Observing the Evolving Central Arctic Ocean with Ice-Tethered Profilers (2004-2013): goals, objectives, capabilities, challenges and sustainability

J. Toole, R. Krishfield, A. Proshutinsky, and S. Laney
Woods Hole Oceanographic Institution, USA
M.-L. Timmermans, Yale University, USA

Summary

Since 2004 nearly 60 Ice-Tethered Profiler (ITP) instruments have been deployed in the Arctic Ocean with the major goal of sampling the upper ocean water properties through all seasons. While the base design includes only a CTD sensor package, additional physical, bio-optical and biogeochemical sensors have been implemented on a number of units. In conjunction with companion instrument systems sampling meteorological, sea ice and ocean mixed layer parameters, this combined Ice-Based Observatory monitoring program represents a major contribution to the Arctic Observing Network. Studies conducted over the last decade indicate that the Arctic is both a sensitive indicator of climate change and an active driver of climate variability. As evidenced by the strikingly low summer sea ice extent estimates recorded since August 2007 and large anomalies in liquid fresh water content (manifested by upper-ocean salinity), significant Arctic Ocean changes are underway now. It is critical that we continue to observe the Arctic using proven instrumentation like the ITP during this time of rapid evolution to quantify the physical changes that are occurring, to better understand their causes, and to assess their impacts on the Arctic Ocean climate system and associated ecosystem.

Introduction

Arguably, the international Argo float program has become the cornerstone of the ocean observing system. The array of some 3500 instruments (maintained by successive deployments) is returning upper-ocean water properties and circulation information at ~300 km horizontal resolution and ~10-d interval throughout the temperate seas (Roemmich and Owens, 2000; Roemmich et al., 2009), though the challenge of sustaining the array is ever present (Roemmich and Argo Science Team, 2009). Due to the requirement that floats surface for location determination and data telemetry, Argo has not ventured very far north into the Arctic owing to the extensive sea ice cover there. Nevertheless, data are now being obtained regularly from selected seasonal and marginal ice zones using innovative approaches including instrumented marine mammals (Boehme et al., 2009). Around the time that Argo was going global, several research groups began work to develop an analogous measurement capability for the deep Arctic. Systems employing discrete sensors suspended on a tether below a drifting ice floe have a long history in the Arctic (e.g. Morison et al., 1982; Krishfield et al., 1993). The new development efforts utilize a single instrument package traveling up and down along a tether to return repeated high-vertical resolution profiles, akin to those obtained by free-drifting Argo floats. The WHOI Ice-Tethered Profiler (ITP) is one such system.

The WHOI ITP field program, begun in fall 2004, has supported the deployment of 59 ITP systems in the Arctic that collectively have returned more than 50,000 temperature and salinity profiles from the central Arctic upper ocean (nominally 7-750m). Support for this effort has to date come from the U.S. National Science Foundation (NSF) Office of Polar Programs, supplemented by WHOI internal funding, plus significant contributions from collaborating European scientists (whose programs also contributed ITP systems to the array as well as provided logistical support for deployments). ITP data have been made publicly available in "quick-look" form (raw as well as nominally edited and binned to a uniformly incrementing pressure grid) in near-real time (including being distributed in decimated form over the Global Telecommunications System (GTS) for use in forecast modeling: e.g. D. Hebert, Naval Research Laboratory, (personal communication), with final calibrated and edited data produced on a somewhat longer time scale. All final data (with accompanying metadata) are submitted to national data centers for permanent archival. Data from the ITP network have been utilized by researchers world-wide in studies focused on a range of physical phenomena and increasingly, ecosystem problems (utilizing data from biogeochemical sensors interfaced to the ITP). A partial list of peer-reviewed papers, books and dissertations that utilized ITP data is given here: http://www.whoi.edu/page.do?pid=110976.

The chief goals of the ITP program are to sample the central Arctic Ocean stratification (temperature, salinity, and at reduced rate, dissolved oxygen), to provide these data to the research community and general public, to support other research endeavors by supporting additional supplied sensors on ITP systems, and to work collaboratively with fellow researchers observing other elements of the Arctic system to carry out coordinated sampling.

The ITP instrument

Krishfield et al. (2008a,b) describe the ITP technology and data processing/distribution system in detail, while Toole et al. (2011) give a status report on the program. Borrowing heavily from these documents, the ITP system consists of three main components: a surface instrument package that typically sits atop an ice floe, a weighted, wire-rope tether up to 800 m in length suspended from the surface package, and an instrumented underwater unit that travels up and down the wire tether (Figure 1).

The current design of the ITP surface expression is a conical-shaped buoy (Figure 1 right) that houses a controller, inductive modem electronics, a GPS receiver and an Iridium satellite phone with associated antennae and batteries within a water tight aluminum housing capped by an ultra high molecular weight polyethylene dome. The electronics case sits within a high-density foam body designed to provide buoyancy for the plastic-jacketed wire rope tether and end weight should the ice fracture or melt and provide modest protection in the event of ice ridging. The ITP tether is constructed from conventional 1/4"-diameter plastic-jacketed wire rope with the upper 5-m of the wire tether cast within a 3.5"-thick protective urethane jacket that also houses the electrical ground lead for the inductive modem. The profiler unit mounts on the tether and cycles vertically along it using a small traction drive wheel mounted midway along its body that draws ~1 W of power to move at 0.25 m/s.

