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# Ice-tethered observational platforms in the Arctic Ocean pack ice

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**Abstract:** The Arctic Ocean faces rapid climate change, which impacts both physical and biological components of the marine ecosystem. Due to complicated and costly logistics inherent to sampling ice-covered areas, most studies conducted in the Arctic are based on relatively short-term sampling (weeks to months) centered around the minimum ice season. Given the need for longer-term monitoring, several autonomous ice-tethered observational platforms have been developed and deployed in the Arctic since the last decade. This review outlines their abilities, conception, and limitations. Most platforms were developed to measure physical data, which highlights a critical need for ice-tethered observatories monitoring biological processes.

*Keywords:* Arctic, Ice-tethered platforms, Biosphere, Cryosphere, Autonomous observations.

## 1. INTRODUCTION

The complex interactions within and between the biosphere, hydrosphere and cryosphere are central, yet poorly understood, features of the Arctic Ocean. Environmental variability and change result from the dynamic and complex interactions between these realms in time and space. A perturbation in one or more may propagate and amplify through complex interactions, resulting in disproportionately large changes and/or regime shifts (Duarte et al., 2012). The fast warming of the Arctic and loss of sea ice (Parkinson et al., 2013) are two well-documented examples of such amplifications, potentially affecting most living organisms in the region. There is already evidence for altered pelagic and benthic trophic dynamics due to changes in primary productivity, biomass and biodiversity, species range expansions, shifts in phenology cascading through trophic levels, and an increased zooplankton diel vertical migration affecting the biological pump (Brierley et al., 2009, Wassmann et al., 2011, Kortsch et al., 2012).

Several observations and predictions suggest that an *ice-free Arctic summer* is likely to occur within the next few decades (e.g. Cavalieri et al., 2012), posing even more *significant consequences and challenges for ice-adapted flora and fauna*. A suite of animal taxa depends on the sea ice habitat for food and reproductive success, and some complete their entire life cycles in association with the ice (Bluhm et al., 2011). The current reduction of Arctic sea ice is, thus, likely to have both direct and indirect impacts on marine organisms, their interactions and ultimately ecosystem processes (Slagstad et al., 2011). However, such ecosystem effects resulting from climate change have been primarily considered from the perspective of the polar summer, while the polar winter has essentially remained a black box (Berge et al., 2015) – *a box that is rarely considered and less frequently opened*. Autonomous observational platforms deployed in the Arctic Ocean to monitor several seasons or a complete annual cycle have the capability to fill this seasonal gap. Detecting and characterising climate and ecosystem variability and/or change requires long-term observations on seasonal, interannual, and decadal time scales. Inherently, such observations are challenging to obtain in any system, but especially so in the ice-covered Arctic Ocean. Technological advances have resulted in great strides in physical measurements of atmospheric, hydrographic, and sea ice properties, but biological measurements are lacking (Grebmeier et al., 2010; Wassmann et al., 2011). Yet, the need for providing answers on ecosystem response to climate variation (e.g. light regime, temperature and ice cover) and change has never been greater than in this era of rapid increase of the human footprint in all areas of the Arctic marine ecosystem (Ruddiman, 2013). Our view of the Arctic is shaped by summer studies that capture only a part of the highly seasonal production and life cycles of Arctic biota (Berge et al., 2015). Highly seasonal patterns are particularly obvious in the development of the spring bloom and its subsequent fate, DVM, ontogenic migrations, reproductive cycles, body composition such as lipid content, etc., and stress the need for seasonal coverage. Based on this incomplete seasonal coverage, we have been extrapolating estimates of total primary and secondary production, and essentially have made educated guesses on biological activity in the missing seasons. The few seasonal and interannual studies available (e.g. Rozanska et al., 2009, Kortsch et al., 2012, Laney et al., 2014, CASES, CFL, Tara Oceans Polar Circle, N-ICE) document the challenge of separating variability from long-term change and provide context for the short point-in-time studies that prevail (Grebmeier et al., 2015).

