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# THE ICE-TETHERED PROFILER: ARGO OF THE ARCTIC

BY JOHN M. TOOLE, RICHARD A. KRISHFIELD,
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Figure 1. (a) Schematic drawing of the Ice-Tethered Profiler system with components labeled. Photographs of (b) the underwater profiling module being attached to the wire-rope tether during deployment and (c) the final buoy installation (present surface buoy design), the latter with CCGS *Louis S. St-Laurent* in the background.
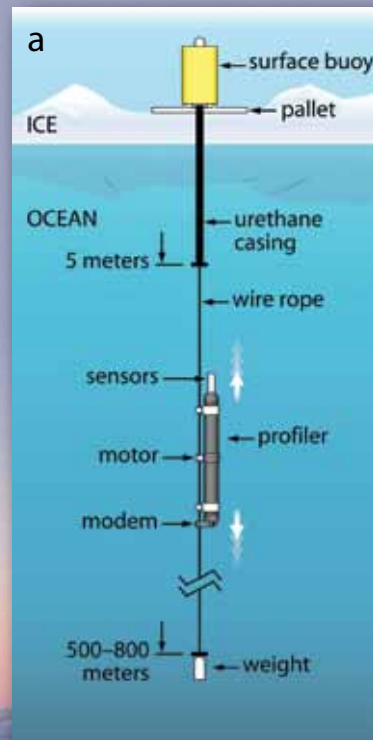
**ABSTRACT.** Ice-Tethered Profilers (ITPs), first deployed in fall 2004, have significantly increased the number of high-quality upper-ocean water-property observations available from the central Arctic. This article reviews the instrument technology and provides a status report on performance, along with several examples of the science that ITPs and companion instrumentation support.

## INTRODUCTION

At the turn of the last century, the international Argo float program was beginning to make good on its promise to return upper-ocean water properties and circulation information at ~ 300 km horizontal resolution and ~ 10-day intervals throughout the temperate seas (Roemmich and Owens, 2000). Indeed, Argo has been very successful this last decade (Roemmich et al., 2009), with a maintained array of more than 3,000 operational floats that has to date returned some 700,000 usable temperature and salinity profiles that have fueled an exponential growth in the number of published science papers that use those data (total number of papers is now around 700), though the challenge of sustaining the array is ever present (Roemmich and the Argo Steering Team, 2009). Due to the requirement that floats surface for positioning and data telemetry, Argo has not ventured very far north into the Arctic because of the extensive sea ice cover there. However, 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 use 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. Here, we present a status report for one of these systems—the Woods Hole Oceanographic Institution (WHOI) Ice-Tethered Profiler—along with highlights of some scientific analyses based on data obtained by these instruments. We note that complementary data are being collected in the Arctic by Polar Ocean Profiling Systems (POPS) buoys, an instrument system developed jointly by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Metocean Services International (Kikuchi et al., 2007).

## ITP TECHNOLOGY, DEPLOYMENT PROCEDURES, AND DATA PROCESSING

Krishfield et al. (2008a) describe the Ice-Tethered Profiler (ITP) technology in detail. Briefly, the system consists of three main components: a surface instrument package that typically sits atop an ice floe, a weighted, wire-rope tether of arbitrary length (up to 800 m) 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 that houses a controller, inductive modem electronics, a GPS receiver, and an Iridium satellite phone with associated antennae and batteries within a watertight aluminum housing capped by an ultra-high-molecular-weight (UHMW) polyethylene dome. The electronics case sits within a foam body designed to provide buoyancy for the plastic-jacketed wire rope tether and end weight should the ice fracture or melt, and to provide modest protection in the event of ice ridging.

The ITP tether is constructed from conventional ¼ in (.6 cm) diameter plastic-jacketed wire rope commonly used in ocean mooring applications. The upper 5 m of the wire tether is cast within a 3.5 in (8.75 cm) thick protective urethane jacket that also houses an electrical ground lead for the inductive modem. A custom termination is used to mechanically join the tether to the surface unit and preserve the electrical isolation of the wire tether from seawater. A 250 lb (112.5 kg) ballast weight (made up of 50 lb [22.5 kg] plates to facilitate transportation) is fixed to the bottom wire termination to add tension to the wire and minimize its catenary when the supporting ice floe moves.