The ITP is fitted with the Sea Bird Electronics, Inc. model 41-CP CTD (whose response characteristics were quantified using ITP data by Johnson et al., 2007). A subset of systems has additionally carried a dissolved oxygen sensor, and prototype ITPs with a velocity sensor have also been fielded (Thwaites et al, 2011). A subsystem developed to acquire bio-optical information has been implemented on five ITP profiling units so far, and one has successfully returned the first-ever year-long autonomous assessment of phytoplankton biomass in the Arctic ocean (Laney et al., 2011; 2013). Furthermore, sensor packages for $p\mathrm{CO}_2$ and pH have also recently been integrated on ITP tethers just below the ice-water interface and fielded on several systems (DeGrandpre et al., 2013). Each standard ITP is designed to return 1600 or more high-vertical resolution profiles of upper Arctic Ocean temperature and salinity (and other variables) in near real time spanning all seasons over a two-to-three-year lifetime (if the system survives this long). Via inductive modem, the raw CTD and associated engineering data files are relayed from the underwater vehicle to the surface buoy, which then transmits them by satellite to a logger computer at WHOI, along with a daily status message that includes hourly position estimates.

Figure 1: Schematic drawing (left) and photographs of the WHOI Ice-Tethered Profiler System (center: deployment, right: after 1 year prior to a recovery-of-opportunity effort).

Data Processing and Distribution

Raw and quick-look processed data from ITPs are made available automatically by our support computer system within hours of each profile being acquired by ITPs in the field. At regular interval, the data files that arrive on the WHOI logger computer are accessed by a separate computer that automatically unpacks the binary data files, performs basic edits, averages the profile data into uniformly-incrementing pressure bins, updates plots of the CTD and engineering data and archives the observations. These plots and the associated data files are accessible from the ITP project web page (www.whoi.edu/itp) where additional documentation describing the data processing procedures is available. Decimated versions of the real-time data are being distributed by the GTS. Since all acquired data are transmitted to shore at full resolution and the hardware is relatively low-cost (in comparison to icebreaker time), ITP systems may be considered expendable (thus alleviating the need for expensive recovery operations to collect the data).

At irregular intervals, edited and calibrated ITP data are produced (see Krishfield et al., 2008b) and these final data and associated metadata are made available on the ITP web site and also submitted to AON-CADIS and NODC for archival. Furthermore, we are working to implement ITP data submission into the Argo data system. We rely on manufacturer-derived calibration information for the temperature and pressure sensors of the ITP CTDs. Post-deployment laboratory calibrations of two recovered ITPs documented temperature and pressure offsets after 2–3 years of 1–2 m°C and around 1 dbar, respectively. We take these as the uncertainties of the final ITP temperature and pressure data. Time-varying conductivity and oxygen sensor calibrations are derived with reference to mapped recent shipboard calibrated CTD/O2 data on deep potential temperature surfaces (see Krishfield et al., 2008b; Timmermans et al., 2010). Apart from profiles that experienced significant cell fouling (for which no final data are reported), we judge the final ITP data sets to have an uncertainty in salinity of 0.005 and in dissolved oxygen of 5 μmol/kg.

Performance History

At the present time, a total of 59 ITP instruments have been deployed in the Arctic by researchers from Germany, France, Great Britain, Russia and the United States. Current funding will support deployment of another 12 systems in 2013 and five in spring of 2014. By agreement, data from all ITP instruments are routed through the WHOI servers and immediately made publicly available.

As of this writing, ITPs deployed in the Arctic have attempted more than 50,000 CTD profiles, the majority between ~7 and 750 m depth (Figure 2). Of these, approximately 80% returned usable temperature and salinity data over their programmed profiling depth interval. Focusing on those systems that have now terminated, the average lifetime of the ITP surface buoy (time over which telemetry is received) is 520 days; the average number of CTD profiles received per instrument deployed is 760. In comparison to traditional sampling from icebreaker and aircraft, the ITP array is returning vastly more upper-ocean temperature and salinity data from the central Arctic over all seasons.

There is a wide distribution in ITP lifetimes and CTD data recovery (Figure 2a & 2b). Commonly, the surface buoy functions for longer time periods than are data received from the underwater profiling module. Reasons for data termination are varied. Only 3 systems have functioned until the battery in the profiling module was exhausted. Five complete ITP systems have been recovered; a sixth system was damaged and lost during a failed recovery attempt. Tether breaking is believed to be responsible for many of the premature stoppages of CTD data acquisition. The underwater vehicles of 8 ITP systems have been damaged or lost communication after dragging into shallow water. Remarkably, 8 ITP systems that had been deemed lost after a year or more (and in one case, approximately 2.5 years) of silence, reinitiated data telemetry. We believe these surface units were buried by ice during rafting events, then re-emerged in subsequent ice deformation events or melted out. The ITP surface unit is designed to store data when its satellite telemetry system is unable to relay information to shore. In these cases, many more months of additional CTD profile data were recovered from these reborn systems (data acquired while the surface unit was buried in ice).

