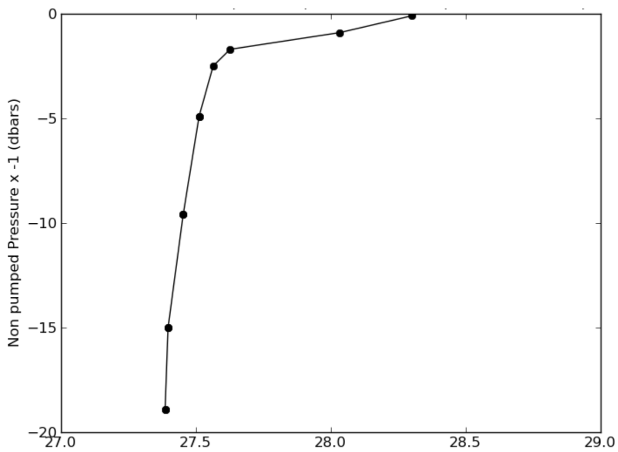


Figure 18. Example of a shallow warm layer in top 2-3 dbar. ΔT10 = +0.85 °C. Apex WMO #2901262, profile 71: lat 20.41S, lon 58.55E, 31 Dec 2011 22:36 local.

SOLO-II (pumped)

These floats use Iridium communications and have been deployed by the US (Scripps Institute of Oceanography). Temperature and salinity are recorded at 2 dbar resolution from 2000 to 10 dbar, and at 1 dbar resolution from 10 to 1 dbar. The advantage of Iridium is that the float requires much less time at the sea surface to transmit its data so reducing the likelihood of contamination of the sensor. The pressure sensor is reset on every profile to remove any drift.

STS (Surface Temperature Salinity) Apex floats

These floats have been developed to facilitate calibration of the surface salinity measurements made from satellites (e.g. Aquarius, Soil Moisture and Ocean Satellite (SMOS)) and are designed to sample up to the sea surface at cm resolution. They have an additional free flushing conductivity cell with a companion thermometer that operates independently of the main CTD which samples right up to the sea surface. This secondary sensor pair is calibrated against the main float CTD measurements between 30 and 3 dbar to correct for any drift (due to fouling) of the secondary salinity sensor. Murphy et al. (2008) present results that indicate the agreement of the primary and secondary measurements are 0.0003±0.004 °C and -0.002±0.005 PSU. Such STS Apex floats have been deployed by the US (University of Washington). Today, about 30 STS Apex floats are active in the global ocean.

Goal for the future

Near surface temperature measurements

GHRSST is developing diurnal SST analysis systems based on satellite data, e.g. While and Martin (2012). The NST data from Argo could provide a unique data-set for assessing the accuracy of the diurnal cycle estimates from these systems in regions not otherwise observed.

There is growing interest in coupled ocean-atmosphere data assimilation systems that can make better use of the observations in the surface boundary layer of these media (Laloyaux et al 2015, Lea et al 2015). This will require broad scale and frequent sampling of the ocean mixed layer. Changing the sampling frequency of depth of Argo floats on demand to better sample relevant air-sea interaction events (tropical cycle, westerly wind burst) could be considered on Iridium floats.

The goal for the future is to observe the mixed layer of the global ocean with Argo floats. It will be necessary to increase the vertical resolution in the upper 50 m to 1m or less to be able to adequately observe mixed layer dynamics. Although diurnal warming events are common, warming events exceeding 1 °C are much rarer and to capture such events it is recommended that all floats with Argos communications should record (and report) unpumped NST data as demonstrated for Apex floats. Although, the likelihood of capturing stratification can be increased by programming floats to surface in the afternoon hours, it is not recommended that this is done as standard across the Apex floats as near-surface stratification can occur at any time of the day and it is important to observe near surface layers throughout the diurnal cycle.

Near surface salinity measurements

As noted above the pump on the CTD sensor on Argo floats is normally switched off at around 4-5 dbar to avoid contaminating the salinity cell. SOLO-II floats will however profile while pumping right to 1 dbar with profiles at 1 dbar-resolution, an option also proposed for PROVBIO floats (although pumping currently stops on those floats at 3 dbar).

Just as with SST, there is a requirement in the salinity from the space community for near-surface measurements of salinity. These data are required not only for cal/val but they can potentially lead to scientific investigations such as those proposed in the ESA funded SMOS+SOS project (http://www.smos-sos.org/case-studies).

European needs

These are essentially the same as those internationally: for validation of satellite SST and salinity (especially SMOS and the SMOS follow-on) products, to better elucidate the diurnal variation (stratification) of the temperature profile through the mixed layer. Such understanding of the mixed layer temperature profile is needed to better model the fluxes at the air-sea interface. Coupled ocean-atmosphere models are now being developed for short-range weather forecasts and better initialization of the ocean surface layer will have a beneficial impact on such forecasts (e.g. in constraining the amount of heat in the upper ocean available for transfer to the atmosphere during the passage of hurricane systems).

Requirements

Increase communication rates: At present of the ~3,900 floats, slightly more than half of them use Irridium for communications. This proportion is likely to increase, leading to new possibilities in terms of sampling.

Argos floats - With Argos floats there is no impediment to all of these being specified to report un-pumped temperatures up to the surface, hence it is recommended that all floats with Argos communications should record (and report) NST data as has been demonstrated for Apex floats. The likelihood of capturing stratification can be increased by programming floats to surface in the afternoon hours. However, it is not recommended that this is done as standard across the Apex floats as near-surface stratification can occur at any time of the day and it is important to observe near surface layers throughout the diurnal cycle. As noted earlier, including this capability is cost neutral as it does not increase either the cost of the floats or the Argos communications.

Iridium floats - At this time the standard Iridium mission for Apex floats is to record temperature and salinity at 2 dbar intervals up to the time the pump is switched off. This is normally between 2 and 5 dbar and there is a need to investigate whether leaving the pump on for longer has any effect on the quality of the salinity measurements. The Scripps's Solo-II (Iridium) floats provide continuous profiles at 2 dbar resolution with higher (1 dbar) resolution above 10 dbar until the pump is switched off at 1 dbar. This sampling should resolve all but the shallowest of temperature and salinity features and it is recommended that it be adopted as a standard by all floats that use Iridium communications.