The profiler unit (much like an Argo float in shape and size) mounts on the tether and cycles vertically along it. Unlike a float or the profiling module of the POPS instrument, which adjust buoyancy to profile, ITP uses a small traction drive wheel mounted midway

along its body to move up and down. Typically, the drive system draws only 1 W of power as an ITP profiles at 0.25 m s⁻¹. ITP employs the same conductivity-temperature-depth (CTD) sensor package that is currently used on many of the Argo floats (the Sea-Bird Electronics Inc. model 41-CP) mounted in the instrument's top hemispherical end cap. A subset of the systems deployed in the Arctic have additionally carried a dissolved oxygen sensor integrated into the CTD, the SBE model 52-MP (Timmermans et al., 2010); a subsystem to acquire bio-optical information is in development. Two prototype instruments that were also equipped with a Nobska Inc. MAVS acoustic current meter have been fielded. Each ITP is designed to return 1,600 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 supporting ice floe survives this long). Via an inductive modem, the raw CTD and associated engineering data files are relayed from the underwater vehicle to the surface buoy at the completion of each one-way profile, which then transmits them to a logger computer at WHOI by satellite. In addition to full-resolution CTD and engineering profile data transmitted to shore, the ITP surface unit sends a daily status message that includes hourly position estimates. At regular

intervals, the data files that arrived on the WHOI logger computer are accessed by a separate computer that unpacks the binary data files, performs basic edits, averages the profile data into uniformly incrementing pressure bins, produces 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 (http://www.whoi.edu/itp) where additional documentation of the data processing procedures is available. The Global Telecommunications System is distributing decimated versions of the real-time data. Because all acquired data are transmitted to shore at full resolution and the hardware is relatively low cost (in comparison to ship time), ITP systems may be considered expendable (thus alleviating the need for expensive recovery operations to collect the data).

Most commonly, ITPs are deployed on multiyear ice floes after augering an 11 in (27.5 cm) diameter hole in the ice. As a test in late August 2009, two ITP systems (#s 36 and 37) were deployed in open water between 78 and 82°N, 120 and 125°E from I/B *Kapitan Dranitsyn* in conjunction with the Nansen and Amundsen Basins Observational System project (NABOS; http://nabos.iarc.uaf.edu). This generation ITP was fitted with a conical flotation element, as opposed to the cylindrical shape of the original design (Figure 1). Both systems reported data

daily prior to October 13, although some of the CTD profiles were not full range because the underwater unit was moved along the wire while resting between profiles by surface-wave heaving of the buoy and tether. Communications from ITP #36 ceased at this point, perhaps because the buoy was over-rafted by sea ice. ITP #37 survived the fall 2009 freeze-up and collected and transmitted a total of 961 CTD profiles up until December 24, 2010, when the underwater unit appears to have been damaged or lost as the system dragged over shallow water bathymetry between Franz Joseph Land and Spitsbergen. To improve survivability in thin ice and open water, the ITP surface buoy was again redesigned after this experience to increase its buoyancy and allow the surface buoy to sit even higher in open water. A separate engineering effort to allow real-time user modification of the profiling parameters is underway. The idea here is to restrict the maximum profiling depth of the underwater vehicle when it appears that a given system will drift over shallow bathymetry.

At irregular intervals, the real-time data from ITPs are reprocessed to derive and apply sensor calibration adjustments and edit segments of bad data (typically where the CTD sensor has been fouled by foreign material.) A handful of ITP systems have been recovered. Post-recovery laboratory calibrations of the temperature and pressure sensors from these instruments indicate drifts of 1–2 millidegree C and around 1 dbar, respectively, over time periods of two to three years. To date, no attempt has been made to adjust ITP temperature and pressure data for these small shifts in sensor calibration. Conductivity sensor data are adjusted on a profile-by-profile

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basis using, as reference, mapped potential conductivity on selected deep potential isotherms (source data being roughly contemporaneous calibrated ship CTD data) as described by Krishfield et al. (2008b). (A similar procedure is carried out to derive oxygen sensor calibration adjustments.) After applying conductivity calibration adjustments, the resultant ITP salinity data have an uncertainty (relative to the ship data) of 0.005 or less. When reprocessed, the "final" ITP data are made available on the program Web site and are submitted to national data facilities for archiving. Work is currently underway to submit ITP observations to the Argo data system in parallel.

## ITP PERFORMANCE AND DATA RETURN

Thus far, a total of 41 ITP instruments have been deployed in the Arctic (between August 2004 and October 2010) by researchers from Germany, France, Great Britain, Russia, and the United States. By agreement, all data from ITP instruments are routed through servers based at WHOI and immediately made publicly available. As of this writing, ITPs deployed in the Arctic have attempted more than 30,000 CTD profiles between ~ 7 and 750 m depth (Figure 2). Of these, approximately 80% returned usable temperature and salinity data over a

vertical interval greater than 700 m. Including those systems still operational (and thus biasing the following mean estimates low), the average lifetime of the ITP surface buoy (time over which telemetry is received) is 500 days; the average number of CTD profiles longer than 700 m received per instrument deployment is 741. In comparison to traditional sampling from icebreakers and aircraft, the ITP array is returning significantly more data from the central Arctic over all seasons (Figure 2). As deployed to date with long tethers, ITPs are not well suited to sample the broad, shallow continental shelves that surround the Arctic; alternate technology is needed there.

