

ARCTIC ARGO-TYPE FLOATS: THE NEEDS, POTENTIALS AND CHALLENGES

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ABSTRACT

Since its first deployment in 1999, the array of Argo profiling floats has revolutionized the way the ocean is observed in the lower latitudes. Ocean state estimates constrained by Argo data over the last two decades have significantly improved representation of the global ocean. In contrast, observations in the Arctic Ocean remain sparse in both spatial and temporal coverage, and biased toward the summer months. Ice-tethered profilers greatly increase the number of hydrographic observations. However, ITPs are limited to locations and movements of stable surface ice floes. As a consequence, understanding Arctic circulation and changes, and being able to represent them in numerical models, continue to pose great challenges. Arctic Argo-type floats are scalable to a broad and distributed spatial and temporal coverage of the Arctic interior and can address the deficiencies in data coverage. The primary challenge for deployment of Argo-type floats in the Arctic has been the presence of sea ice. A preliminary uncertainty quantification of hydrographic measurements, using the Estimating the Circulation and Climate of the Ocean (ECCO) state estimation tools, showed that even if the floats cannot surface regularly during the winter months when the entire Arctic basin is covered with ice, collecting sub-surface hydrographic samples will still be very useful. If a path for moving Argo-type floats into the Arctic can be demonstrated, an Arctic Argo float program can become part of the global Argo portfolio, thus drawing on its resources and infrastructure.

1. THE NEED FOR PROFILING FLOATS IN THE ARCTIC OCEAN

Since its first deployment in 1999, the array of Argo profiling floats has revolutionized the way the ocean is observed, with ~3900 active floats currently sampling the upper 2000 m of the ocean equator-ward of 60° latitudes. In conjunction with satellite observations, Argo data have been used to estimate the mean and time-evolving oceanic heat, salt and freshwater content (e.g. Levitus et al., 2012, Hosoda et al., 2009, vonSchuckmann et al., 2011, Ren et al., 2014), circulation (e.g. Willis et al., 2008), and ocean mixing (e.g. Whalen et al., 2012, Wu et al., 2011, McCaffrey et al., 2015). Ocean state estimates constrained by Argo data over the last two decades (e.g. the Estimating of the Circulation and Climate of the Ocean (ECCO) global state estimate, Stammer et al., 2002, Wunsch et al., 2007, Wunsch et al., 2009, Forget et al., 2015) have improved representation of the global ocean and have been used to investigate the deep ocean heat content (e.g. Wunsch et al., 2014, Liang et al., 2015) and meridional overturning circulation variability (e.g. Wunsch et al., 2009, Wunsch et al., 2013, Buckley et al., 2014, Buckley et al., 2015, Zanna et al., 2011, Heimbach et al., 2011, Pillar et al., 2016).

In contrast to the recent drastic increase in Argo float coverage in most parts of the world ocean interior, observations in the Arctic Ocean are still obtained via conventional techniques using ships and moorings that provide sparse spatial and temporal resolution, biased toward the ice-free summer months. The introduction of the ice-tethered profilers (ITPs) beginning in 2004 [Toole et al., 2006, Toole et al., 2011, Krishfield et al., 2008] has greatly increased the number of hydrographic observations, and has contributed to the improved understanding of vertical hydrographic properties [Timmermans et al., 2011, Timmermans et al., 2012] and mixing [Timmermans et al., 2008, Toole et al., 2010, Cole et al., 2014] in the upper 800 meters in the central Western Arctic. However, the distribution of ITPs has been limited by both political boundaries and the distribution of ice thick enough to support deployment. In addition, most ITP trajectories are constrained to the circulation of the near-surface Beaufort Gyre and the trans-polar drift, leaving a large part of the Arctic interior and the region along deep (AW) boundary currents under-sampled. The Eurasian Basin interior, especially following the Atlantic Water pathway, where recent mooring and ship-based observations have indicated an enhanced heat flux [Dmitrenko et al., 2008, Polyakov et al., 2012], is a prominent example of a critical, but poorly-sampled, region. Upwelling and watermass transformation take place along the Siberian shelf-break, with implications for sea ice retreat, freshwater pathways, and downstream heat flux in the Canada Basin / Chukchi Shelf [Dmitrenko et al., 2010]. The recent deployments of

several ITPs in the Eastern Arctic will help alleviate the lack of continuous observations. However, sampling coverage remains limited to availability of vessel support and thick ice floes upon which ITPs can be deployed.