However, to better meet the requirements it is suggested that floats that use Iridium should have 2 dbar sampling below 20 dbar, with 1 dbar resolution from 10 to 20 dbar depth and 0.5 dbar resolution above 10 dbar to 1 dbar. This would add a further 14 data levels (over and above the SOLO-II mission), which is a minimal (1.5%) increase in the data transmission. It is not expected that this would lead to any increase in the cost of the float and negligible (if any) increase in the Iridium communications cost.

All Euro-Argo floats are configured to sample up to 2 dbar from the surface.

Data processing

The additional unpumped NST and STS measurements are being handled by the Argo data system; data are stored in an additional profile. For Provor, the salinity measured after the pump was turned off are all flagged as bad data, unlike temperature data that are kept as good.

The QC procedures for real-time and delayed modes need to be adapted for handling near-surface temperature (and salinity) data. The additional data processing procedures needed for Apex unpumped NST data are:

- ingest the three or four pumped/un-pumped calibration samples between 25 and 5 dbar and use these to adjust the near-surface temperature measurements.
- detect the point at which the float surfaces and retain only the 'in-water' samples;
- determine the surface pressure correction, and apply this to the profile data.

The aim is to create a 'seamless' temperature profile from 2000 dbar to the surface.

6 MONITORING ABYSSAL OCEANS

Scientific objectives and European needs

Deep-ocean (> 2000 m) hydrographic observations are limited to sparse ship-board hydrographic sections repeated every decade and short-lived moored arrays of confined spatial coverage. Upper-ocean (< 2000 m) sampling, largely carried out by the conventional Argo array, has much higher resolution in space and time. The need for more intensive sampling in the deep ocean has been widely recognized by the scientific community.

Indeed, many recent studies have highlighted the crucial contribution of the intermediate, deep and abyssal oceanic layers to the global energy and sea level budgets (Fukasawa et al., 2004; Johnson, 2008; Purkey and Johnson, 2010 and 2012; Church et al., 2011; Frajka-Williams et al., 2011). When considering deep heat content changes, global figures actually reflect complex patterns with regional differences both in amplitude and sign (Figure 19; Kouketsu et al., 2011), with vertical differences (Kouketsu et al., 2011; Desbruyères et al., 2014) and temporal variability at decadal, interannual and even shorther time scales variability in some areas (Aucan and Llovel, 2013; Desbruyères et al., 2014). Investigating the spatial distribution of this variability would help understand the variability of heat content changes. To date more regionalized and precise budgets of heat content changes and sea level rise are hampered by the lack of a global data set at depth below 2000m. Therefore, there is a strong requirement from the ocean and climate research community to have floats able to go deeper than 2000 m (e.g. Freeland et al., 2010; Church et al., 2011) and to implement a Deep-Argo array that will contribute to a deep ocean observing system in conjunction with other observing system (GOSHIP, OceanSites). The goal for the Deep-Argo array is thus to establish a long-term observation system to monitor large-spatial scale variability and change in the deep ocean of temperature and salinity on timescales of a decade and longer. This monitoring is necessary to understand the contribution of the deep ocean to heat content change and sea-level variability, to monitor deep circulation as well as heat and freshwater transports and for the validation of climate models. On the long term, this deep observation system needs to be global and has to be integrated within the international Argo program.

The European climate depends on the northward transport of heat by the circulation in the North-Atlantic, and European coastal areas are vulnerable to sea level changes. Observations of the whole climate system, including the deep ocean, are required to evaluate models used for climate projections. In particular, such models demonstrate decadal variability whose realism has not been established because of the lack of the necessary deep observations. Therefore, Europe needs to complement existing arrays funded by Europe that focus in the upper ocean (e.g. core Argo) or in regional areas (e.g. the 26°N overturning array). The deep ocean observing system will achieve this.

Toward a Deep-Argo array

Johnson et al. (2015) proposed a design for a future Deep Argo array (Figure 20). This design consists of a 5º latitude x 5º longitude x 30-day cycle Deep Argo array, which corresponds to about 1228 Deep Argo floats randomly populating the global ocean excluding areas shallower than 2000m and areas covered by ice (see Johnson et al. 2015 for more details). This hypothetical Deep Argo array would be capable of resolving, on average, at one standard error, local trends of < 1 mºC per decade in the abyssal Pacific and about 26 mºC per decade within the deep Antarctic Circumpolar Current. During an international Deep-Argo workshop that was held in Hobart in May 2015 (Zilbermann and Maze, 2015), it was agreed that the straw-plan described in Johnson et al., (2015) (Figure 20) was achievable and met nearly all of the science goals and that regional pilot experiments and other sparse deployments will be the pathway toward a global array.

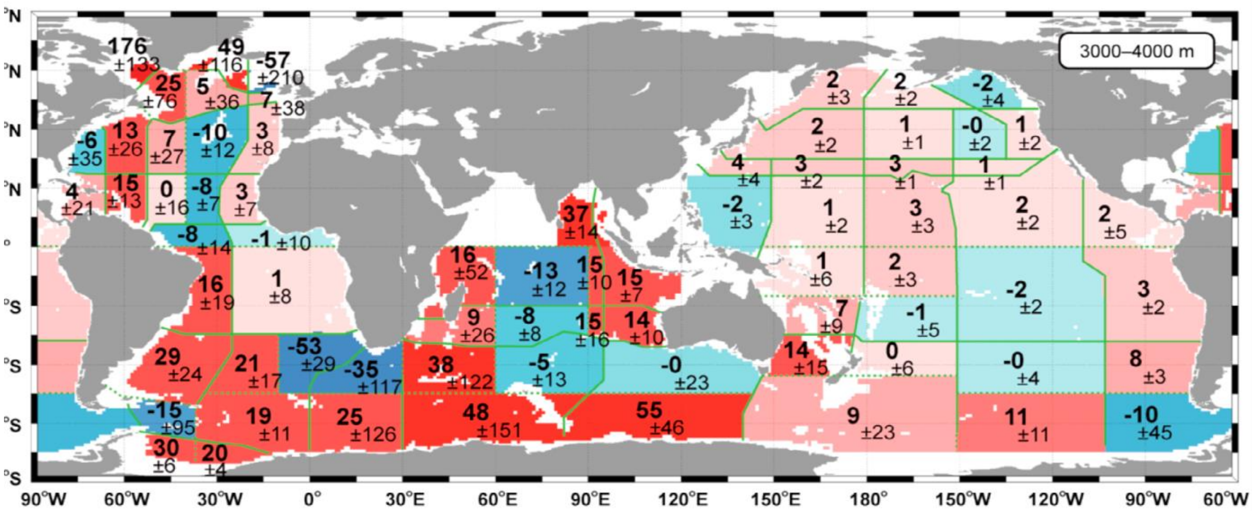


Figure 19. Horizontal distribution of the temperature change rate with 90% confidence intervals (× 10−3 °C decade−1) in the 3000–4000 m. Red indicates positive change (temperature increase); blue indicates negative change (temperature decrease). (Kouketsu et al., 2011).