There is a wide distribution in ITP lifetimes and CTD data recovery (Figure 3). Commonly, the surface buoy functions for longer time periods than data are received from the underwater profiling module. Reasons for data termination
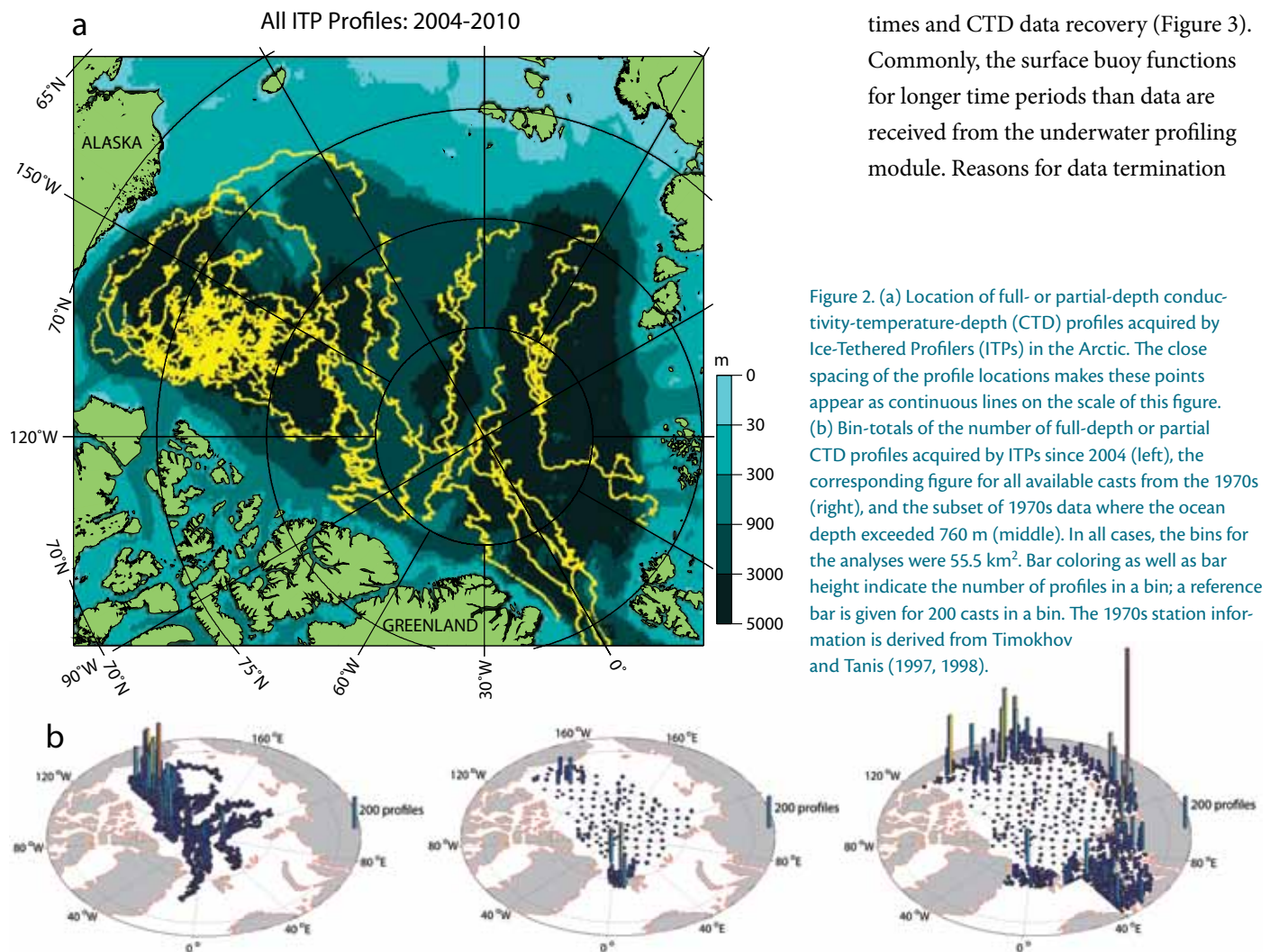


a
All ITP Profiles: 2004-2010

Figure 2. (a) Location of full- or partial-depth conductivity-temperature-depth (CTD) profiles acquired by Ice-Tethered Profilers (ITPs) in the Arctic. The close spacing of the profile locations makes these points appear as continuous lines on the scale of this figure. (b) Bin-totals of the number of full-depth or partial CTD profiles acquired by ITPs since 2004 (left), the corresponding figure for all available casts from the 1970s (right), and the subset of 1970s data where the ocean depth exceeded 760 m (middle). In all cases, the bins for the analyses were 55.5 km$^2$. Bar coloring as well as bar height indicate the number of profiles in a bin; a reference bar is given for 200 casts in a bin. The 1970s station information is derived from Timokhov and Tanis (1997, 1998).