As a consequence of lack of uniform spatial and temporal data coverage, understanding Arctic circulation, and hydrographic changes and being able to represent them in numerical models, have continued to pose great challenges [Holloway et al., 2007, Nguyen et al., 2011, Bourassa et al., 2013, Ilicak et al., 2016].

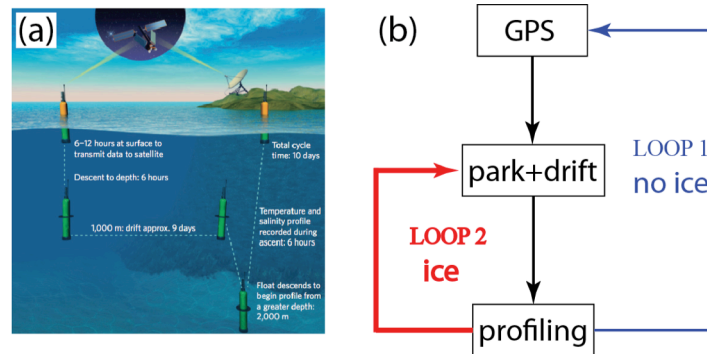


Figure 1. (a) Schematic of an Argo float's current sampling and surfacing algorithm in the absence of sea ice (Figure taken from Riser et al., [2016]). At deployment time the float will communicate with GPS before descending to its parking depth and drifting with the current. It is programmed to dive down to 2000 m and take a vertical profile to the surface every 10 days. (b) Flowchart of the two modes that an Argo-type float will operate in the Arctic, with LOOP 1 corresponding to lower latitude mode shown in (a). In the presence of sea ice, the float will operate in LOOP 2 without surfacing to communicate with the satellite and relaying data. In the seasonal ice zone the float could potentially remain in LOOP 2 mode through the winter months.

2. THE TIMING FOR ARCTIC ARGO FLOAT DEPLOYMENT

With the recent technological advances in float design, Argo-type instruments can now be deployed under seasonal ice covered regions [Riser et al., 2016, Wong et al., 2011, Wong et al., 2013]. Adopting an Argo float prototype and infrastructure for the Arctic has several very important advantages. The floats are relatively inexpensive and can be deployed from a wide range of platforms by untrained personnel with no skill or special equipment required as long as there is open water. In addition, there is an existing structure for assembling, processing and disseminating the data at Argo data centers (DAC). All of these factors imply that the floats are scalable to a broad and distributed spatial and temporal coverage of the Arctic interior in a way that is not achievable with ITPs or gliders. In political terms, Argo is a large international, well supported, near global program. If a path for moving it into the Arctic can be demonstrated, it can be convincingly argued that the Arctic Argo float program can become part of the global Argo portfolio, thus drawing on its resources and infrastructure.

Two Office of Naval Research (ONR) Departmental Research Initiatives (DRIs) offer excellent opportunities for collaboration with an Arctic Argo effort. The 2016-2017 Canadian Basin Acoustic Propagation Experiment (CANAPÉ) includes an array of low- and mid-frequency acoustic sources that will ensonify a large portion of the central Beaufort Sea. These sources will be used to investigate long-range acoustic propagation and to provide geolocation services for autonomous gliders. Following this, the 2018-2019 Stratified Ocean Dynamics or the Arctic (SODA) program will maintain an array of science moorings, including acoustic navigation sources and autonomous assets in the central Beaufort Sea. A third initiative, currently being competed, will likely extend key elements of the SODA array, including acoustic navigation, into 2020. The combination of these programs will provide acoustic navigation in the central Beaufort Sea from autumn 2016 through autumn 2019. The gap in 2017-2018 might be bridged with a small number of sources to support SODA pilot activity, and there is a strong possibility that the array would remain active into autumn 2020. This offers significant advantages for the proposed Arctic Argo pilot, including:

- Use of the ONR array for accurate geolocation. This would provide ground-truth data for evaluating drift and for assessing experimental approaches for geolocation (e.g. terrain-aided navigation, electromagnetics);

- Full systems testing and refinement of hardware and software systems designed specifically for providing acoustic geolocation on floats.

Acoustic networks require a significant commitment of resources for installation and maintenance. The multi-year presence of an ONR-supported network in the central Beaufort Sea, in addition to the ongoing international efforts to implement acoustic arrays at the Fram Strait [Mikhalevsky *et al.*, 2014], offer a rare opportunity that may not be easy to replicate in the near future.