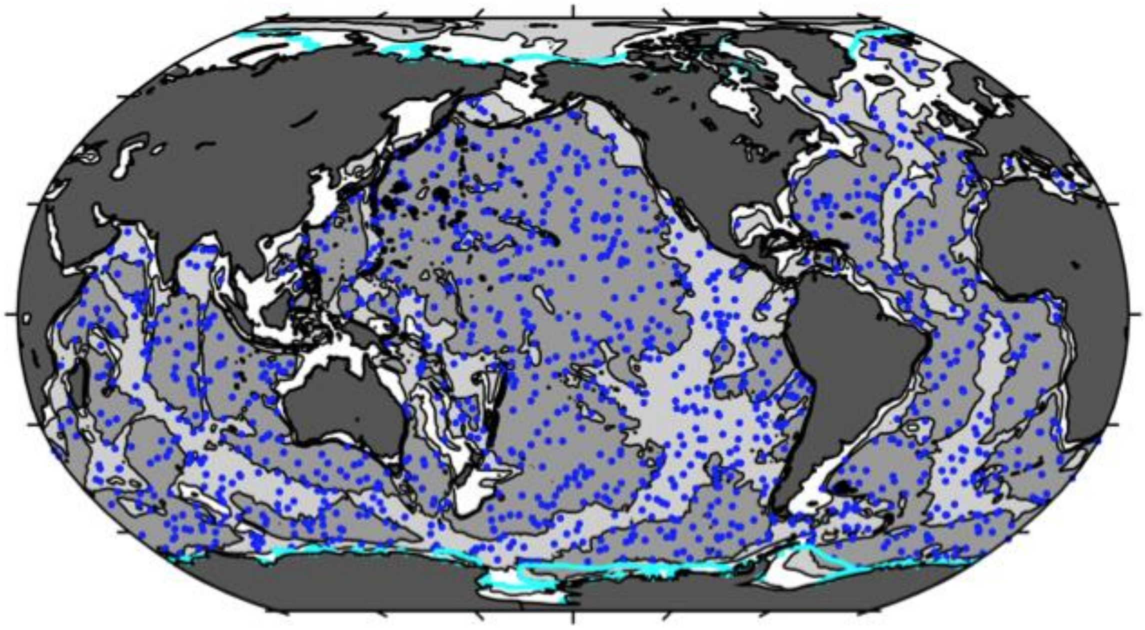


Figure 20. Straw-plan of a nominally 5° x 5° distribution of 1228 Deep Argo floats (blue dots) randomly populating the global ocean excluding areas shallower than 2000 m (white areas), and areas with mean 1981-2010 ice concentrations > 75% (poleward of thick cyan contours). Lightest gray areas indicate bottom depths between 2000 m and 4000 m, darker gray areas indicate bottom depths exceeding 4000 m, and darkest gray areas indicate land (Johnson et al., 2015).

Technological advances during the past few years have made float prototypes available, which could probe the deep ocean down to 4000 m or 6000 m. Four different type of Deep floats are now available: Deep ARVOR (Ifremer, NKE, 0-4000m), Deep APEX (TWR, UW, 0-6000m), Deep SOLO (SIO, 0-6000m) and Deep NINJA (TSK CoLTD, Jamstec, 0-4000m). The first deployments of Deep APEX (0-6000m) in 2013 and Deep ARVOR in the North Atlantic in 2014 were successful and followed by the deployment of 4 Deep ARVOR floats in the Charlie Gibbs Fracture Zone area of the North Atlantic, during the RREX (Reykjanes Ridge Experiment) 2015 cruise (Figure 21).

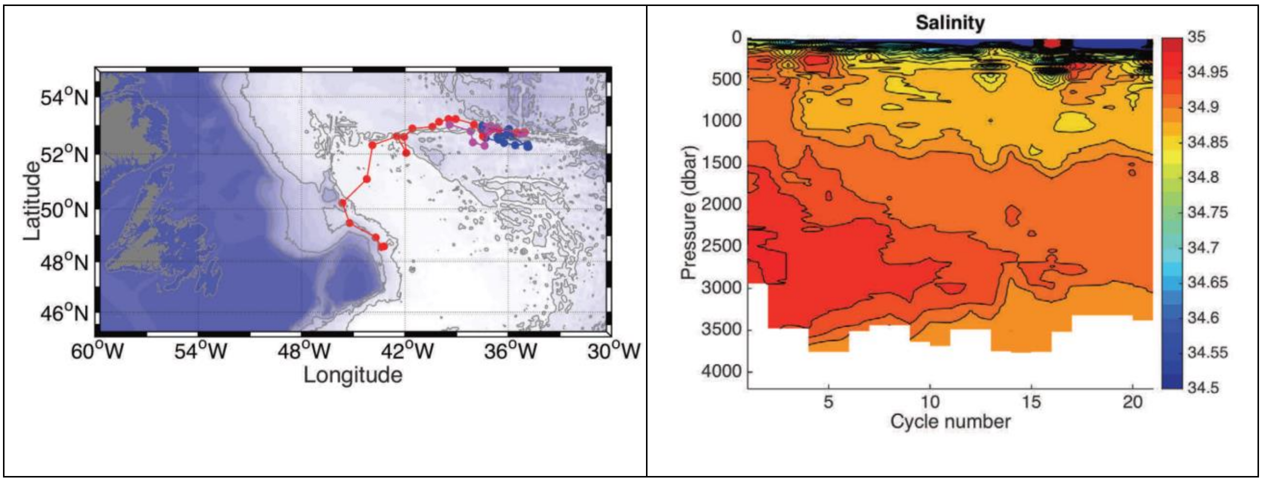


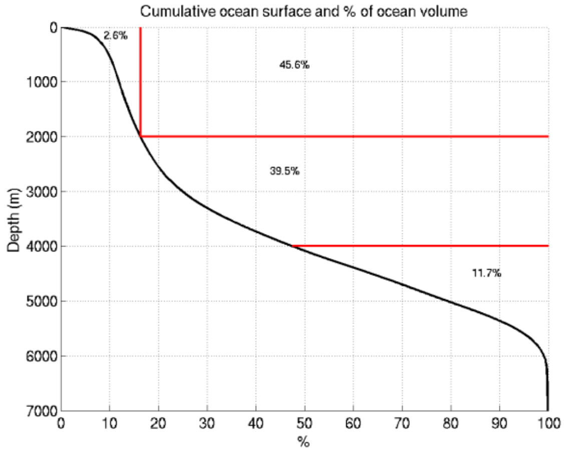
Figure 21. Trajectory of 3 of the 4 Deep floats deployed during the RREX 2015 cruise (left) (the fourth float died prematurely probably due to hydraulic failure. Salinity section of the float which trajectory is in red (right).