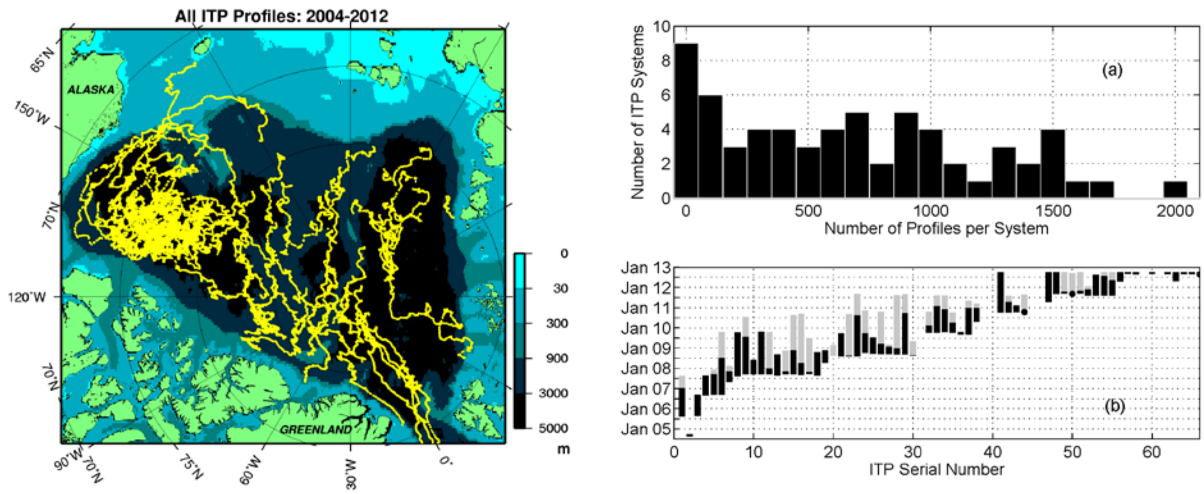

Figure 2: Left: Location of all full- or partial-depth CTD profiles obtained by ITPs since the first system was deployed in late summer, 2004. Owing to the close spacing of the profiles, these profile position locations at this plotting resolution look like continuous drift tracks of the ITP systems. Right: (a) Histogram of the number of CTD profiles obtained from individual ITP units as of 1 October, 2012. Newly-deployed systems (8 in 2012) bias the median number per system low. (b) Lifetimes of individual ITP systems. The black bars mark the time span during which data were received from the underwater vehicle; the gray bars show the lifetimes of the surface buoys. Gaps in the figure represent ITP systems deployed in the Southern Ocean, Crater Lake, OR and Flathead Lake, MT.

Science Supported by the ITP Program

Data from ITPs, on their own or in conjunction with observations from other measurement systems (Ice-Based Observatories, ship, aircraft, remote sensing, etc), are increasingly being used in scientific analyses that span a wide range of temporal and spatial scales (Figure 3). A subset of that research is highlighted below.

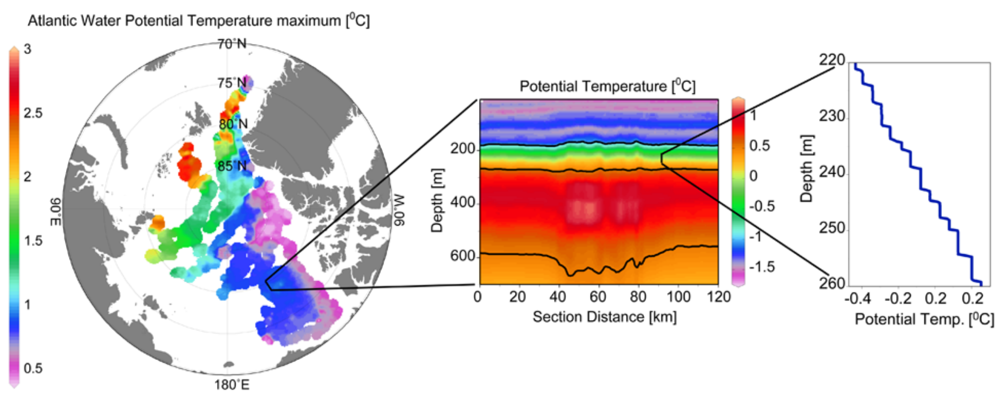

Figure 3: ITPs enable the study of ocean phenomena across a wide range of spatial scales: from the basin-scale circulation and properties (left: Atlantic Water temperatures across the Arctic measured by ITPs operating between 2004 – 2012), to mesoscale motions (middle: an Atlantic Water eddy of radius about 15 km sampled by an ITP), to the very small scales relevant to ocean mixing (right: ITPs resolve the finestructure of a double-diffusive staircase at the top boundary of the Atlantic Water layer.).

a. Basin- and Gyre-Scale Variability

Proshutinsky et al. (2009) investigated freshwater content changes that occurred in the Beaufort Gyre region since 2003. Observations from ITP instruments complemented shipboard measurements in building improved understanding of the year-round freshwater dynamics in the Beaufort Gyre. ITP data were used in order to estimate the rate of freshwater accumulation in the region. The analysis that used observations from 8 ITPs drifting in the region from 2003 to 2008 revealed a 1.93 m per year accumulation of freshwater in the center of the Beaufort Gyre. Morison et al. (2012) attribute much of this accumulation to wind-driven redistribution of river runoff.