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are varied. Only three systems 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. In addition, the surface electronics packages from another three systems were recovered (two after washing up on Iceland, the other by the Canadian Coast Guard south of Nares Strait). The wire rope tethers of two of the latter had broken, likely during ice-rafting events. Indeed, tether-breaking is believed to be responsible for many of the premature stoppages of CTD data acquisition. The underwater unit of the third recovered surface electronics package was lost, presumably when that system dragged over shallow water bathymetry while transiting Nares

Strait. In total, the underwater vehicles of eight ITP systems have been damaged or lost communication after dragging.

Remarkably, eight 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 (acquired while the surface unit was buried in ice—obviously, the rafting did not immediately sever the tether in these

cases). However, these GPS receivers, when buried by ice, were unable to fix the locations of these instruments, requiring use of data from collocated instruments or independent ice-drift estimates to derive positions for those CTD profiles. Similarly, the ITP underwater unit will store data if the inductive modem subsystem fails. Full records of profile data were extracted from those recovered ITP systems that had experienced modem problems. The recovered data from reborn and recovered ITPs are included in the statistics reported above.

## 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-ecosystem. We term such collection of buoys an Ice-Based Observatory (IBO; see Proshutinsky et al., 2004). In total, 22 of the 41 ITP systems deployed thus far in the Arctic have been accompanied by at least one companion instrument; 15 of these IBOs included three 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 (1) a National Oceanic and Atmospheric Administration (NOAA)-Pacific Marine Environmental Laboratory (PMEL) Web Cam, (2) a Polar Area Weather Station (PAWS; http://www.arctic.noaa.gov/gallery_np.html), (3) a Cold Regions Research and Engineering Laboratory (CRREL) Ice Mass Balance Buoy (IMB; http://



Figure 3. (a) Histogram of the number of conductivity-temperature-depth (CTD) profiles exceeding 700 m in vertical extent obtained from individual Ice-Tethered Profiler (ITP) units. (b) Lifetimes of individual ITP systems. The blue bars mark the time span during which data were received from the underwater vehicle; the gray bars show the lifetimes of the surface buoys. ITP units #1 and #2 are shown swapped in this panel for visual esthetics. Gaps in the figure represent ITP systems deployed in the Southern Ocean or Crater Lake, OR.

imb.crrel.usace.army.mil), (4) a Naval Postgraduate School (NPS) Autonomous Ocean Flux Buoy (AOFB; http://www.oc.nps.edu/~stanton/fluxbuoy), and (5) an ITP (#38) (Figure 4). This collection of instrumentation was deployed on a 1.7 m thick ice floe in the Transpolar Drift on April 19, 2010, at 88°39.4'N, 145°35.7'E. Over the following nine months, the IBO drifted south while sampling the full summer melt and fall refreeze cycles, eventually passing through Fram Strait. As melting, fracturing, and rafting events slowly destroyed the supporting ice floe, the various IBO systems dropped offline; contact with the underwater unit of

ITP 38 was lost on December 28, 2010, when the unit dragged onto the East Greenland shelf. As of this writing, the ITP's surface buoy continues to send its daily status message.

## SCIENCE HIGHLIGHTS FROM ITPs AND IBOs

Data from ITPs, on their own or in conjunction with observations from other measurement systems (e.g., IBOs, ships, aircraft, remote sensing), are increasingly being used in scientific analyses. In one analysis example of basin-scale variability, Rabe et al. (2011) combined recent ITP observations with hydrographic observations obtained