The pilot experiments have demonstrated the capability of floats to make interesting measurements (Figure 21). Sensor development is continuing as well as evaluation of the design of the Deep-Argo array proposed by Johnson et al. (2015).

Ocean Volume Census

Sampling of Argo floats is in essence a volumetric sampling of the ocean. Similarly to remote sensing satellite data that are meaningful for a given surface area of the ocean, in situ Argo profiles data are meaningful for a given volumetric region of the ocean. Therefore, based on ETOPO2 bathymetry, we estimated the ocean volume census in considering the *coastal* area and the *open* ocean characterized by depths shallower than 2000m or deeper than 2000m, respectively (Figure 22). Within the *open* ocean, the *core* Argo box occupies the 0-2000m layer, the *deep* Argo box occupies the 2000-4000m layer and the *abyssal* box occupies the 4000-6000m layer. The *coastal* box occupies about 2.,6% of the ocean volume. The *core* Argo box represents 45,6% of the ocean volume, the *deep* Argo box represents 39.5% of the ocean volume and the *abyssal* box represents 11.7% of the ocean volume. In other words, the *core* and *deep* Argo boxes together cover 85.1% of the ocean volume.

(a)



(b)

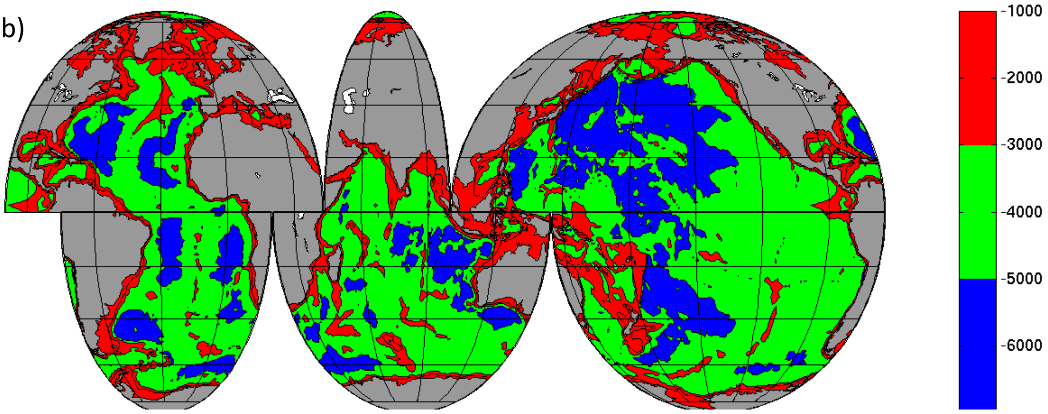


Figure 22. (a) Cumulated surface of the ocean (in %) as function of depth (black curve). Numbers represent the % of total ocean volume in each box delimited by the red lines. (b) Bathymetry of the ocean.

European strategy

On the long term, the target for the European contribution to the Deep-Argo array is about 20% of the international target, which, based on the Johnson et al. (2015)'s straw-plan would correspond to about 240 active floats. Considering a life-time of 150 cycles (without O2 sensor, 130 cycles with O2) and a 15-day-cycle, the float life time is about 6 years. The European target could be to deploy 40 floats per year. Note that on the long-term, the Deep-Argo floats should sample the ocean from the surface to the bottom.

Before implementing the Deep-Argo array with new floats and because we are still in a demonstration phase, our plan is to upgrade part of the existing core Argo floats. Based on the 10-day cycle of the core Argo floats, the life-time of the deep floats is reduced to 4 years. Using a 10-day-cycle for the Deep-Argo float is also better since the long-term stability of the sensor has not been demonstrated yet. This means that the European plan for the next 4 years is to upgrade 50 of the 200 core Argo floats to Deep-Argo floats (that is 25% of the core Argo floats).

Although the objective is to deploy a global Deep-Argo array, we will focus the European deployment where large deep signals are located, that is where deep-water masses are formed, namely the North-

Atlantic Ocean and the Southern Ocean. Then, the European deployment of Deep-Argo floats will follow deep-water mass pathways in the Atlantic and the Southern Ocean.

While 4000m Deep–Argo floats are sufficient to sample the entire water column in the North-Atlantic ocean (Figure 22a), 6000m Deep-Argo floats should be preferred where the ocean is the deepest (Figure 22b) and especially in the Southern Ocean where warming of the abyssal layers is the largest (Kouketsu et al., 2011).

The Atlantic Ocean is one of the Deep-Argo regional pilot experiments. This reflects the European need for a precise and more complete sea level budget, and an improved state estimate of the ocean in the region for the initialization of models used for seasonal to decadal prediction.

Technical developments

The final number and distribution of deep floats required to achieve our long-term goal will be decided at the end of the pilot experiments conducted by the various countries involved in the implementation of a global Deep-Argo array (US, Japan, Europe (UK, Spain, France), Australia).

In addition to the design of the final Deep-Argo array, a number of technical developments need to be completed:

- to demonstrate that deep Argo floats can routinely meet the mechanical requirements of deep profiling and lifetime survival
- to demonstrate that the sensors have the required quality (stability and accuracy) to meet the scientific needs identified by OSSE (Ocean Observing System Experiments)
- to develop a rigorous data quality procedure that satisfies the criteria for climate studies in the deep ocean and the careful collection of a reference database for the quality control of the data.

Some European floats will be deployed in the Iberian Abyssal Plain because of the relatively quiescent environment in this region, which should make possible to assess the long term stability of the float sensors at depth.