(a) (b)

(c)

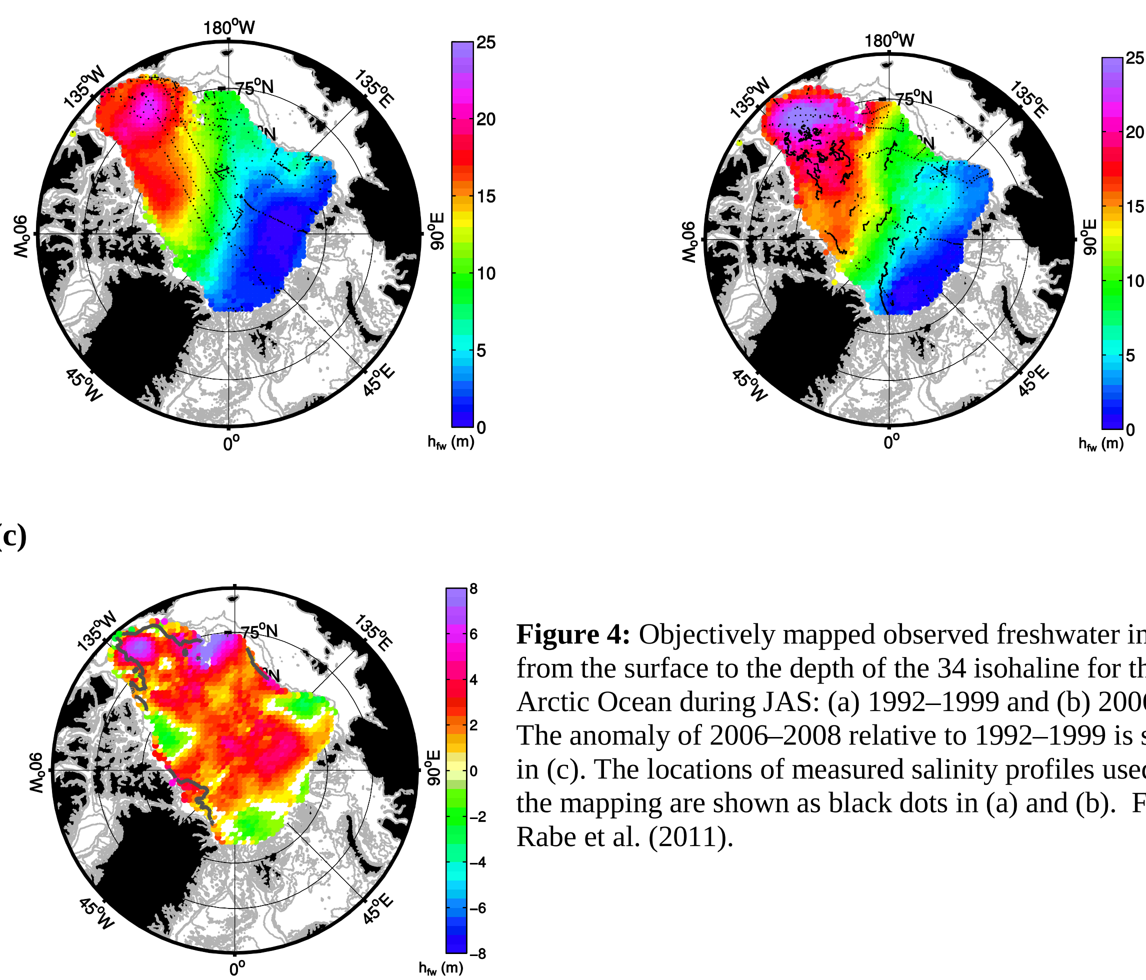

Figure 4: Objectively mapped observed freshwater inventory from the surface to the depth of the 34 isohaline for the deep Arctic Ocean during JAS: (a) 1992–1999 and (b) 2006–2008. The anomaly of 2006–2008 relative to 1992–1999 is shown in (c). The locations of measured salinity profiles used for the mapping are shown as black dots in (a) and (b). From Rabe et al. (2011).

Similarly, McPhee et al. (2009) reported 2008 observations from ITP instruments and airborne surveys obtained in the Canada and Makarov Basins indicating that total freshwater content had increased by as much as 8,500 km^3 in the area surveyed, effecting significant changes in the sea-surface dynamic topography including a 75% increase in steric level difference between the Canada to Eurasian Basins and a major shift in both surface geostrophic currents and freshwater transport in the Beaufort Gyre.

At larger scale, Rabe et al. (2010) combined ITP observations with hydrographic observations obtained from other autonomous instruments, manned icebreaker and aircraft surveys spanning the deep Arctic to construct a map of summer-season liquid fresh water content for the 2006-2008 period (Figure 4). In comparison to the summer seasons of 1992-1999, these authors found local increases in liquid fresh water within the Arctic region of 2 to 4 or more meters; summed over the Arctic they estimated a total fresh water volume increase of 8400 ± 2000 km^3, similar to McPhee et al.'s estimate. Such observations represent a reference point for climate models to accurately reproduce and ultimately explain the responsible mechanisms.

b. Upper Ocean Processes and Ice-Ocean Interactions

The sea ice cover in the Arctic exists in a sensitive balance between atmospheric cooling and the supply of ocean heat to the surface mixed layer. The Atlantic Water layer (AW) centered at 200-400 m depth constitutes the greatest ocean heat reservoir in the Arctic. Combining observations and models, Polyakov and coauthors (2010; 2012) suggested that the ocean upward heat flux from the AW has increased of late, possibly contributing to a thinning sea ice cover. In the western sector of the Arctic, shallower warm intrusions have become more prominent than AW. Due in part to greater area fraction of ice leads in summer, the Near Surface Temperature Maximum Layer (NTSM) in the Canada Basin has been strongly expressed of late (Jackson et al., 2010). Moreover, the Pacific Summer Water (PSW) Layer typically found below the NSTM at 50-75 m depth has warmed dramatically in recent years. Much of the NSTM is re-entrained into the mixed layer in fall causing delayed or reduced seasonal ice growth. An intense salinity stratification appears to be insulating the surface mixed layer and sea ice from PSW heat at present (Toole et al., 2010), but that may change in future if the Beaufort Gyre relaxes and exports its low salinity cap to other environs.