Pioneered by Nansen from the *Fram* during its ice-drift, sampling across the Arctic Basin became increasingly important in the latter half of the 20th century. Historically, drifting platforms have played a key role for the exploration and scientific discoveries in the Arctic. The Transpolar Drift was documented by the Fram expedition's unanticipated drift with the sea ice, and drifters on the ice have demonstrated close connections between the Kara Sea and the Fram Strait (Vize, 1937). In 1957, the US initiated their first year-round drifting scientific base when the Fletcher ice Island T-3, last visited in 1979, was established (Crary et al 1952). Since 1937, Russian drift ice stations (Frolov et al., 2006) have been instrumental in documenting that Atlantic water is circulating in the Eurasian Basin, and returning into the Fram Strait on the Greenland side as Arctic Intermediate Water (e.g. Proshutinsky et al., 1999). Since 2002, autonomous platforms have been developed and deployed to monitor the Arctic Ocean during the ice season. Here, we review these and outline their abilities, conception, and limitations. The review is based on information available through published descriptions / sources, resulting in a sometime uneven level of detail in the descriptions.

## 2. DESCRIPTION AND APPLICATIONS OF EXISTING PLATFORMS

### *2.1 WHOI's ice-tethered profiler (ITP)*

The Woods Hole Oceanographic Institution's (WHOI, USA) Ice-Tethered Profilers (ITP) were developed and deployed for the first time in 2004 (Krishfield et al., 2008). The ITP is designed to measure temperature and salinity down to 800m depth, and is based upon the ARGO float (Roemmich et al., 2009) which essentially is an autonomous undulating temperature and salinity profiler that transmits data in semi real-time via the Iridium network to a ground station. In 2004 and 2005, three ITP prototypes were deployed in the central Arctic Ocean, and two units were still functional after 10 months and 1200 profiles. Based on the WHOI-developed Moored Profiler (Krishfield et al., 2008), the ITP system consists of three components: (1) an above-ice unit that is frozen into an ice floe and houses a GPS, controller and data telemetry electronics, (2) a weighted, plastic-jacketed wire-rope of up to 800m in length suspended from the surface instrument, and (3) an instrumented underwater unit that profiles up and down the wire tether at a user-selected frequency. The profiling underwater unit has similar shape and dimensions as an ARGO float, except that the float's variable-buoyancy system is replaced with a traction-drive unit (Krishfield et al., 2008). Between 2004 and 2008, a total of 30 ITPs were deployed in the Arctic Basins (Rachold et al., 2011) with an autonomy of up to 3 years (Timmermans et al., 2011), and the last deployment of an ITP was in September 2015. In 2011/2012 a set of upgraded ITPs with instruments for biological measurements got deployed. The upgraded ITPs included ECOtriplets measuring chlorophyll and dissolved organic matter fluorescence and optical scatter. In addition a PAR and dissolved oxygen sensor was attached (Laney et al, 2014). Several upgraded ITPs are still operational today. Many ITP deployments are accompanied by SIMBA (see below) deployments to study variations in ice thickness. For further details about specifications of the ITPs and online data see http://www.whoi.edu/itp or key references (Krishfield et al., 2006; Williams et al., 2010; Jackson et al., 2012; Timmermans et al 2010).