7 MONITORING ECOSYSTEM PARAMETERS

7.1 Biogeochemical-Argo implementation

What exists

The observation of biogeochemical cycles and ecosystems has traditionally been based on ship-based platforms with the obvious consequence that measured properties have always been under sampled. Recent technological advances in miniature biogeochemical sensors and autonomous platforms now open remarkable perspectives for observing the "biological" ocean and its ecosystems, notably at critical spatio-temporal scales which have been out of reach until recently (Claustre et al., 2010a).

While the deployment of sensors for dissolved oxygen (O_2 in the following) on Argo floats has been ongoing since 2003, the progressive addition of new bio-optical [e.g. Chla fluorescence, backscattering (b_b), radiometry] and other chemical sensors (nitrate, pH) to the system starts to let Biogeochemical-Argo become a reality. The biogeochemical and bio-optical community has already begun to benefit from the increase in observational capacities through profiling floats that allow the measurement of key variables of biogeochemical and ecosystem relevance.

The rationale for the development of a Biogeochemical-Argo (or BGC-Argo) array is to enable a cost effective global observation system that would greatly reduce the uncertainties in our estimation of elemental (C, N, O) fluxes at the global scale and our ability to detect change in these fluxes and ecosystem processes. This objective will be achieved by deploying a bio-optical/biogeochemical payload on Argo floats measuring six core-BGC variables (oxygen, chlorophyll, particulate organic carbon via backscattering, radiometry, nitrate, and pH). BGC-Argo would be disseminated through the Argo network and would take advantage of the existing infrastructure.

As a step towards a global network of evenly distributed floats, pilot studies on a regional scale at biogeochemically relevant "hot-spots" have been proposed to demonstrate the utility, impact, and feasibility of a BGC-Argo array (Johnson et al., 2009; Claustre et al., 2010a). There are indeed regional "hot-spots" that are natural laboratories for addressing key scientific questions of global relevance, which have been tackled in a highly integrated way. These pilot studies have served as test cases for evaluating the design and efficiency of a Biogeochemical-Argo array, in particular with respect to data management and dissemination. Among these regional hotspots, the North Pacific, the North Atlantic sub-polar gyre, the Mediterreanean Sea, the oxygen minimum zones associated with upwelling areas, or the Austral Ocean (Johnson et al., 2009; Claustre et al., 2010a; Johnson and Claustre 2016) were particularly monitored. For all these areas, the potential link and synergy with ocean color products is obvious. These regional sampling efforts, in parallel with sensor developments, culminated in a workshop that was held from 11 to 13 January 2016 at the Laboratoire d'Oceanographie de Villefranche (France). The scientific and implementation plan of Biogeochemical-Argo plan was subsequently prepared and was open to discussion and inputs by the community during summer 2016 (Biogeochemical-Argo Planning Group, 2016).

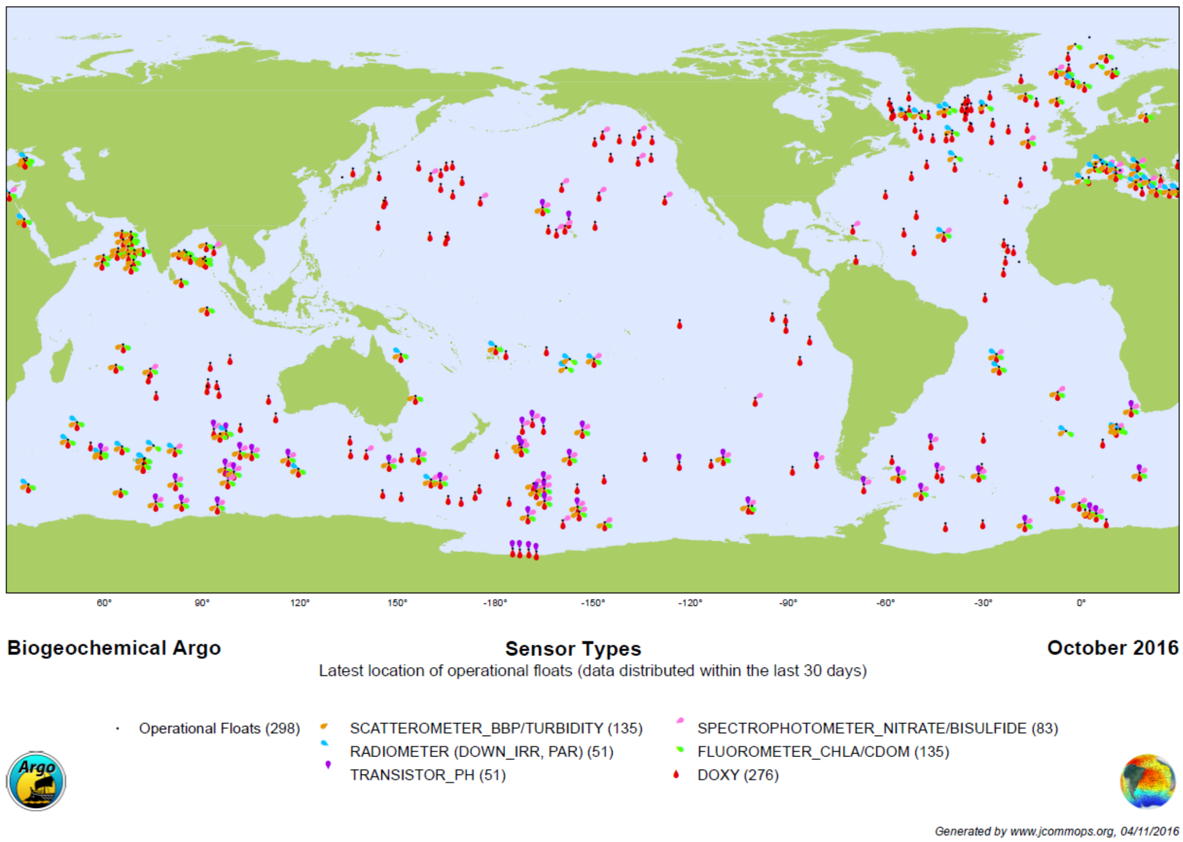


Figure 23. The distribution of biogeochemical sensors on Argo floats as of October 2016, provided by the Argo Information Centre.