c. Eddies and Sub-Mesoscale Variability

Owing to their frequent sampling (two or more profiles per day) and the slow drift velocity of the supporting ice floes (typically 0.1 m/s or less), individual ITPs return hydrographic section data at unprecedented horizontal resolution (though at times, along a "drunken sailor" track depending on the vagaries of the ice drift). Timmermans et al. (2008a) exploited this characteristic to extract high-resolution transects across upper-ocean eddies in the Canada Basin from selected subsets of ITP observations that "cleanly" bisected these features. The full ITP data set supported an eddy census and map of eddy variability in the Canada Basin. In similar spirit, the high horizontal resolution ITP data were used by Timmermans et al. (2012) to characterize submesoscale variability in the Arctic surface layer and assess lateral restratification mechanisms.

d. Mixing Processes

High vertical resolution data from ITPs (raw data sampled at 0.25 m) are being used to investigate finescale mixing and stirring processes in the Arctic. Timmermans et al. (2008b) presented observations of the double-diffusive thermohaline staircase stratification above the core of the Atlantic Water Layer in the Canada Basin and estimated vertical heat and salt fluxes through this stratification. As testament to the achievable accuracy of *in situ* - calibrated conductivity data, temperature-salinity observations through the double diffusive staircase reveal remarkable lateral coherence with layer aspect ratios (thickness divided by width) of order 10^{-6} and a narrow range of lateral density ratio ($\beta S_x/\alpha\theta_x$) of around 4.0. Cole et al. (2012) explore surface layer turbulence and internal wave variability using data from an ITP additionally fitted with a velocity sensor.

e. Biogeochemical Observations

Seasonal and interannual variability in phytoplankton biomass and other bio-optical properties is poorly examined in perennially ice-covered regions of polar oceans, yet such data are critical for understanding climate-driven changes in polar pelagic ecosystems. Addressing this need, to date, 5 ITP systems equipped with a bio-optical sensor suite in addition to a CTD/O2 sensor have been deployed in the Arctic (Laney, et al., 2011; 2013ab). In addition, 3 ITPs have been deployed with a SAMI-CO2 sensor system fitted just below the ice-ocean interface (DeGrandpre et al., 2013). These systems are now providing the first, year-round measurements at daily resolution of phytoplankton biomass in the deep Arctic (directly monitoring the timing and magnitude of under-ice phytoplankton blooms and the subsequent export of particulate organic matter at the end of the growing season) and shedding light on the carbon cycle in this remote region.

f. Sea Ice Motion

In addition to ocean observations, hourly position data reported by ITP surface buoys are being used to validate and monitor the operational Sea Ice Drift products, including that of the International Arctic Buoy Program (IABP) and EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF, http://osisaf.met.no), Lavergne et al. (2010).

The Ice-Based Observatory Concept

As frequently as possible, ITPs are deployed together with other autonomous buoy systems to sample a wide range of variables characterizing the Arctic ocean-ice-atmosphere-eco- system. We term such collection of buoys an Ice-Based Observatory (IBO, see Proshutinsky et al., 2004). So far, 34 of the 59 ITP systems deployed in the Arctic have been accompanied by at least one companion instrument; 15 of these IBOs included 3 or more instrument systems. The prototypical example of an IBO is the collection of drifting buoys that have been deployed annually in conjunction with the North Pole Environmental Observatory program (http://psc.apl.washington.edu/northpole/). The April 2010 deployment included a NOAA-Pacific Marine Environmental Laboratory (PMEL) Web Cam and Polar Area Weather Station (PAWS - http://www.arctic.noaa.gov/gallery_np.html), a Cold Regions Research and Engineering Laboratory (CRREL) Ice Mass Balance Buoy (IMB - http://imb.crrel.usace.army.mil/), a Naval Postgraduate School (NPS) Autonomous Ocean Flux Buoy (AOFB - http://www.oc.nps.edu/~stanton/fluxbuoy/index.html) , and an ITP (#38). Timmermans et al. (2011) analyze data from this instrument collection to examine ice-ocean-atmosphere interactions and possible causes of upper-ocean freshening. In similar vein, Toole et al. (2010) jointly analyzed ITP, IMB and remote sensing data to investigate seasonal evolution of the ice-ocean system in the central Canada Basin. Clearly great synergy is achievable by co-locating instrument systems in IBO complexes and analyzing the resulting data in conjunction with remote sensing measurements and models within dynamical frameworks to build understanding of the Arctic climate system. In addition, the ITP program has in years past assisted with IMB, AOFB, O-Buoy (Knepp et al., 2010) and Up-Tempo (http://psc.apl.washington.edu/UpTempO/) buoy deployments within IBOs. We intend to continue to do so in future by engaging fellow AON scientists in planning field programs, sharing resources and maximizing efficiency.

Future Plans

The WHOI team has proposed to continue the Ice-Tethered Profiler observing program as a contribution to the Arctic Observing Network at the same level we have been operating these past 4 years: building and fielding 6 systems per year. We have nominally planned for 3 deployment expeditions per year - a spring ice camp operation supported by aircraft and two late-summer operations from icebreaker platforms of opportunity. We will do our best to distribute ITP systems over the deep Arctic but rely heavily on other national and international research programs to achieve good spatial coverage.

