Low-Cost Expendable Buoys for Under Ice Data Collection

Conference Paper · October 2018

DOI: 10.1109/OCEANS.2018.8604752

6 authors, including:

Christian Meinig
National Oceanic and Atmospheric Administration

Shaun W. Bell
National Oceanic and Atmospheric Administration

Heather McRae Tabisola
University of Washington Seattle

Low-Cost Expendable Buoys for Under Ice Data Collection

D. Langis, P.J. Stabeno, C. Meinig
Pacific Marine Environmental Laboratory
National Oceanic and Atmospheric Administration
Seattle, WA USA
daniel.p.langis@noaa.gov; phyllis.stabeno@noaa.gov; christian.meinig@noaa.gov

C.W. Mordy, S.W. Bell, H. M. Tabisola
Joint Institute for the Study of Atmosphere and Ocean
University of Washington; and
Pacific Marine Environmental Laboratory
National Oceanic and Atmospheric Administration
Seattle, WA USA
mordy@uw.edu; swbell2@uw.edu; hnmac@uw.gov

***Abstract*—The NOAA Pacific Marine Environmental Laboratory (PMEL) has designed a new, low-cost, expendable under-ice buoy capable of collecting oceanographic data at the water-ice boundary to address gaps in knowledge during these critical periods. The buoys are designed to be deployed from a research vessel during the ice-free season, where they collect data while anchored to the seabed until the surface is completely covered in sea ice. At a designated time for each device, a release is triggered, which allows the buoy to ascend and be buoyant just under the ice, collecting a vertical profile of the water column during its ascent. The buoys remain at the ice-water interface collecting data, until break-up or melting of sea ice, when their data are transmitted to shore. Preliminary versions of the instrument were deployed in the Chukchi Sea in 2015 (Generation 1) and the Bering Sea in 2017 (Generation 2), collecting data on temperature, depth, and photosynthetically active radiation (PAR). These deployments successfully demonstrated the viability of the low-cost design, its robust nature, and its ability to provide high-quality data. Ongoing developments (Generation 3) include measurement of fluorescence and collection of daily images for situational awareness and to assess the presence of ice-associated algae. Onboard GPS provides precise location data from open water, and all data are transmitted to shore using Iridium Short Burst Data (Generations 2 and 3). These compact instruments are optimized for use in the relatively shallow waters of the continental shelf (up to 100 m depth) in the Bering and Chukchi seas. Their cost advantages can be best leveraged to provide improved spatial coverage over this enormous area, where observations are typically sparse. These under-ice buoys are one of several new technologies being developed as part of the Innovative Technology for Arctic Exploration (ITAE) project—a collaborative effort between scientists and engineers at NOAA and the University of Washington. Collectively, they represent a unique opportunity to improve the basic understanding of the changing Arctic environment and to cost-effectively monitor future changes.**

Keywords*— *Lagrangian, platform, technology, ocean observation, Arctic, sea ice, ecosystem monitoring, instrumentation, NOAA, PMEL, ITAE

I. Introduction

A. *The Need for Under-Ice Measurements*

Conditions directly under Arctic sea ice during spring and early summer months are largely a mystery, but it is clear that they play a critical role in shaping one of the world's most productive ecosystems. Massive phytoplankton blooms have been identified under Arctic sea ice [1], but the timing and prevalence of such events are unknown [2]. Additionally, the character of the ice-edge environment is changing with the loss of multiyear sea ice and overall thinning of the ice matrix, which has complex implications for marine and terrestrial ecological dynamics [3]. Improved understanding of the processes that govern sea-ice evolution in the Marginal Ice Zone (MIZ) is needed to improve sea-ice models, inform planning for transpolar shipping, and formulate responses for coastal communities [4]. However, the dynamics associated with sea-ice retreat and advance in the MIZ of the Arctic pose significant observational challenges.

Transition periods during ice retreat and ice advance exhibit the most dynamic changes in the ecosystem, but are difficult to measure because both ships and aircraft struggle to provide access to the region [4]. The small number of ship-based observations are costly due to the limited availability of ice-capable vessels, which are required to provide access during these key periods. Even with the inclusion of ship-based measurements, a wide network of moorings and autonomous systems is necessary to capture the variability inherent in the Arctic [4].

Funding for Innovative Technology for Arctic Exploration is provided by NOAA Research with in-kind support for the under-ice buoy from the Ecosystems and Fisheries-Oceanography Coordinated Investigations program at NOAA/PMEL. This publication is partially funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement NA15OAR4320063.