### *2.2 AWI's ice-tethered acoustic current profiler (ITAC)*

*The Ice-Tethered Acoustic Current Profiler (ITAC) was developed by the Alfred Wegener Institute (AWI, Germany) within the DAMOCLES programme (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies,* www.damocles-eu.org*) for the International Polar Year 2007-2008. The system was designed by Optimare Sensorsystem AG (Germany) in collaboration with AWI. The main purpose of the ITAC was to measure ocean velocities in the upper 500m using a RDI 75 kHz Long Ranger Acoustic Doppler Current Profiler (Rachold et al., 2011). The system includes two separate GPS units to account for the ice floe orientation and horizontal drift. The ITAC was deployed three times, with a prototype deployed for the first time over a period of three months in 2007. The other two deployments, in 2008 and 2011 failed.*

*Additional key references: Dickson et al., 2007; Rabe et al., 2008.*

### *2.3 Department of Oceanography Naval Postgraduate School's Arctic Ocean Flux Buoy (AOFB)*

The Autonomous Ocean Flux Buoy (AOFB) developed by the Naval Postgraduate School (USA) is designed for measuring turbulent fluxes in the upper ocean (5-10m) below the sea ice. It consists of two main units – one above and one below the sea ice. The surface unit consists of a GPS, Iridium modem, processing electronics and batteries. The unit below the ice has two main components; a RDI 300kHz workhorse ADCP and a custom-built flux package (Shaw et al., 2008). The latter comprises an acoustic travel-time current meter (model ACM 3D, Falmouth Scientific Inc.), an inductive conductivity cell and platinum resistance thermometer (model OEM C-, Falmouth Scientific Inc.), and a fast-response thermistor. The three flux sensors are designed to directly measure the turbulent fluxes of momentum, heat, and salt. The sensor package is installed at a fixed depth below the sea ice, with the ADCP sampling bin size of 2m starting at around 6.5m below the sea ice. Flux measurements are taken 5m below the bottom of the sea ice. The first AOFB was deployed in 2002 and drifted over the course of a year from near the North Pole out through the Fram Strait. The latest deployment (AOFB 37) occurred in the Beaufort Sea in October 2015.

### *2.4 Jamstec's Polar Ocean Profiling System (POPS)*

*The Japan Agency for Marine-Earth Science and Technology (Jamstec) has developed and deployed ice-tethered autonomous observatories since 2000 (Kikuchi et al., 2007). Over the years, several units have been deployed in the multiyear pack ice of the high Arctic to study inter-annual variability in the atmospheric and oceanographic conditions (Morrison et al., 2006 and references therein) and the effects of atmospheric forcing on ice-albedo feedback (Inoue et al., 2005). More recently, Vivier et al. (2016) used the last version of these ice-tethered platforms, named Polar Ocean Profiling System (POPS), to study lead openings near the North Pole. Kikuchi et al. (2007) provided a detailed description of the POPS. In short, it consists of an ice-anchored platform and a subsurface CTD profiler, which provide meteorological and oceanographic profiling data via Iridium satellite communication. The ice platform and the subsurface CTD profiler communicate through an inductive modem telemetry system (Sea-Bird Electronics, Bellevue, WA, USA), which in turn allows downloading data and sending remote commands from the laboratory through bidirectional satellite communication using the Short Burst Data transmission method.*

*Additional key reference: Inoue and Kikuchi 2007, Enomoto et al 2013.*

### *2.5 University of Manitoba's ice-tethered moorings (ITM)*

Researchers at the Centre for Earth Observation Science (http://umanitoba.ca/ceos/), based at the University of Manitoba in Canada, have been deploying ice-tethered moorings (ITM) since the last IPY (2007-2008). These moorings initially consisted in ice beacons solely documenting ice drift, but several oceanographic instruments allowing additional measurements have been added since then. The last version was deployed to study sea-ice characteristics, thermodynamics, winds, and currents from drifting multiyear pack ice in the Beaufort Sea (Babb et al., 2016), as well as from landfast ice in Eastern Greenland (Dmitrenko et al., 2015). A recent study also used data collected with an ADCP deployed from one of these moorings to document the vertical migrations and distribution of zooplankton (Petrusevich et al., 2016).