Our long-term goal for the international ITP program has been to maintain an array of approximately 18 fully-functioning ITP systems in the deep Arctic (Figure 5): an average of one instrument every 500 km (based on an ocean area of the deep Arctic of approximately 4 million km^2 - Jakobsson, 2002), which is the adopted correlation scale employed by Steele et al. (2001) when producing the PHC hydrographic climatology. For comparison, the Argo float program has a target of 300-km average spacing between floats at temperate and tropical latitudes, with higher density recommended at polar latitudes due to the smaller natural lateral scale (Rossby radius of deformation) of variability there. The Argo specification would seem to require an impractically-large array of 40 or more working systems in the deep Arctic. Note however that Argo floats typically return one vertical CTD profile every 10th day, whereas ITPs typically return 2 profiles per day. As a result, in the along-drift direction with ice floe speeds of around $0.1\ ms^{-1}$, ITPs generally return water column information at much better than 10 km horizontal resolution: adequate to resolve upper-ocean mesoscale eddies (Timmermans et al., 2008a) and even shed light on submesoscale mixed layer structures (Timmermans et al., 2012).

Figure 5: Simulated displacement (using monthly IABP ice-drift data) over a one-year period of 19 ITPs distributed about the ice covered Arctic Ocean in September. The grey vectors are annual IABP ice-drift averages. The wide solid line indicates the mean annual 90% ice concentration, and the broken line indicates 500 m bathymetry.

We have not conducted a formal objective array design assessment. Indeed, this is the current subject of an AON working group (see for example, Panteleev et al., 2012). For a prior proposal we carried out a preliminary assessment using the Environmental Working Group (EWG) hydrographic climatology and mean monthly IABP ice drifts. That study indicated that with 18-20 buoys distributed over the deep Arctic one is able to reproduce the EWG fields on a weekly basis. More fundamentally, we feel that an ITP array of the proposed scope is presently returning the necessary statistics about Arctic Ocean variability that such array design assessments require (for example, data to allow direct estimation of correlation scales and provide information to validate numerical simulations) as well as making new discoveries. Finally we note that theoretical array design studies usually do not take into consideration the constraints of actual field work, including the limited availability of platforms, and seasonal and distance restrictions.

Through the life of the ITP program, we have worked to expand the network beyond that funded by NSF. The ITP program has been greatly enhanced by contributions of ITP systems and fieldwork support by collaborators from Canada, Germany, France, United Kingdom, Russia, Norway and Iceland. We will strive to continue to involve these colleagues in future ITP activities. Within the U.S., our group has been successful obtaining additional Office of Naval Research funding to deploy ITP-V instruments within the Marginal Ice Zone process experiment. Though localized, these instruments will contribute to the ITP network during that field study period (2014) and we will continue to explore possibilities with the Navy for broad spatial monitoring by the ITP array.

The data reception, processing and distribution system now in operation for the ITP program will continue. In parallel with the operational work associated with building and fielding ITPs and processing/distributing the recovered data, we will continue to evolve the mechanical hardware, electronics and software of the ITP system over time to enhance system capabilities, improve reliability and control costs. For example, in past years we redesigned the ITP surface buoy to better survive the thinning Arctic sea ice environment (more conical shaped than the initial cylindrical buoy). Initial trials of this design in open-water deployments were promising: ITP # 37 survived fall freeze-up and collected 962 CTD profiles before the system dragged ashore in northern Svalbard. A companion system (# 36) deployed on the same cruise became over-rafted by ice but continued to profile and log data internally for several weeks afterwards. Those internally-recorded data were recovered when this buoy washed ashore in Iceland and was recovered. We used independent estimates of sea ice drift to estimate the location of those profiles that were acquired when the surface buoy was buried in ice (and thus unable to acquire GPS fixes).

In development now is a change to a different inductive modem specified to operate at significantly faster baud rate, which will improve the endurance of the underwater unit of the ITP by reducing the battery power needed to relay data to the surface buoy controller. Also nearing completion is a control system upgrade that will allow the shore-side operator to change the sampling scheme of ITP systems in the field. One immediate application we envision for this capability is to limit the depth excursions of a given ITP underwater vehicle when it looks like a system is about to drift into shallow water. Holding the ITP vehicle near the surface will hopefully keep it safe from dragging over shallows and being damaged or lost. Should the unit subsequently drift back into deep water, we could manually command it to resume deep profiling (subject to the wire tether being undamaged). Also on the near horizon is a change of the surface controller hardware to a more capable processor. The key new capability this will allow is data compression prior to Iridium telemetry. Tests with previously acquired data files from real deployments suggests ITP file sizes could be reduced by 50 to 75%, resulting in significant savings in telemetry costs and buoy power. Importantly, we will use loss-less compression techniques and so will still be recovering full-resolution, full-data rate observations. We hope to implement these enhancements to the ITP system in the coming years and devise additional improvements as the need and opportunity present.

Final Remarks

As described above, the ITP program is a key component of the AON: one that contributes to the "Observing Change" component of SEARCH. Like several other Arctic Ocean AON projects, the ITP program also contributes to the "Understanding Change" and "Responding to Change" components of SEARCH and is referenced (though not explicitly named) in the SEARCH Implementation Plan. Most importantly, continuing observations of the upper Arctic Ocean is undeniably essential to address the recently formulated draft SEARCH goal to "Improve Understanding and Prediction of Sea Ice Changes and the Consequences for Ecosystems, Human Activities, and Climate" and the previously formulated question "Is the Arctic System moving to a new state?" Together with other AON elements, we are well positioned to measure any new state of the Arctic climate system.