During winter, fast-moving ice keels up to 20 m deep in the northern Bering Sea [5] and greater than 30 m deep in the Chukchi Sea [6] have been recorded. Instruments on typical subsurface moorings must be kept below these thresholds to prevent them from being dragged or damaged by ice keels. Innovative methods must be used to access the upper water column during winter and transition periods. Arctic winches have been designed to address this problem by tethering the subsurface mooring to an instrumented float, which periodically rises to the underside of ice (or surface) to measure the upper water column. However, the tethered float can be destroyed by ice keels sweeping past. Mechanical complexity also increases cost ($130,000 per system) and logistic demands, thus limiting spatial coverage due to the number of systems that can be deployed. Ice-tethered profilers (ITPs), called the 'Argo of the Arctic', are another system capable of measuring the upper water column [7]. ITPs are typically deployed on multiyear ice floes through a hole that has been augered in the ice. They are designed to collect vertical profiles of data along a tether that can be up to 800 m in length. Efforts have been introduced to allow for open water deployments and to modify profiling parameters for shallow water drift, but almost all data collection efforts for ITPs are limited to the deep water of the Arctic basin where they are most cost-effective, since landing and drilling holes on floes are required, and they are also less vulnerable to ice dynamics seen in the MIZ [7].

Autonomous platforms—such as gliders, profiling floats, and drones—can provide cost-effective monitoring and expanded spatial coverage of the ocean. Presently, many are being utilized and tested in Arctic observational networks [4]. However, accessing the under-ice regime is still problematic for these systems. Few underwater gliders have the ice-avoidance capabilities that are especially necessary in shallow water, and Autonomous Surface Vehicles cannot transit into the ice pack. Profiling floats, such as Argo or ALAMO, can be deployed in the ice-free season and collect measurements during the fall transition period (ice advance), but these Lagrangian systems lack the station-keeping ability needed to stay at a desired deployment location and have not yet been proven to work directly under arctic ice.

B. *Design Concept for an Under-Ice Buoy*

NOAA's under-ice buoys are made to fill a specific gap in technology: to provide a cost-effective method of monitoring conditions directly under ice, primarily in the MIZ during springtime ice retreat. The instruments are optimized for use in shallow waters (up to 100 m), where primary productivity is high and conditions are highly dynamic, but historical observations are scarce.

The buoys are designed to be deployed from a research vessel during the ice-free season, where they collect data while anchored to the seabed until the surface is completely covered in sea ice. A release triggered at a designated time for each device allows the buoy to ascend and bob just under the ice, collecting a vertical profile of the water column during the ascent. The buoys remain under ice collecting data until break-up or melting of sea ice, when their data are transmitted to shore via Iridium Short Burst Data (SBD). Several design requirements drove the concept for these devices.

They must be able to access the regime directly under sea ice during springtime ice retreat. The delayed release concept allows the instruments to be deployed without the need for aircraft or an ice-capable vessel. One drawback to this technique is that the timing of release is set months earlier, before deployment, and buoys cannot respond to any unusual occurrence (e.g. early ice retreat). The compact, lightweight design chosen for these instruments allows them to be deployed without any specialized equipment from nearly any vessel, reducing logistic constraints and providing more possibilities for ships of opportunity.

In order to access and continuously sample the springtime retreat, the instruments must be robust. They must be able survive situations such as being frozen in ice, being caught between compressing and rafting floes, or being pushed onto the surface of an ice floe where temperatures can reach –20 °C or colder. The physical shape and configuration of the instrument plays a critical role in survivability, as does ensuring that all sensors and any antennas are extremely well-protected. The buoys encapsulate all sensors and antennas within a spherical housing to allow the instruments to 'ride' smoothly under ice. A counterweight mounted at the bottom of a vertical frame acts as a pendulum to keep the buoys upright at all times. These Lagrangian platforms are designed to drift easily with ice floes, eliminating any tethers that could possibly be severed by ridging and shifting ice.

Even the most robust instruments deployed near the surface in the MIZ during springtime ice retreat will be exposed to significant risk due to ice dynamics; thus, the possibility of instrument loss cannot be eliminated. This risk must be accounted for and mitigated, either by providing a method of data recovery or reducing the impact of such losses. The low per-unit cost of these expendable instruments is advantageous as a large number of units can be deployed and a small percentage of instrument loss can be tolerated more easily than the potential loss of large, expensive systems. The expendable design and simple deployment procedure also reduce total life-cycle costs by minimizing required ship time and labor.