Initial float deployments were made on an ad hoc basis or coordinated only regionally in case of the pilot studies. To guarantee the quality and the future large use of these data, deployments for the global array should be coordinated as much as possible in the early step of this implementation. Thanks to recent actions (e.g. SCOR UNESCO Working Group 142 on "Quality Control Procedures for Oxygen and Other Biogeochemical Sensors on Floats and Gliders") and the new Biogeochemical-Argo program (see also Johnson and Claustre, 2016), this required coordination is now beginning to take place.

In the future, an intensification of the measurements of the six core-BGC variables (oxygen, chlorophyll, backscattering, radiometry, nitrate, and pH) by Biogeochemical-Argo floats will permit the elaboration of a unique data set, allowing key questions in the role of the ocean in climate to be addressed.

Goal for the future

The strength of BGC-Argo relies on the combination of the six core-BGC variables. They encompass ecosystem indicators (chlorophyll, particulate organic carbon via backscattering, radiometry) and key chemical species (oxygen, nitrate, dissolved inorganic carbon via pH) that will allow tracing the flux of carbon (and energy) through the base of the marine ecosystem. For this reason, BGC-Argo floats should encompass all six core-BGC variables.

The present Argo array with 4000 operational floats provides a horizontal resolution (average distance between floats) of around 300 km, assuming the floats are evenly distributed. This is adequate to derive mean quantities such as the average heat content or temperature, on a monthly time scale. The same large-scale properties can be derived from floats of the Biogeochemical-Argo network, since they carry the same high-accuracy temperature and salinity sensors. However, from the analysis of Biogeochemical-Argo float data (Boss et al., 2008), it has been clearly shown that the space and time correlation of biological variables can be much shorter than that of physical variables. Looking at various assessments and indicators to scale the size and distribution of a global BGC-Argo network (Biogeochemical-Argo Planning Group, 2016), a target size of 1000 fully equipped BGC-Argo floats with uniform regional distribution is anticipated for the global array, which corresponds to 25 % of all Argo floats.

The overall array, realizing true multi-scale, multi-disciplinary, sustained observations of global marine biogeochemistry and bio-optics, should satisfy the requirements for validation of ocean color remote sensing as well as the needs of a wider community investigating the impact of global change on biogeochemical cycles and ecosystems.

European needs

The use of biogeochemical sensors on Argo floats can revolutionize our understanding of the coupling between ocean physics and biology (e.g. Claustre et al., 2010b). Additionally, this is the only way to start the acquisition of global long term time series of biogeochemical variables in the ocean interior from which climatic trend could be eventually detected in the future.

The development of more complex ecosystem models has benefited from improved availability of biogeochemical data required to parameterize and validate them. The increase in complexity in biogeochemical models can help progress towards the resolution of important scientific questions in two distinct domains: climate change and the availability of food resources.

Ecosystem models can help quantify the feedbacks between high carbon dioxide and marine ecosystems in climate change scenarios, including those mediated by surface warming, changes in ocean circulation and ocean acidification. The models can also help to determinate the factors that control global and regional marine biomass, the stability of marine ecosystems and their resilience to environmental change, and the availability of food for fish/seafood larvae, higher predators and humans.

Models can only provide useful answers if there are sufficient data to constrain the underlying processes and validate the model output. New approaches to assimilate biological and chemical data into these models are advancing rapidly (Brasseur et al., 2009). Notably, the progressive integration of biogeochemical variables in the next generation of operational oceanography systems and marine services is one of the long-term objectives of the GODAE (Global Ocean Data Assimilation Experiment) OceanView international program. Nevertheless, and in view of refining these models for improving their representativeness and predictive capabilities, the presently available datasets remain too scarce. There is an obvious and imperative need to reinforce biological and biogeochemical data acquisition and to organize databases (Le Quéré et al., 2010).

The overall priorities of a European Biogeochemical-Argo are totally in phase with those defined at an international level with respect to scientific and societal questions, variables to be acquired and float mission configuration. Areas of preferential deployment are essentially (but not exclusively) the European Marginal Seas (Mediterranean Sea, Black Sea, Baltic Sea, Nordic Seas) and the Atlantic Ocean.

Requirements

At global level, the target is to implement BGC-Argo measurements on 25 % of all Argo floats within a five-year term (Biogeochemical-Argo Planning Group, 2016). At European level, it is proposed to contribute to the maintenance of 200 active Biogeochemical-Argo floats (1/5 of the total array).

With an average life expectancy of 4 years, this would be achieved by deploying 50 floats per year equipped with the full suite of biogeochemical sensors (i.e., oxygen, chlorophyll a, backscattering, radiometry, nitrate, and pH).

These deployments will mainly take place in the North Atlantic, in the European marginal seas and in the Atlantic part of the Southern Ocean.

Technical advances needed

Biogeochemical-Argo floats are essentially multi-disciplinary platforms. Unlike core Argo, it is thus likely that more than one expert needs to be consulted to delayed-mode quality control all six core-BGC parameters, and that some of these experts may not have previous experience with the Argo data system. It will therefore be necessary to establish a workflow for (a potentially distributed, or sequential) DMQC of multi-parameter BGC-Argo floats. This includes the development of tools to facilitate delayed-mode tasks for new Argo users.

Beside the first six variables to be implemented on the developing Biogeochemical-Argo array, there are important additional measurements, some of them being developed for implementation on the array, that are required for a proper observation of biogeochemical cycles and ecosystems. These include CO_2 sensors and acoustic/optical sensors for measuring the zooplankton.

Data management

A strong focus on data management is a high priority for the Biogeochemical-Argo program in Europe. The organization of the biogeochemical float processing at European level both in real-time and delayed mode is under discussion and will rely on agreement between the European partners to avoid duplication of efforts.

Biogeochemical-Argo data processing follows the same rules as the core Argo data set. Regarding Quality Control, using data from a first version of a Biogeochemical-Argo float, D'Ortenzio et al. (2010) shows that, among the 19 RT Argo QC tests, three tests require modification to be adapted for Chla Fluorescence while four tests are not applicable. Taking into account the specificity of the Chla fluorescence signal (e.g. spikes, quenching) for QC have been discussed within the ADMT (Argo Data Management Team) Biogeochemical-Argo group and ended-up with first recommendations (Schmechtig et al., 2014). The general principles established for Chl-a fluorescence QC have served as a basis for developing QC procedures for other bio-optical variables like the backscattering, described together with QC procedures on Oxygen in Schmechtig et al. (2016). The development of RT QC for radiometry, nitrate and pH is on its way.