The ITP program has promoted widespread access to information about the Arctic Ocean to both researchers and the general public. On-going partnerships with European and Japanese investigators employing the WHOI ITP and other similar instruments holds promise for continued broad spatial coverage of the Arctic as well as strengthening international scientific collaborations. We will continue to use the ITP program to support outreach activities designed for both specialized and general audiences including giving briefings to teachers and science journalists, contributing to museum presentations, making school visits and ongoing evolution of our project web site *http://www.whoi.edu/itp*.

This is a remarkable time in the earth's climate system with global-scale changes in temperature and precipitation patterns underway. Climate models predict significant warming about the poles as a response to increased atmospheric greenhouse gas concentrations. Arctic sea ice extent shows a marked downward trend with time over the satellite era with a record minimum just recorded this past summer. It is imperative that we observe these changes in the Arctic atmosphere-ice-ocean system to document and understand what is now occurring and to improve our ability to forecast the future state. We argue that continuing the Ice-Tethered Profiler program within the Arctic Observing Network will contribute to this effort.

References

Boehme, L., P. Lovell, M. Biuw, F. Roquet, J. Nicholson, S. E. Thorpe, M. P. Meredith, and M. Fedak, 2009. Technical Note: Animal-borne CTD-Satellite Relay Data Loggers for real-time oceanographic data collection. Ocean Science Discussions, 6: 1261–1287. www.ocean-sci-discuss.net/6/1261/2009/

Cole, S. T., M.-L. Timmermans, J. M. Toole, R. A. Krishfield, and F. T. Thwaites, 2013. Ekman veering, internal waves, and turbulent fluxes observed under Arctic sea-ice. J. Phys. Oceanogr, in review.

DeGrandpre, M.D., Peterson, B., Beatty, C., Krishfield, R. and J. Toole, 2013. An Arctic Ocean Observing Network for Sea Surface pCO2 and pH. Poster presented at the Association for the Sciences of Limnology and Oceanography National Meeting, New Orleans, LA, February 2013.

Jackson, J. M., E. C. Carmack, F. A. McLaughlin, S. E. Allen, and R. G. Ingram, 2010. Identification, characterization and change of the near-surface temperature maximum in the Canada Basin, 1993–2008, Journal of Geophysical Research, 115, C05021, doi:10.1029/2009JC005265.

Jakobsson, M., 2002. Hypsometry and volume of the Arctic Ocean and its constituent seas, Geochem. Geophys. Geosyst., 3(5), 1028, doi:10.1029/2001GC000302.

Johnson, G. C., J. M. Toole, and N. G. Larson, 2007. Sensor corrections for Sea-Bird SBE-41CP and SBE-41 CTDs. Journal of Atmospheric and Oceanic Technology, 24, 1117-1130.

Knepp, T. N., J. Bottenheim, M. Carlsen, D. Carlson, D. Donohoue, G. Friederich, P.A. Matrai, S. Netcheva, D.K. Perovich, R. Santini, P.B. Shepson, W. Simpson, R. Stehle, T. Valentic, C. Williams, and P.J. Wyss, 2010. Development of an Autonomous Sea Ice Tethered Buoy for the Study of Ocean-Atmosphere-Sea Ice-Snow Pack Interactions: the O-buoy. Atmos. Meas. Tech., 3, 249–261.

Krishfield, R., S. Honjo, W.B. Tucker III, T. Nakanishi, T. Takizawa, 1993. Automated Ice-Ocean Environmental Buoys (IOEBs) for the Telemetry of Air, Ice and Ocean Data from the Polar Oceans. Proceedings of the IEEE Oceans '93 Conference, Vol. II: 47-52.

Krishfield, R., J. Toole, A. Proshutinsky & M.-L. Timmermans. 2008a. Automated Ice-Tethered Profilers for seawater observations under pack ice in all seasons Journal of Atmospheric and Oceanic Technology, 25: 2091-2095.

Krishfield, R., J. Toole, and M.-L. Timmermans. 2008b. ITP Data Processing Procedures. Unpublished manuscript available from http://www.whoi.edu/page.do?pid=23096

Laney, S., R. Krishfield, C. Ashjian, M.-L. Timmermans and J. Toole, 2011. Optical Assessment of Under-Ice Biology in the Arctic using Ice-Tethered Profilers. Poster presented at the 2011 AOMIP meeting, Woods Hole, MA.

Laney, S., J. Toole, R. Krishfield and C. Ashjian, 2013. Year-long monitoring of uncer-ice phytoplankton assemblages in the Arctic by Ice-Tethered Profilers. Paper presented at the Third International Symposium on Arctic Research (ISAR-3), Tokyo, January 15-17, 2013.

Laney, S.R., R.A. Krishfield, J.M. Toole, T.R. Hammar and C.J. Ashjian, 2013. Bio-optical Seasonality in Perennially Ice-Covered Arctic Ocean Ecosystems. in preparation.

Lavergne, T., S. Eastwood, Z. Teffah, H. Schyberg, and L.-A. Breivik, 2010. Sea ice motion from low-resolution satellite sensors: An alternative method and its validation in the Arctic, J. Geophys. Res.,115, C10032, doi:10.1029/2009JC005958.

McPhee, M. G., A. Proshutinsky, J. H. Morison, M. Steele, and M. B. Alkire, 2009. Rapid change in freshwater content of the Arctic Ocean. Geophys. Res. Lett., 36, L10602, doi:10.1029/2009GL037525.