3. THE NEED FOR UNCERTAINTY QUANTIFICATION

A major challenge to the deployment of Argo in the Arctic has been the presence of sea ice, which inhibits the floats' ability to surface and thus prevents the use of such floats in ice-covered regions [Riser *et al.*, 2016]. As depicted in Fig. 1, for an Argo float in the Arctic, geopositioning via satellite and transmission of data will be limited to seasonally ice-free areas or through leads/cracks in the Arctic interior. During winter months, when the Arctic is 100% covered by sea ice, the floats may continue to drift at their parking depth and take sub-surface profile measurements, but without direct knowledge of the location where these measurements were taken. Acoustic navigation can alleviate some of these problems by providing the ability to geolocate when operating under ice, but given the challenge of providing pan-Arctic acoustic navigation, it is likely that instruments operating in the Arctic interior will often be forced to work without direct geolocation for the foreseeable future.

Even if the floats cannot surface regularly during the ice-covered winter months, it is plausible that collecting sub-surface hydrographic samples will still remain very useful. An assessment of the importance and usefulness of such measurements requires an understanding of how uncertainty in float positions accumulates with non-surfacing (silent) time and how this uncertainty maps into uncertainty in the measured hydrography. A powerful way to address these unknowns is to use the estimating tools existing within the ECCO consortium to quantify uncertainties associated with potential Argo-type float deployments in the Arctic. Arguably this is an appropriate usage of the mean and time evolving ocean-sea ice state obtained by the state estimate to quantify possible scenarios of non-surface duration and trajectories of the floats, to assess the usefulness and impact of the data as a function of silent time, both in absolute terms and in conjunction with formal state estimation.

The uncertainty quantification aims to answer these targeted objectives:

- The expected fraction of surfacing time to the float's lifetime as a function of the float's position relative to the time-varying surface ice cover and ocean circulation in the Arctic;
- The hydrographic uncertainty implied by the position uncertainty during silent time when the float drifts without communication with satellite to relay positions;
- The usefulness of the hydrographic data in constraining and improving modeling efforts.

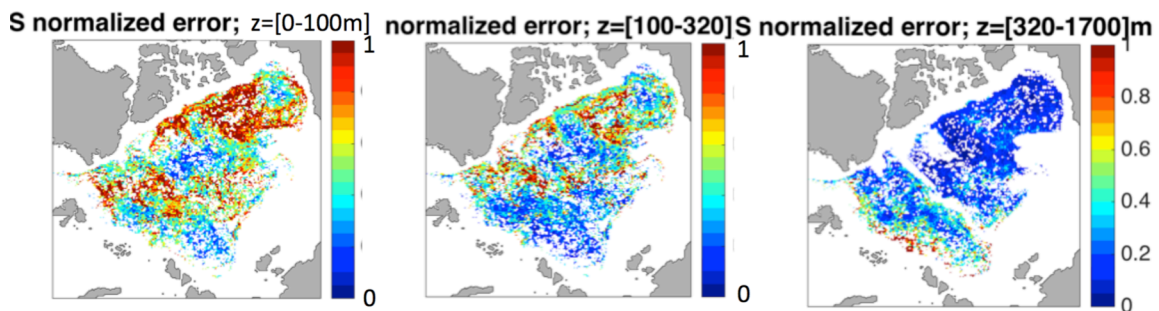


Figure 2. Spatial distribution of normalized error for Salinity within depth ranges 0-100m (left), 100-320m (mid) and 320-1700m (right). In the upper ocean where variability in ocean temperature and salinity is high both spatially and temporally, normalized errors are high in areas where either (i) the presence of multi-year and thick sea ice prevents the float from surfacing often or (ii) where the salinity uncertainty is low. However, below 100m, potential Arctic Argo float data are useful (error < 1) almost everywhere and have significant potential in contributing to the improvement of Arctic mean state.

The measure of usefulness of the Arctic Argo float measurements will depend on the current knowledge of *a priori* uncertainty and the duration of silent time (Nguyen *et al.*, 2017, Fig. 2). In regions not well sampled, *e.g.* the Eastern Arctic, the mean state and temporal variability are not well constrained, and thus additional measurements even with high uncertainty can contribute significantly to the improvement of knowledge and modeling efforts. With the recent negative trends in summer sea ice cover (Fig. 3) and longer melting seasons [Markus *et al.*, 2009], a larger open water fraction will provide higher chance of float surfacing and increase the data yield with lower uncertainty.