from other autonomous instruments and manned icebreaker and aircraft surveys to construct a map of summer-season liquid freshwater content for the 2006–2008 period (roughly corresponding to the International Polar Year; Figure 5). In comparison to the summer seasons of 1992–1999, these authors found local increases in liquid freshwater within the Arctic region of 2 to 4+ m; summed over the basin, this translates to a total volume increase of 8,400 ± 2,000 km$^3$. Such observations provide reference points for climate models to accurately reproduce and ultimately explain the responsible mechanisms.
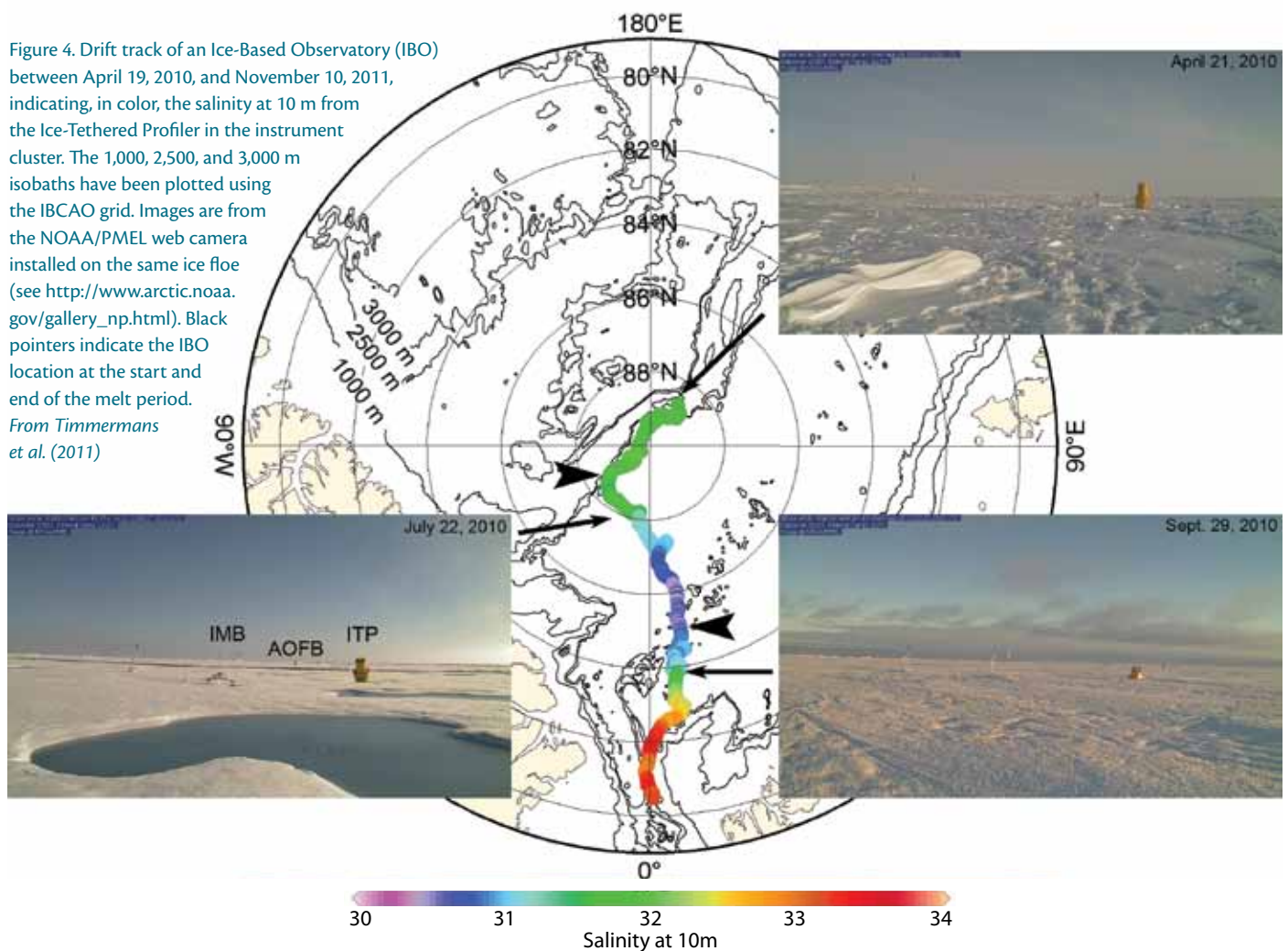
The Rabe et al. (2011) maps highlight



Figure 4. Drift track of an Ice-Based Observatory (IBO) between April 19, 2010, and November 10, 2011, indicating, in color, the salinity at 10 m from the Ice-Tethered Profiler in the instrument cluster. The 1,000, 2,500, and 3,000 m isobaths have been plotted using the IBCAO grid. Images are from the NOAA/PMEL web camera installed on the same ice floe (see http://www.arctic.noaa.gov/gallery_np.html). Black pointers indicate the IBO location at the start and end of the melt period. *From Timmermans et al. (2011)*

Salinity at 10m

the Beaufort Gyre in the Canada Basin as a key region of liquid freshwater storage. Proshutinsky et al. (2009) focused on this region, finding evidence for an increase in liquid freshwater from 2003 to 2008. More recent observations suggest the rate of increase has slackened or even reversed. Part of the variability in Arctic liquid freshwater content is mirrored by changes in sea ice thickness. The IBO marriage of ITP, IMB, and AOFB instruments is ideal for quantifying these changes in water state and their relationships to upper-ocean salinity. For example, from the repeated IBO observations in conjunction with the North Pole Environmental Observatory, Timmermans et al. (in press) report a recent mixed-layer freshening along the prime meridian (Figure 4) significantly greater than can be accounted for by ice and snow melt that might result from a release of waters that had previously been accumulated in the Beaufort Gyre.

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 centered at 200–400 m depth constitutes the greatest ocean heat reservoir in the Arctic, but shallower warm intrusions may recently have become more important in the western sector. Due in part to a greater fraction of ice leads in the area in summer, the Near-Surface Temperature Maximum Layer (NSTML) in the Canada Basin has been strongly expressed of late (Jackson et al., 2010; Figure 6). Moreover, the Pacific Summer Water (PSW) layer typically found at 50–75 m depth has warmed dramatically in recent years. Much of the NSTML is re-entrained into the mixed layer in fall, causing delayed or reduced seasonal ice growth; intense salinity stratification appears to be isolating the PSW heat so far (Toole et al., 2010), but that may change in future.