Morison, J.H., S.P. Burke, H. Steltner and R. Andersen,1982. SALARGOS temperature-conductivity buoys, Proceedings of the IEEE Oceans `82 Conference, 1255-1260.

Morison, J., R. Kwok, C. Peralta-Ferriz, M. Alkire, I. Rigor, R. Andersen and M. Steele, 2012. Changing Arctic Ocean freshwater pathways. Nature,481, 66–70, doi:10.1038/nature10705

Panteleev, G., M. Yaremchuk, P. Posey and D. Nechaev, 2012. Toward optimization of observational arrays in the Arctic Ocean. Workshop presentation available from: http://www.arcus.org/files/page/documents/18998/nechaev_dmitri.pdf

Polyakov, I. V., and Coauthors, 2010. Arctic Ocean warming contributes to reduced polar ice cap. J. Phys. Oceanogr., 40, 2743–2756, doi:10.1175/2010JPO4339.1.

Polyakov, I., John E. Walsh, and Ronald Kwok, 2012. Recent Changes of Arctic Multiyear Sea Ice Coverage and the Likely Causes. Bulletin of the American Meteorological Society, DOI:10.1175/BAMS-D-11-00070.1.

Proshutinsky, A., A. Plueddemann, J. Toole, R. Krishfield, eds., 2004. Ice-Based Observatories: A strategy for improved understanding of the Arctic atmosphere-ice-ocean environment within the context of an Integrated Arctic Observing System. Woods Hole, Massachusetts: Woods Hole Oceanographic Institution, 65 pp.

Proshutinsky, A., R. Krishfield, M.-L. Timmermans, J. Toole, E. Carmack, F. McLaughlin, W. J. Williams, S. Zimmermann, M. Itoh, and K. Shimada, 2009. Beaufort Gyre freshwater reservoir: State and variability from observations, J. Geophys. Res., 114, C00A10, doi:10.1029/2008JC005104.

Rabe, B., M. Karcher, U. Schauer, J. M. Toole, R. A. Krishfield, S. Pisarev, F. Kaukera, R. Gerdes, and T. Kikuch, 2010. An assessment of pan-Arctic Ocean freshwater content changes from the 1990s to the IPY period. Deep Sea Res. Part I, 58, 173–185, doi:10.1016/j.dsr.2010.12.002.

Roemmich, D. and W. B. Owens, 2000. The Argo Project: global ocean observations for the understanding and prediction of climate variability. Oceanography, 13,45-50.

Roemmich, D., G. C. Johnson, S. Riser, R. Davis, J. Gilson, W. B. and S. L. G. Owens, C. Schmid, M. Ignaszewski, 2009. The Argo Program: Observing the global oceans with profiling floats. Oceanography, 22: 24-33.

Roemmich, D. and A. S. Team, 2009. Argo: The Challenge of Continuing 10 Years of Progress. Oceanography, 22: 46-55.

Steele, M., R. Morley, and W. Ermold, 2001. PHC: A global ocean hydrography with a high quality Arctic Ocean, J. Climate, 14, 2079-2087.

Thwaites, F. T., R. Krishfield, M.-L. Timmermans, J. M. Toole, and A. J. Williams 3rd, 2011. Flux Measurements from an Ice-Tethered Profiler: First Look, Proceedings Oceans 2011 IEEE-Santander Spain, 6-9 June 2011, IEEE/OES

Timmermans, M.-L., Toole, J., Proshutinsky, A., Krishfield, R. & Plueddemann, A., 2008a. Eddies in the Canada Basin, Arctic Ocean, observed from Ice-Tethered Profilers. Journal of Physical Oceanography, Vol. 38, No. 1, 133-145.

Timmermans, M.-L., J. Toole, R. Krishfield, and P. Winsor, 2008b. Ice-Tethered Profiler observations of the double-diffusive staircase in the Canada Basin thermocline. Journal of Geophysical Research, Vol. 113, C00A02, doi:10.1029/2008JC004829.

Timmermans, M.-L., R. Krishfield, S. Laney, and J. Toole, 201. Ice-Tethered Profiler Measurements of Dissolved Oxygen under Permanent Ice Cover in the Arctic Ocean, J. Atmos. Oceanic Technol., 27(11), 1936.

Timmermans, M.-L., A. Proshutinsky, R.A. Krishfield, D.K. Perovich, J.A. Richter-Menge, T.P. Stanton and J.M. Toole. 2011. Surface freshening in the Arctic Ocean's Eurasian Basin: an apparent consequence of recent change in the wind-driven circulation. Journal of Geophysical Research, 116, C00D03, 1, doi:10.1029/2011JC006975 doi:10.1029/2011JC006975.

Timmermans, M.-L., S. Cole and J. Toole, 2012. Horizontal density structure and restratification of the Arctic Ocean surface layer. Journal of Physical Oceanography, 42, 659–668.

Toole, J. M., M.-L. Timmermans, D. K. Perovich, R. A. Krishfield, A. Proshutinsky, and J. A. Richter-Menge, 2010. Influences of the ocean surface mixed layer and thermohaline stratification on Arctic Sea ice in the central Canada Basin, J. Geophys. Res., 115, C10018, doi:10.1029/2009JC005660.

Toole, J.M., R.A. Krishfield, M.-L. Timmermans, and A. Proshutinsk, 2011. The Ice-Tethered Profiler: Argo of the Arctic. Oceanography 24(3):126-135, http://dx.doi.org/10.5670/oceanog.2011.64.