Different configurations of instruments can be installed on these ice-tethered moorings. They generally comprised a temperature probe to measure air temperature (model 109, Campbell Scientific, accuracy 0.10–0.20°C), a position only beacon, and a 300 kHz down-looking ADCP (model Workhorse Sentinel, Teledyne RD Instruments) deployed just below the ice through a 8” PVC pipe. In addition to measurements of water currents, the temperature measured internally by the ADCP provides sea-surface water temperatures with a precision of ±0.4°C. The ice-tethered moorings also comprise an ice mass balance (IMB) system. The IMB records air temperature, surface-level pressure, wind at 2 m above the snow-ice interface, GPS location, and a vertical temperature profile that extends through the ice into the upper ocean. It consists of a 6 m long temperature acquisition cable 7 mm in diameter (Beaded Stream Inc.) with 61 addressable temperature sensors (accuracy ± 0.1°C) at 10 cm intervals. The bottommost temperature sensor is located under the ice cover and provides measurements of the top water layer. Time resolution of the IMB is 30 minutes (Dmitrenko et al., 2015; Babb et al., 2016). Ice-tethered moorings deployed from drifting multiyear pack ice are lost once the ice flow on which they are deployed melts. Data transfer thus has to be done through satellite communications. To achieve this, data are collected on a CR1000 Data logger enclosed within a weather-proof case and transmitted via the Iridium network (Babb et al., 2016). For past studies, the ice flow generally melted or broke within a few months, but the autonomy of the mooring could theoretically reach one or two years (D. G. Babb, CEOS; personal communication).

*The landfast ice-tethered mooring array deployed to study the ocean-atmosphere interactions in Eastern Greenland consisted of 4 units. Each unit comprised a combination of ADCPs, to measure* the velocity and direction of under-ice currents, and CTD sensors to measure temperature and salinity from the ice-water interface to the bottom. One of the units also comprised an IMB buoy. Temperature-salinity sensors consisted either in CTDs located at discrete depths (model SBE-37, Sea-Bird Electronics Inc.), or in a McLane mooring profilers with CTD sensors profiling the water column. It is relevant to note that other oceanographic sensors can be installed on MMPs, for instance fluorometers, $CO_2$, $CH_4$, or turbidity sensors. The landfast ice-tethered mooring array was deployed for 7 months covering the winter season, and data were manually downloaded after recovering the instruments.

### *2.6 SAMS’s Sea Ice Mass Balance buoys (SIMBA)*

The Sea Ice Mass Balance buoy (SIMBA) system (Jackson et al., 2013) was developed by the Scottish Association of Marine Science (SAMS), and has two main components; a chain of temperature sensors in ice and the underlying water and an Iridium communication unit above the ice. This system has replaced the more expensive and traditional thermistor strings for monitoring temperature profiles in the ice and snow with a chain of inexpensive digital temperature chip sensors linked by a single-wire data bus. By incorporating a heating element into each sensor, the instrument is capable of resolving material interfaces (e.g., air–snow and ice–ocean boundaries) even under isothermal conditions. The instrument is small and low cost. Chain sections have been produced with 2-, 4-, or 50-cm sensor spacing, allowing chains to be tailored for particular applications. Typically, 2-cm-spaced sensors are now used for IMB buoys but larger spacing is used for applications such as monitoring of ocean mixed layer depth. The chain is connected by a cable to a microcontroller unit housed in an enclosure on the ice surface.

In 2013, 50 units had been manufactured and were in operation by 13 different institutions. The in situ life-time of a unit has reached more than one full year.

### *2.7 UiT The Arctic University of Norway’s Ice-tethered Platform cluster for Optical, Physical and Ecological sensors (ICE-POPEs)*

The ICE-POPEs are developed in combination between SAMS (UK), the Norwegian University of Science and Technology (NTNU) and UiT (Norway), and are part of the Norwegian Research Council’s roadmap for national infrastructure. The ICE-POPEs will be test-deployed in fast-ice in January-April 2017 on Svalbard, and in the drift-ice from the autumn 2017. The system is divided into six separate and autonomous units with GPS and data transmitters, including one SIMBA unit.

