ALPS in the Arctic Ocean

Mary-Louise Timmermans, Rick Krishfield, Craig Lee, and John Toole

Arctic ALPS should exploit synergy between the various platforms and approaches to maintain operations across the full range of seasonal conditions, from ice-free open water, through marginal ice zone conditions, to fully sea-ice covered. Ice-based ALPS, a critical tool for Arctic observing, must evolve in response to the anticipated continuing loss of multiyear sea-ice floes.

For decades, sea ice has been used successfully to support ALPS in the Arctic Ocean to monitor atmospheric, snow, sea-ice, and ocean properties year-round and in some cases across the entire Arctic basin. Because the Arctic is warming substantially faster than the global average and sea-ice decline is projected to continue, there is a critical need for sustained observations of this rapidly evolving system to characterize and understand the changes. How will solar absorption, ocean heat storage, and ocean/atmosphere heat advection influence the sea-ice cover in the future? What are the associated feedbacks (e.g., ice albedo) and how are they changing? What processes control the upper Arctic Ocean stratification and freshwater content, and how will these change? How will the Arctic Ocean marine ecosystem and carbon cycle respond to the reduced sea-ice cover? Beyond science issues, uninterrupted observations of the Arctic system will become increasingly needed for forecasting and monitoring (e.g., pollutant dispersal) as the Arctic becomes more accessible to shipping and other activities such as resource exploration and extraction (NRC, 2014).

Although sea ice can impede sustained observation of the Arctic Ocean, conventional approaches to observation such as ships and profiling floats, and instrument systems mounted on or in sea ice have been immensely effective. For example, since the 1970s, the Arctic Ocean Buoy Program, later designated the International Arctic Buoy Program (IABP), has been returning sea-ice motion information, as well as atmospheric pressure and temperature information throughout the Arctic. These data have proven to be key to weather forecasting at high northern latitudes. Since publication of the first ALPS workshop report in 2003 (Rudnick and Perry, 2003), the variety and number of ice-based platforms and sensors have increased considerably, many of which were impelled by the International Polar Year (IPY) in 2007–2008. Systems currently operational include the Ice Mass Balance buoy (IMB, Perovich et al., 2013; a similar system is described by Jackson et al., 2013), designed for operation in multiyear sea ice to measure changes in sea ice and snow thickness, and the Autonomous Ocean Flux Buoy (AOFB; Shaw et al., 2008) that returns estimates of turbulent fluxes of heat, salt, and momentum at around 4 m below the ice-ocean interface. Recent enhancements to the AOFB system include sampling of the atmospheric boundary layer and ocean mixing measurements in the halocline. Several variants of under-ice sampling systems are also being fielded, including the Ice-Tethered Profiler (ITP, Toole et al., 2017), POPS (Kikuchi et al., 2007), Integrated Arctic Ocean Observing System (IAOOS) profiler (Provost et al., 2015) and the Measuring the Upper layer Temperature of the Polar Oceans (UPTEMPO) and Ice-Tethered Mooring (ITM) buoys. These systems typically provide ocean profiles (or samples at discrete depths) of salinity, temperature, and pressure from just below the ice-ocean interface to as much as 750–1,000 m depth. Some of these systems additionally sample dissolved oxygen (DO; Timmermans et al., 2010), bio-optical properties (Laney et al., 2013), and velocity (including mixed-layer turbulent fluxes; Cole et al., 2014). Another important development relates to predictions of air-ice-ocean CO_2 fluxes and ocean acidification, which is being addressed by interfacing CO_2 and DO sensors on these systems (Islam et al., 2016).

Advances in understanding Arctic system behavior have been made through the collocation of different ice-based systems on a single ice floe to form a multi-platform Ice-Based Observatory (IBO). The combination of data from the coupled atmosphere-ice-ocean environment allows, for example, the partitioning of heat sources and attribution of sea-ice melt, and determination of freshwater sources and distribution processes. But the continued losses of large, stable, multiyear sea-ice floes is threatening the future viability of IBOs due to the difficulty of deploying buoys on thin ice, buoy survivability during ridging events, and the enhanced fracturing of thin floes, which can disperse the systems. In recent years, several individual systems have been modified to be able to operate in thinner, seasonal ice conditions. A Seasonal Ice Mass Balance Buoy (SIMB) has an enhanced buoy design in order to survive complete sea-ice melt; ongoing SIMB refinements are aimed for a capability to operate reliably through the fall freeze-up. Similarly, the surface float of the ITP system has been redesigned for open-water deployments and to withstand seasonal freeze-up (although the tether through the ice remains a potential failure point during ridging). While these design changes are advancements for individual systems, the feasibility of collocated deployments continues to be at risk.