II. Generation 1: Satellite Tag Prototype

A. *Design*

The first step in development was to construct prototype instruments and test the concept of an expendable under-ice buoy. This concept was tested in 2015 by using commercially available satellite tags to measure, record, and telemeter data, and building a superstructure around the tags to provide protection and flotation. In this initial test, temperature, photosynthetically active radiation (PAR), pressure, and tilt data were collected.

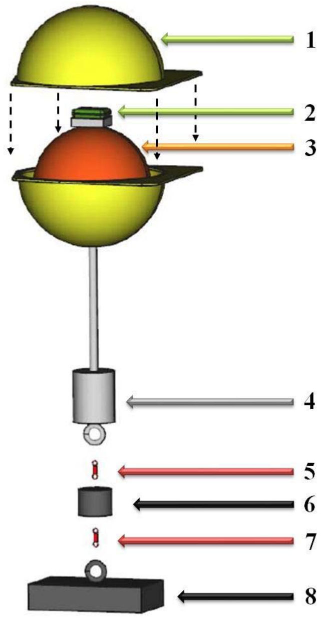

Fig. 1. Schematic of under-ice buoy prototype: (1) 'hard hat' casing; (2) satellite tag; (3) trawl float; (4) counterweight; (5) secondary release; (6) drop weight; (7) primary release; and (8) anchor.

Satellite tags were an excellent basis for prototype instruments as they are robust, can provide dynamic profile data and offer a commercial solution during development before investing in the engineering.

Satellite tags, developed by the University of St. Andrews' Sea Mammal Research Unit (SMRU) were used because of their high-quality data. SMRU also provided support to integrate a unique PAR sensor into the tags and to modify their sampling schedule for NOAA's under-ice application.

Fig. 1 shows a diagram of the prototype under-ice buoy. The satellite tags were each attached to a trawl float for buoyancy. The floats were covered by a 'hard-hat' shell for physical protection and fitted with a counterweight to keep them upright. The flotation unit was rigged to an anchor, drop weight, and two galvanic timed releases. After the units were deployed, the lower (primary) release would corrode after a few days to release the unit from the seafloor. After several more days, the upper (secondary) release would corrode, making the buoy more positively buoyant and providing extra freeboard to facilitate data transmission after emerging from the ice.

B. Deployment (2015)

Two prototype buoys were deployed in the Chukchi Sea from the USCGC *Healy* in July 2015 (Fig. 2). Buoy-1 was deployed on 11 July at 71.7° N, 160° W and Buoy-2 was deployed on 14 July at 70.9° N, 149.7° W. In each case, the ship was in eight-tenths to nine-tenths ice cover, approximately 40 km from the ice edge. The prototype buoys were designed to anchor on the bottom for two days before releasing under the ice and collecting a profile of temperature and PAR as they surfaced. They were expected to measure conditions under the melting ice for a few days, or perhaps weeks, and then transmit data to shore once free of ice. This deployment was designed to test the feasibility of the delayed-release concept, quality of satellite-transmitted data, and survivability of the buoys under sea ice.

Buoy-2 was deployed on 14 July and worked as expected. The buoy was anchored for several days before beginning to record data on 16 July. Bottom temperatures at the deployment site were fairly constant at approximately –1.8°C (Fig. 3), which is typical bottom temperature in these waters. Upon release on 17 July, the buoy rose to the surface and collected a vertical profile. The temperature was relatively constant until reaching a depth of approximately 2 m, when temperature began to increase, reaching –1 °C at the surface (Fig. 4). While anchored to the bottom, a PAR signal was just discernible (Fig. 3). As the buoy rose through the water column, PAR increased as expected even though it was released during the darker part of the day. When it reached a depth of approximately 3 m, PAR unexpectedly began to decrease. This small decrease in PAR (relative to the large daily changes observed at the surface) is most likely a consequence of the large spatial variability in ice thickness and/or presence, and perhaps spatial variability in ice-associated particulates (e.g. microbial communities). Thus, as the buoy rose, it entered into the shadow of a floe and eventually came to rest under that floe. Over the next four days the buoy remained trapped under the ice. During this time, a weak PAR signal is evident (Fig. 3). Eventually, on 21 July, the floe either melted or broke apart; the buoy arrived at the surface and transmitted the data it had been collecting over the past six days. After 21 July, a strong diurnal signal is evident in both temperature and PAR. It must be noted that the thermistor was no longer measuring ocean temperature but was exposed to the atmosphere at this point. The large variations in temperature are consistent with the air space between the trawl float and hard-hat shell being heated by sunlight. The PAR signal saturates at 650 μmol photons $m^2\ s^{-1}$, which is the upper limit of the sensor's measurement range.