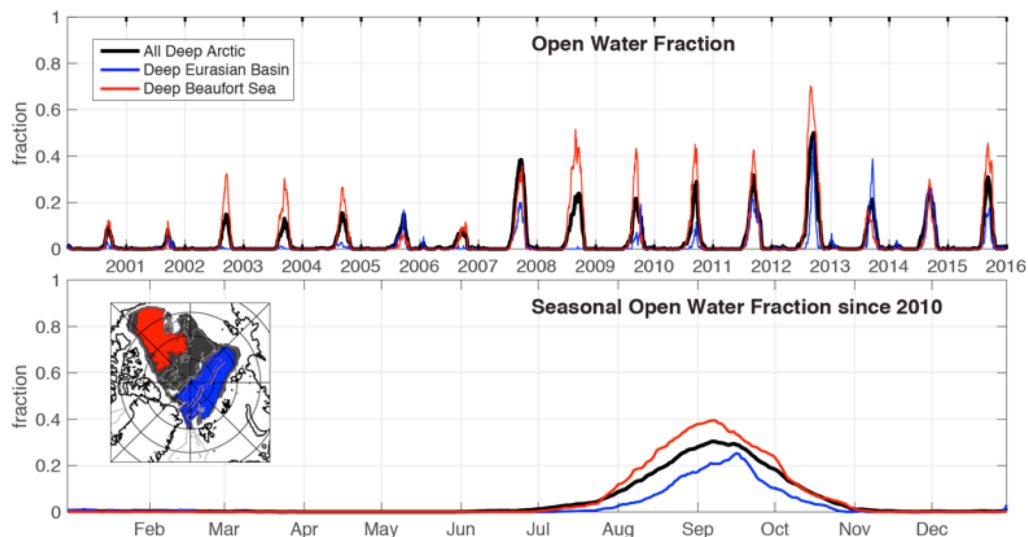


Figure 3. (top) Time series of open water fraction in the deep Arctic basins (regions with depth > 3000 m) from SSM/I satellite data showing an increasing pattern beginning in 2008. (bottom) Mean 2010–2015 open water fraction showing ice-free conditions (when floats can surface) in up to 40% of the deep Arctic basin during summer months.

Overall, the uncertainty quantification will be used to inform a float network design with suggested locations of float deployments and associated expected hydrographic uncertainties. A positive feedback is built with strong collaboration between the observing and modeling communities. A state estimate that is constrained by existing observations and a full-fledged GCM is used to extract as much information as possible on (a) the uncertainty associated with operating existing/near-future float technology in the harsh Arctic conditions where sea ice is a limiting factor, and (b) the geographic distribution of locations where new observations have the most impact on the improved understanding the general circulation, watermass distribution and hydrographic changes in the Arctic. In turn, the observations will be crucial in reducing *a priori* uncertainty and improving global and regional state estimates at high latitudes.

4. FLOAT TECHNOLOGY DEVELOPMENT

Although Argo floats and acoustic geolocation are proven, mature technologies, there are several advances that would enhance the effectiveness of floats operating in ice-covered oceans. It may be possible to exploit the earth's electromagnetic signature, ambient noise or bottom bathymetry (for drifts near the shelf-slope system) to improve geoposition accuracy beyond that derived from dead reckoning (interpolation between GPS-derived positions). The ability to identify and exploit open water (*e.g.* leads) would allow floats to obtain intermittent GPS fixes and to transmit data, increasing the probability of data exfiltration. We have implemented simple ice-identification algorithms onto Seagliders, and colleagues have been working on novel approaches for ice identification that rely on measures of downwelling light. The proposed effort would include exploratory technology development aimed at geolocation and ice detection. Floats equipped with the resulting technologies would be deployed as part of the pilot program, ideally within the ONR acoustic array in the central Beaufort Sea; acoustic geolocation would provide ground truth.

5. PILOT FLOAT DEPLOYMENTS

An initial deployment of Argo floats, O (20-50), into various regions of the Arctic will provide data to evaluate the technical and scientific viability of an Arctic float network and inform the design of larger efforts that might follow. Deployments will focus on the central Beaufort, with other regions selected based on the initial numerical uncertainty quantification efforts. Deployments would rely on collaboration with existing field programs, *e.g.* floats piggybacking on cruises undertaken by both US and international efforts. To widen the geographic range of deployment opportunities, floats would be deployed over a two-year period, after which efforts would focus on the processing and analysis of data returned from the pilot array.

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