Similar to the Argo system, delayed mode quality control (DMQC) of Biogeochemical-Argo data should be performed according to a two-step approach: a semi-automatic DM and a final DM QC step based on the assessment of experts.

The semi-automatic DM (SDM) should be based on a set of automatic algorithms, which help verify data accuracy. This step of the DMQC will require long time series. For the Biogeochemical-Argo QC, DM should examine the occurrence of obvious deviations in time series, which could concern a single profile, a series of profiles, or the entire database obtained by a specific sensor. Trends or offsets in the time series should be identified by routine (i.e. 6 months) match-up comparisons between profiling floats and satellite-derived ocean-colour products. However, the use of remote sensing in the DMQC should be limited to identification of error trends (Guinehut et al., 2009), and not to the re-adjustment of float data.

The final DM QC procedure aims to produce the "best" set of data for a specific Biogeochemical-Argo float. It should be based on a comparison with auxiliary data and on visual inspection. The auxiliary data can include the other variables acquired by the float (e.g. T, S, irradiance, or b_b for Chla QC) or data from external sources (i.e. remote sensing, calibration profile at deployment, climatologies).

First suggestions are proposed in Schmechtig et al. (2016) and Thierry et al., 2016a for oxygen data DMQC.

It will be needed in the future to involve new teams in the assessment of the Biogeochemical-Argo data in DM and for the quality monitoring of the new parameters.

7.2 Argo-O_2 strategy

What exists

Dissolved oxygen is one of the most important biological parameters that can be monitored in the ocean to get insights into oceanic biogeochemical (eg. Riser et al, 2008) *and* physical processes (Piron et al, 2016). Dissolved oxygen data are also important for operational oceanography that aims now at monitoring and predicting the biogeochemical state of the ocean and marine ecosystems (Brasseur et al, 2009). Deoxygenation of the ocean is also a major concern in the context of climate change (Keeling et al., 2010). Finally, there is ongoing work to exploit accurate O_2 measurements to estimate, through transfer functions derived from neural network techniques, the concentrations of nutrients (nitrate, phosphate and silicate) and carbonate system parameters (total alkalinity, dissolved inorganic carbon, pH and partial pressure of CO_2) (Sauzède et al., in revision).

There is thus a strong need in the scientific community to set up and maintain a long term observing system that will produce a homogeneous and validated O_2 dataset. Therefore, discussions have started to expand the Argo mission with oxygen sensors to a larger subset of the Argo floats.

Extensive R&D activities helped to understand the behavior of the newer optical oxygen sensors (Bittig et al., 2015a,b; Bittig et al, 2016a,b) and to define quality control procedures when those sensors are implemented on mobile platforms such as Argo floats (Takeshita et al., 2013, Thierry et al, 2016a,b, Schmechtig et al., 2016). As a result of those activities, in part conducted within international projects (AtlantOS) and programs (Argo and BGC-Argo) or international working groups (SCOR Working Group 142 on Quality Control Procedures for Oxygen and Other Biogeochemical Sensors on Floats and Gliders, *http://www.scor-int.org/SCOR_WGs_WG142.htm*), Argo-based dissolved oxygen observations can now reach an unprecedented level of accuracy that is comparable to traditional oceanographic expeditions.

To date, there are over 270 active Argo floats carrying oxygen sensors (Figure 23), which corresponds to about 7% of the active floats, and almost 1000 Argo floats with oxygen sensors have been deployed so far. The case for measuring O_2 in Argo has been made already in the white-paper report by Gruber et al. (2010). Historically, most floats with oxygen sensors, however, have been deployed on an ad hoc basis since there has been no overall framework or coordinated plan for the deployment, acquisition, or use of these observations. Thanks to recent actions (e.g. SCOR UNESCO Working Group 142 on “Quality Control Procedures for Oxygen and Other Biogeochemical Sensors on Floats and Gliders”) and the new Biogeochemical-Argo program (Johnson and Claustre 2016), this required coordination is now fully taking place.

Goal for the future

As a long-term goal (within the next decade), Argo could set out to equip at least half of the core Argo floats with oxygen sensors. The optode O_2 sensor is of proven maturity and can provide very accurate measurements (1 %), owing to in-air measurements done during the float lifetime (Bittig and Körtzinger, 2015).

A global O_2 array would be required to address climate change issues and to monitor current changes in O_2 concentration. The global coverage is key to capture spatial and temporal variability, since the observed loss in the global oceanic oxygen content (greater than 2 % since 1960) (Schmidtko et al, 2017) shows large variations in different ocean basins and at different depths. A full-scale global Argo-O_2 array is also extremely valuable to expand the scope of BGC-Argo, since O_2 data is in a key position of many biogeochemical processes and can be use to interpolate, e.g., through neural network techniques (Sauzède et al., in revision), nutrient concentrations and carbonate system parameters. Besides the usefulness of these O_2 data for biogeochemical studies, they will also provide invaluable information for the investigation of physical processes, such as deep convection, ocean ventilation and circulation (Keeling et al., 2010, Piiron et al, 2016, 2017). Indeed, the difference between the observed O_2 level and that expected at equilibrium with the atmosphere, a quantity known as the apparent oxygen utilization (AOU), reflects a water parcel’s biogeochemical history, increasing with time as the parcel “ages” below the surface. Thus, changes in AOU can provide information on changing circulation not revealed in measurements of physical properties, such as temperature and salinity.

European needs

Essential parts of the research and progress with respect to O_2 sensor characterization and development of processing and quality control procedures for Argo-O_2 took place in Europe. With that expertise, Euro-Argo is primed to pioneer the equipment of half of the core Argo floats with O_2 sensors. This step could lead to a major advance in biogeochemical monitoring of the marine ecosystem and operational services in the European Seas.

Some further, specific needs regarding O_2 data are for instance to:

- monitor the inflow of O_2-rich waters and oxygen depletion in the Baltic Sea (See Section 3.3),

- analyze productivity and ecosystem response to climate change in the Nordic Seas (See Section 4.1.1),

- monitor deep-convection at high-latitudes and especially in the subpolar gyre of the North-Atlantic.

Requirements

The profound scientific interest by European and international scientists and operational data users supports the goal to increase the share of O_2-equipped Argo floats beyond the BGC-Argo target of 25 % of all floats, and to equip at least half of the Euro-Argo fleet with an O_2 sensor in the long-term.