As multiyear and thicker ice floes suitable for safe support of Arctic ALPS become scarce, summer and fall deployments of measurement systems will likely need to take place in open water, precluding establishment of IBOs. Deployments on sea ice may continue to be possible during spring aircraft operations, but with shortened lifetimes of the ice-based systems as they melt out of their host floe each summer. Future developments need to consider the design challenges and cost of a system that can withstand sea-ice growth from open water and subsequent ridging. The most practicable approach may be to devise cost-effective systems, designed with shorter lifetimes and ease of deployment in mind. This would allow for a larger number of systems to be distributed every year, increasing the odds of useful long-term data return.

ALPS that operate independent of the ice, including autonomous underwater vehicles (AUVs), gliders, profiling floats, drifters, and tagged animals (Roquet et al., 2017), provide complementary approaches that will be increasingly relied upon with further decrease of perennial ice cover. For geolocation and communication in ice-covered regions, these systems can rely on underwater acoustic networks, long used to track arrays of drifting subsurface floats (e.g., Rossby et al., 1986). A hierarchy of acoustic systems operate over a broad span of frequencies (ANCHOR Working Group, 2008). Current generation O(1 kHz) systems (e.g., Webster et al., 2015) have provided real-time under-ice navigation and telemetry over hundreds of kilometers for regional-scale studies. More complex 10–100 Hz systems would be required to provide pan-Arctic geolocation (e.g., Mikhalevsky et al., 2015). The Arctic presents challenges beyond those faced at lower latitudes, including reduced signal range due to surface ducting of sound and the resulting reflection off the rough ice bottom. Marine mammal concerns must be integral to the planning of any acoustic networks, with proper care taken to assess and mitigate potential impacts.

Profiling float technology holds promise as a scalable, cost-effective way to achieve sustained, widely distributed sampling. Argo-type air-deployable profiling floats have been fielded in the Arctic's Chukchi Sea that incorporate ice-avoidance schemes (Jayne and Bogue, 2017). Nguyen et al. (2017) show there would be significant improvements in numerical state estimates with the establishment of an Argo float program in the Arctic, finding that the additional water-column measurements would be valuable even if floats could not surface to return position information in the sea-ice covered winter months.

Long-endurance gliders provide a mobile capability that is best used for focused sampling, such as process studies and sustained observations of boundary currents, fronts, and other critical regions dominated by large spatial gradients.