Unit 1 – SIMBA developed by SAMS (section 2.6).

Unit 2 – Physical unit with an array of light, temperature and salinity sensors at 7 discrete depths within the upper 5.5m below the ice.

Unit 3 – Acoustic unit with ecological sensors. Two Acoustic Fish and Zooplankton Profilers (AFZP, ASL Environmental Sciences Inc.) with four frequency bands ranging from 38 to 450kHz are to be deployed at 35m below the sea ice, one upward and one downward looking. EcoTriplets (WETLabs) will be deployed at 5 and 35m depth to measure the concentration of Chlorophyll a (phytoplankton biomass), cDOM (coloured dissolved organic matter) and TSM (total suspended matter), along with downwelling light, temperature and salinity sensors in an array between 5 and 100m.

Unit 4 – Optical unit with an Underwater Hyperspectral Imager (UHI) with HD camera and roll/tilt/compass sensor and an EcoTriplet sensor located 5m below the ice. The UHI will measure spectral radiance (W $m^{-2}$) per image pixel and will be used to measure light climate (spectral radiance and daylength) at different angles, as well as to map objects of interest under sea ice based on optical fingerprints per image pixel (Johnsen et al., 2013).

Unit 5 – Automatic weather station with optical sensors. In addition to all standard meteorological sensors, this unit will carry a sensor for surface irradiance and a 360° camera.

Unit 6 – Data storage and communications. Each unit is equipped with a Iridium SBD modem for transmission of data in the KB range. Units 3-5 produce data in MB-TB range that are stored both internally in sensors and in Unit 6. Data harvesting using drones and micro-satellites will be tested / developed for these data sets.

## 3. CURRENT CAPABILITIES AND FUTURE DEVELOPMENTS

There are currently three types of ice-tethered platforms in use – the ITP, AOFB, and ITM. All three systems are currently deployed in the Arctic sea ice, and data from the former two (ITP and AOFB) are transferred in real-time. Instead of a real-time connection, current deployments of ITMs in landfast ice on Greenland are based on a manual data recovery. A common theme for all currently available systems (Table 1), with exceptions of the upgraded ITP and the landfast ITMs in the fjords of Greenland, is that they mainly focus on physical data measurements, in and below sea ice with exception of the upgraded ITP and the landfast ITMs in the fjords of Greenland. As such, the POPE system developed under the lead of UiT (Norway) will be a significant and important addition to our current abilities to take biological measurements in the Arctic drift ice over complete year cycles. The POPEs will initially be deployed and tested in fast ice on Svalbard, and the first drift ice deployments will be carried out in conjunction with planned ship-based drift stations. Fully autonomous POPEs are scheduled to be in operation from 2019. When successful, the POPEs will provide biological, key environmental variables and biology-relevant data hitherto only achievable through large ship-based sampling programmes, such as the Canadian CASES, Norwegian N-ICE 2015 and other similar investment-heavy operations.

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**Table 1.** Overview of existing ice-tethered platforms with basic capabilities. AZFP – Acoustic Zooplankton and Fish Profiler, ADCP – Acoustic Doppler Current Profiler, UHI – Underwater Hyperspectral Imager.

| **Platform** | **Data real time** | **Profile** | **Ice-Mass Balance** | **Temp** | **Salinity** | **Diss. $O_2$** | **Light** | **Chl a** | **AZFP** | **ADCP** | **UHI** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **ITP** | **X** | **X** | **X** | **X** | **X** | **X** | **X** | **X** | | | |
| **ITAC** | | | | | | | | | | X (75kHz) | |
| **AOFB** | X | | | X | X | | | | | X (300kHz) | |
| **POPS** | X | X | X | X | X | | | | | | |
| **ITM** | | X | X | | | | | | | X (300kHz) | |
| **ICE-POPEs** | X | | X | X | X | | X | X | X | | X |