Because of their frequent sampling (two or more profiles per day) and the slow drift velocity of the supporting ice floes (typically 0.1 m s$^{-1}$), 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. (2008b) 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 (Figure 7). One goal of the development effort to add a velocity sensor to the ITP is to directly measure the currents associated with these features (to complement cyclo-geostrophic estimates such as shown in Figure 8) and better infer eddy center positions and radii (see Plueddemann et al., 1998; Krishfield et al., 2002).

In similar spirit, the unprecedented high vertical resolution data from ITPs (nominally 0.25 m) are being used to investigate fine-scale mixing and stirring processes in the Arctic, as well as to quantify the response
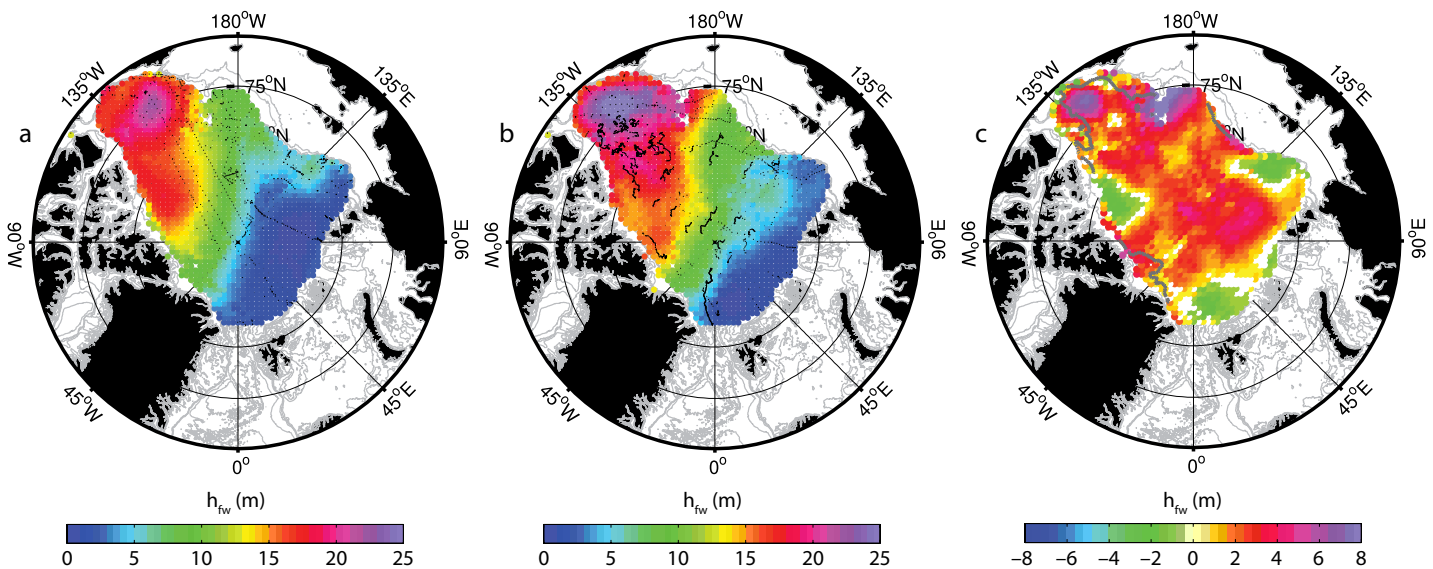


Figure 5. Objectively mapped observed freshwater inventory from the surface to the depth of the 34 isohaline for the deep Arctic Ocean during July-August-September (JAS): (a) 1992–1999 and (b) 2006–2008. The anomaly of 2006–2008 relative to 1992–1999 is shown in (c). The locations of measured salinity profiles used for the mapping are shown as black dots in (a) and (b). *From Rabe et al. (2011)*

characteristics of the SBE-41CP CTD (Johnson et al., 2007). Timmermans et al. (2008a) presented observations of the double-diffusive thermohaline staircase stratification above the core of the Atlantic Water layer in the Canada Basin (Figure 8), 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 these structures 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.
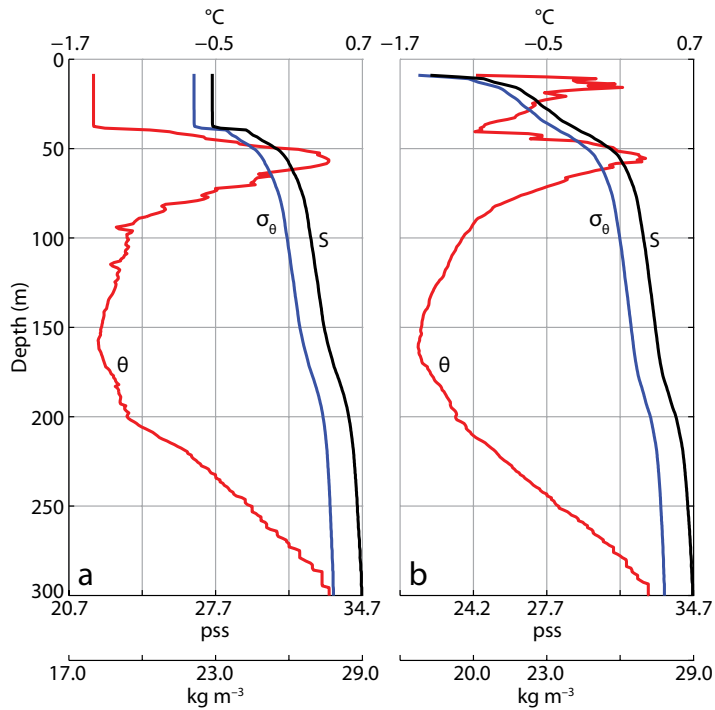