8 DATA MANAGEMENT

Every effort is made to deliver data with the shortest delays possible and with extensive quality control. Hence there are real-time (less than 24hrs), near-real time (order of a few days), and delayed mode delivery systems. The quality control procedures are the highest and most stringent for the delayed-mode data stream which is designed to deliver data of climate quality.

Formal data management procedures are implemented under the auspices of the international Argo Data Management Team, in which the EA-RI plays an active role. All procedures and data formats are fully compliant with recommendations from international bodies such as the WMO-IOC JCOMM. A network of centres is in charge of collecting and processing data from the floats and of delivering quality controlled data to users. All data are available to operational users via the WMO Global Telecommunication System (GTS) and also via Data Centers internet portals for all users.

What exists

The international Argo data system is based on two Global Data Assembly Centres, a series of 13 national Data Assembly Centres, several Argo Regional Centres and Delayed-Mode operators. Their functions are summarized below.

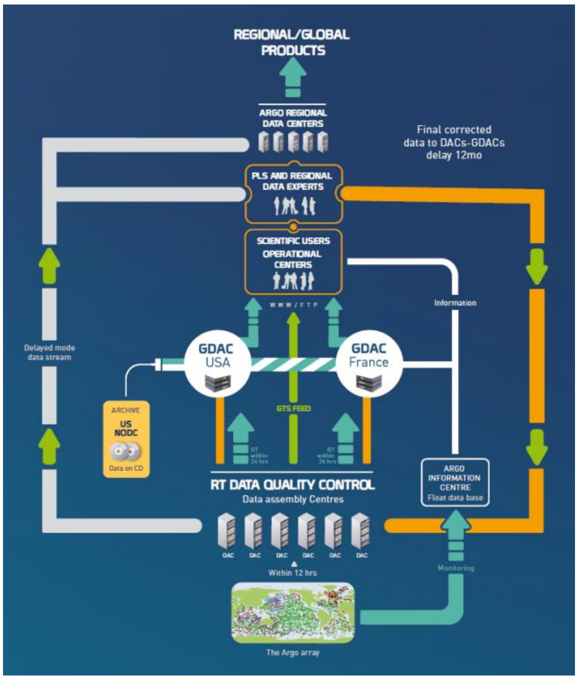


Figure 24. Euro-Argo data system scheme.

- **GDACs** (Global Data Centres), located at Coriolis/France and FNMOC/USA, are in charge of collecting the processed Argo data from the 13 DACs and to provide users with access to the best version of an Argo profile. Data are available, in a standard NetCDF format both on FTP and WWW. The two GDACs synchronize their database every hour.

- **DACs** (Data Assembly Centres), they receive the data from the satellite operators, decode and quality control the data according to a set of real time automatic tests agreed by the international Argo programme. Erroneous data are flagged, corrected where possible and then passed to the two GDACs and to the WMO GTS. The GTS data stream does not presently include quality flags and bad data and grey-listed data are not transmitted on the GTS.
- **ARCs** (Argo Regional Centres) provide wide expertise on specific geographical ocean regions in order to provide the most comprehensive data sets (including non-Argo data) of the highest quality.
- **DELAYED-MODE Operators**, although real time procedures flag the gross errors in the data, there may still remain more subtle errors due to sensor drift (most often in salinity). Although these may be small, it is essential to identify and correct them if one is to extract climate change signals from the data. Elaborate procedures have been devised, based on statistical methods, and scientific expertise from principal investigators (PIs). The procedures are constantly assessed and updated as necessary.

The Euro-Argo RI plays an active role in Argo data management:

- France (Coriolis) hosts one of the two Global Data Assembly Centres (GDAC).
- Two DACs are operated by France (Coriolis) and UK (BODC).
    - The French DAC: The French Argo Data Centre, Coriolis, which is located within Ifremer-Brest and operated by Ifremer with support of SHOM, processes float data deployed by France and from other European (Germany, Spain, Netherlands, Norway, Italy, Finland, Greece, Bulgaria)not processed by UK and several non-European countries (e.g. Chile, Mexico, India…).
    - The UK DAC: The UK Argo Data Centre, which is established at BODC, processes all UK, Irish and Mauritian float data.
- Euro-Argo partners lead and contribute to three ARCs:
    - Atlantic ARC (NA-ARC). France has taken the lead in establishing the NA-ARC, which is a collaborative effort between Germany (IFM-HH, BSH and KDM), Spain (IEO), Italy (OGS), Netherlands (KNMI), UK (NOCS, UKHO), Ireland (IMR), Norway (IMR), Canada (DFO), and USA (AOML). BSH and IFM-HH coordinate the activities in the Nordic Seas.
    - The Mediterranean and Black Seas ARC (MED-ARC). OGS in Italy coordinates the activities described above for the Mediterranean and Black seas.
    - Southern Ocean ARC (SO-ARC): The UK has taken the lead in establishing the SO-ARC. This is a collaborative effort between BODC, CSIRO (Australia), University of Washington (USA) and JAMSTEC (Japan) with BODC having responsibility for the South Atlantic sector of the Southern Ocean.

- Euro-Argo partners operate 4 delayed mode centres:
    - 4 institutes (Coriolis/France, BSH/Germany, BODC/UK and OGS/Italy) perform the delayed mode processing of the floats deployed by the EA-RI.

Goal for the future

Euro-Argo RI has started to deploy floats either in new areas (marginal seas, ice-covered regions, boundary currents, abyssal oceans…) or implementing new type of floats that carry extra sensors.

These improvements of the float technology require data transmission modifications, enhancement of the floats format to integrate the new variables and therefore adaptation of the Euro-Argo data centres processing chains. The two Euro-Argo DACs (Ifremer/Coriolis and BODC) are being upgraded to process the new floats including new biogeochemical parameters. For the new parameters, some real time data quality control tests have been defined by research teams. The QC procedures have been turned into operation by the Euro-Argo DACs after agreement within the International Argo Data Management Team (Schmechtig et al. 2014, 2016), but work still needs to be done on defining Delayed Mode procedures. Note that each novel sensor require endorsement from AST and ADMT before its data enter the Euro-Argo RI data system.

Similarly, sampling marginal seas, abyssal oceans, boundary currents, near surface layer, or partially ice covered regions requires additional delayed validation activities to assess and eventually propose modifications either in the real time or in the delayed mode procedures.

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