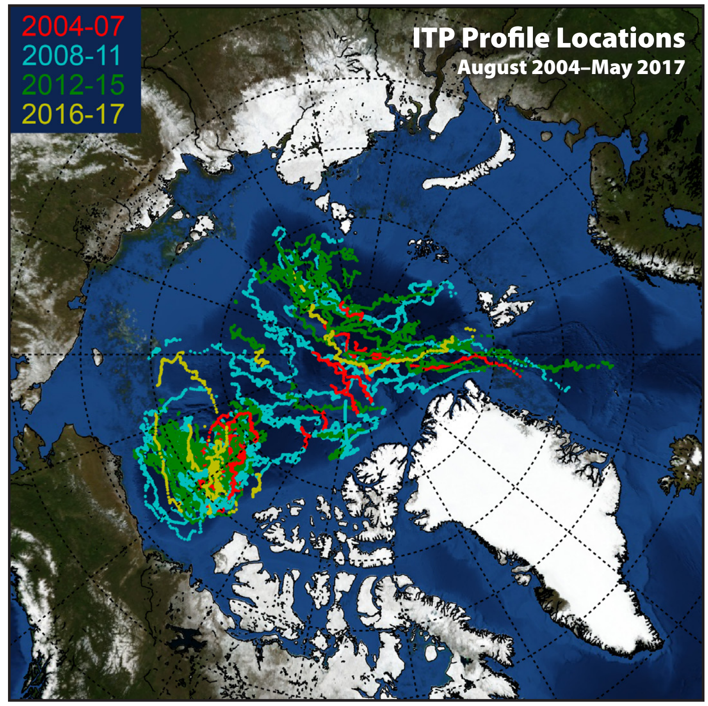

Figure 1. Map showing all ocean temperature-salinity profile locations from Ice-Tethered Profilers (ITPs) since the first ITP was deployed in 2004 through May 2017. The data coverage illustrates the absence of water-column profiles of temperature and salinity in the shallow continental shelf regions.

Acoustically navigated Seagliders with ice avoidance and enhanced autonomy have been used for year-round measurements in ice-covered straits (Curry et al., 2014) and for sampling across open water, marginal ice zone, and into the pack of the spring/summer Beaufort Sea.

While the spatial and temporal coverage of observations, as well as the types of properties sampled by ALPS, have increased in recent years, major gaps remain. A critical deficiency is the lack of year-round measurements at the continental boundaries of the Arctic Ocean (i.e., coastal margins and seas including the Chukchi, East Siberian, Laptev, Kara, and Barents Seas; Figure 1). Over 30% of the Arctic Ocean area is made up of shallow continental shelf regions. These regions are pathways for boundary currents and seasonal river influxes (carrying nutrients, heat, and freshwater), and are subject to great solar input in summer. At the same time, year-round sampling by ice-based ALPS is not feasible in boundary regions; ALPS have short lifetimes in these regions of intense seasonal variability, particularly dynamic and damaging sea-ice forcing, and strong ocean flows. A further complicating issue with respect to ALPS in the boundary regions of the Arctic and its marginal seas relates to observing in Exclusive Economic Zones. Policies and international agreements and/or partnerships need to be in place for sampling protocol and data return from these regions (see Calder et al., 2010).

An additional gap in observations that remains to be addressed by ALPS is sampling at the ice-ocean and air-ice interfaces. First-order physical and biological processes take place well within the top meter of the ocean under sea ice, which is a layer that remains particularly difficult to sample autonomously because of potential stresses to sensors of growing sea ice and ridging. Sustained physical measurements in the atmospheric boundary layer (including vertical profiles) are challenging to make autonomously (and therefore sparse) but are also essential for closing sea-ice mass and momentum budgets. The suite of sampling at these interfaces must also include incident solar radiation, gas transfer measurements, and robust bio-optical and geochemical measurements over a full seasonal cycle.

The use of ALPS to observe the Arctic Ocean in the backdrop of climate change poses new challenges and opportunities for advances. The overarching problem is how to continue sampling reliably in the face of future inevitable sea-ice losses. Ice-based observatories remain the only approach capable of simultaneously sampling atmosphere, ice, and ocean, motivating efforts to redesign these systems for operation in seasonal ice cover. Without reliable sea-ice floes, and while the Arctic Ocean and marginal seas remain entirely ice covered in winter, systems that are air-deployable may become a more practical option. Ice-free regions will be more expansive and open for longer duration, and traditional profiling floats will become viable. Mobile platforms, including long-endurance gliders and AUVs, can provide measurements that span open water, the marginal ice zone, and well into the sea-ice pack. While ice-tethered acoustic sources are becoming less feasible, bottom-moored acoustic sources can provide geolocation for platforms operating beneath the ice. Continued advances should be made through analyses of remote-sensing data in conjunction with ALPS measurements. As the Arctic region becomes more accessible to shipping and resource extraction, integration of ALPS data into models for long- and short-term forecasts and monitoring for operations (e.g., oil-spill tracking) is essential.

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Authors

Mary-Louise Timmermans, Yale University, New Haven, CT, mary-louise.timmermans@yale.edu

Rick Krishfield, Woods Hole Oceanographic Institution, Woods Hole, MA, rkrishfield@whoi.edu

Craig Lee, University of Washington, Seattle, WA, craig@apl.washington.edu

John Toole, Woods Hole Oceanographic Institution, Woods Hole, MA, jtoole@whoi.edu