Figure 6. Representative vertical profiles of potential temperature (red), salinity (black), and potential density anomaly (blue) obtained from ITP #6 on (a) April 30, 2007 and (b) September 13, 2007. These were ITP #6 profiles 475 and 747, respectively; both were taken within 25 km of 76°24'N, 140°45'W. *From Toole et al. (2010)*
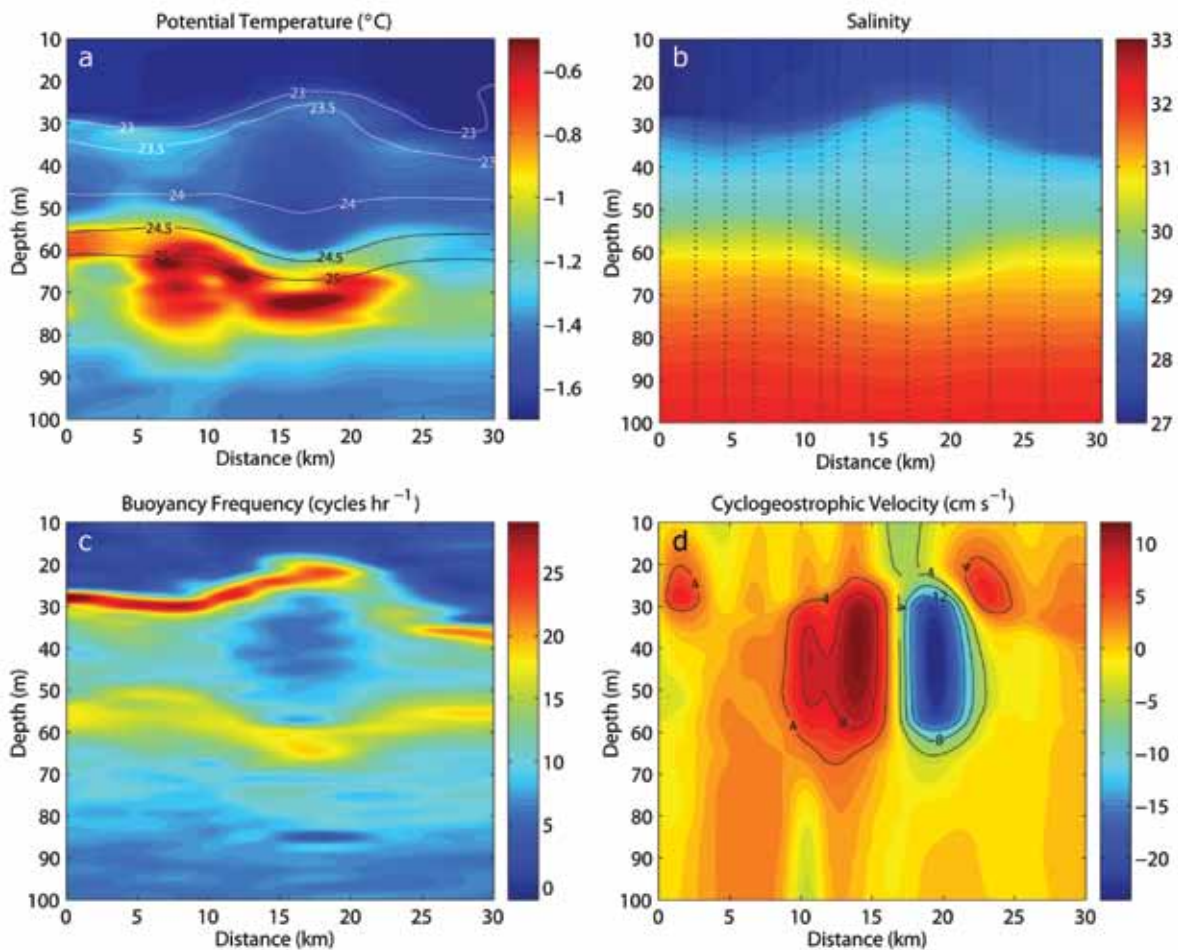


Figure 7. Ice-Tethered Profiler-derived sections of (a) potential temperature, (b) salinity, (c) buoyancy frequency, and (d) cyclogeostrophic velocity through a pycnocline eddy in the Canada Basin. Lines of constant potential density (referenced to the surface) are shown in (a). The section is from west (left) to east, and dotted lines in (b) indicate profile locations. *From Timmermans et al. (2008b, © January 2008 American Meteorological Society)*

Figure 8. (a) Ice-Tethered Profiler (ITP) profiles of potential temperature and salinity in the Canada Basin. The insets with expanded scales show the double-diffusive staircase. In these profiles, the Arctic surface mixed layer extends to about 40 m depth, with shelf-modified Pacific water from Bering Strait immediately below. A strong thermocline denotes the boundary between the upper waters and the Atlantic Water. Within the thermocline, temperature and salinity increase monotonically with depth, a necessary condition for double-diffusive layering. (b) The corresponding potential temperature/salinity curve and lines of constant potential density anomaly (referenced to the surface). (c) Discrete potential temperature/salinity values from 1000 ITP profiles in the Canada Basin (~ 0.25 m vertical resolution), and lines of constant potential density anomaly (referenced to the surface). The region in potential temperature/salinity space is shown by the grey box in panel (b). Staircase mixed-layer properties tend to group along lines in potential temperature/salinity space; Timmermans et al. (2008a) show that individual mixed-layers are coherent for at least 800 km across the basin and persist for several years. *After Timmermans et al. (2008b)*
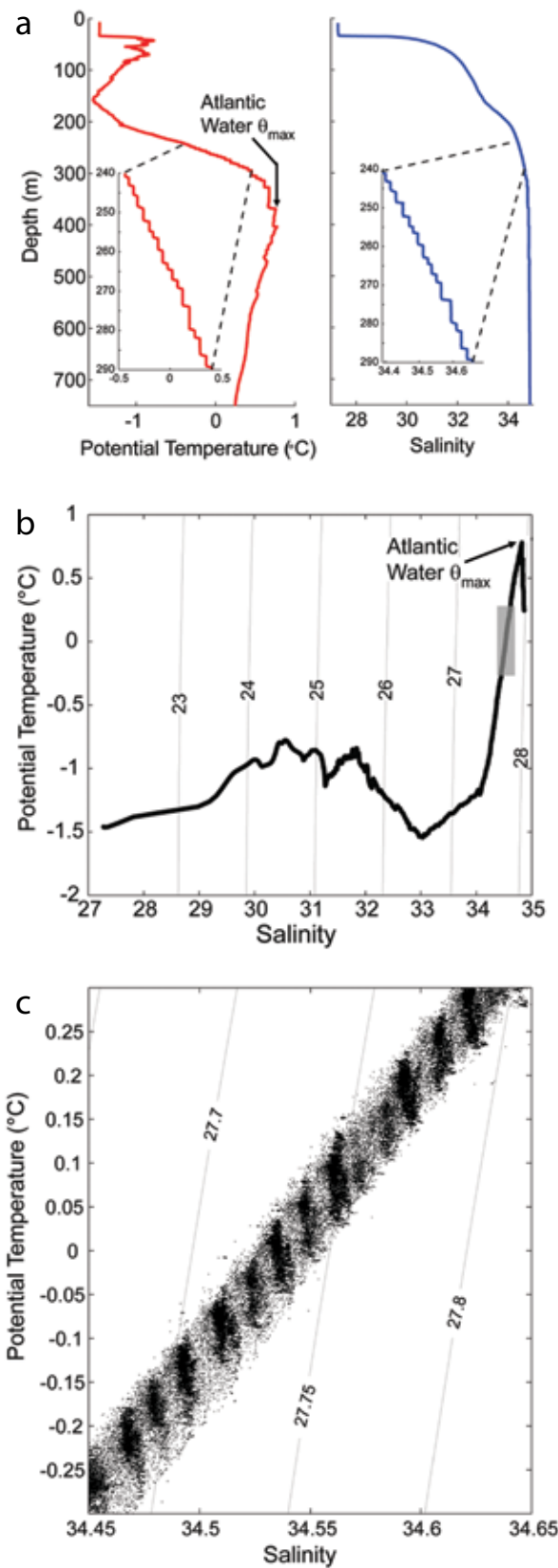
As evidenced by this brief synopsis of analysis activities, ITPs, particularly when integrated within IBO instrument clusters, are enabling significant advances in our understanding of the Arctic system from basin to centimeter scales.

## FUTURE PLANS

ITP systems and companion instruments continue to be deployed under the banners of the US Arctic Observing Network (AON) and internationally under SAON (Sustaining Arctic Observing Networks) and country-specific programs. Like Argo, continued effort is necessary to sustain the deep Arctic sampling effort. Also, as Figure 2 dramatizes, there remains a need for technologies able to return observations in the seasonal ice cover zone and, in particular, over the shallow continental shelves. ITPs deployed with much shorter tethers might be one approach.

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