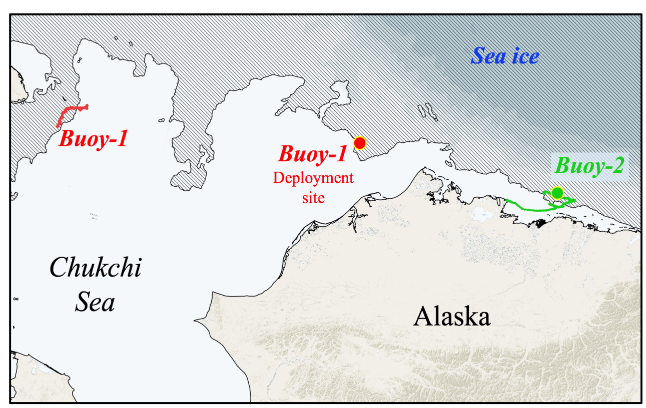

Fig. 2. Map of deployment locations. Buoy-1 was deployed on 11 July 2015 and Buoy-2 was deployed on 14 July 2015. The hatched area represents Multisensor Analyzed Sea-Ice Extent (MASIE) on 10 July 2015. The red and green circles indicate deployment sites. The lines indicate drift track during transmission.

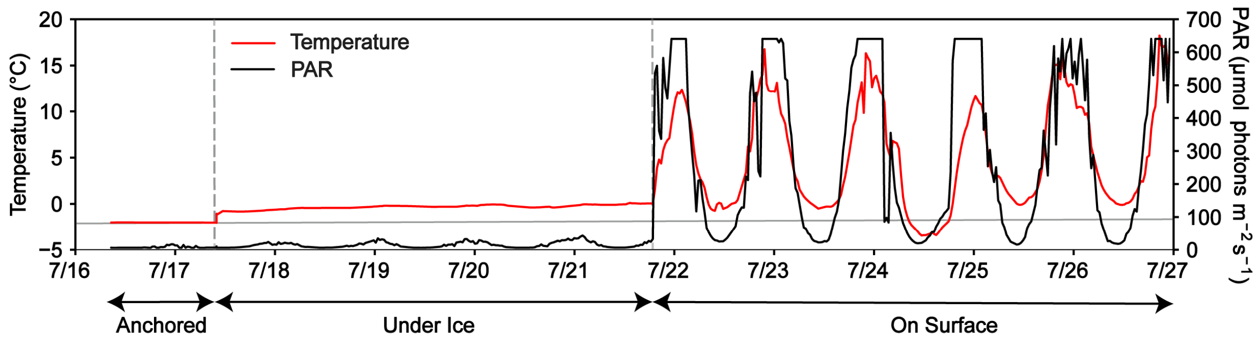

Fig. 3. Plot of temperature (red) and PAR (black) for Buoy-2. Vertical dashed lines indicate times when the buoy was released from the anchor (17 July) and when it surfaced to transmit data to shore (21 July). The horizontal dotted line is the freezing point of seawater having a salinity of 33 (–1.81°C). Note that the time axis is UTC and does not reflect solar days.

Buoy-1 was deployed on 11 July 2015, but did not transmit any data in the summer of 2015. Instead, it transmitted data 13 months after deployment, approximately 560 km west of the deployment location (Fig. 2). A clock error of almost 4 months was evident in the raw data, and was corrected based upon the data transmission date. Results shown in Fig. 5 are consistent with the following scenario. No data were recorded from deployment through the next 3+ months, so the time series begins at the end of November, with the buoy apparently caught in the ice. It then transitioned to more than a meter above the water surface, which could have been the result of rafting of one ice floe over another. From five years of Pacific Marine Environmental Laboratory (PMEL) experience with satellite-tracked drifters, when caught in sea ice, it is not uncommon for the drifters to only intermittently communicate (no transmissions for weeks at a time) with satellites. It is possible that Buoy-1 was on its side or shaded by ice so that no data transmissions occurred during the period in December and January when it appeared to be above the ocean surface. The very cold temperatures are further evidence that the buoy was trapped on an ice floe and exposed to air. The temperature stops decreasing at –5°C, when the sensor reaches the lower limit of its measurement range. In late January, the sharp change in pressure suggests the ice floe changed suddenly (e.g. perhaps turning on its side or another floe rafting on top of it), forcing Buoy-1 several meters into the water, where it remained until the following summer. Between June and late August 2016, the buoy shoaled from 4.5 m to 2.3 m, at which point it suddenly surfaced into open water and transmitted data to shore.

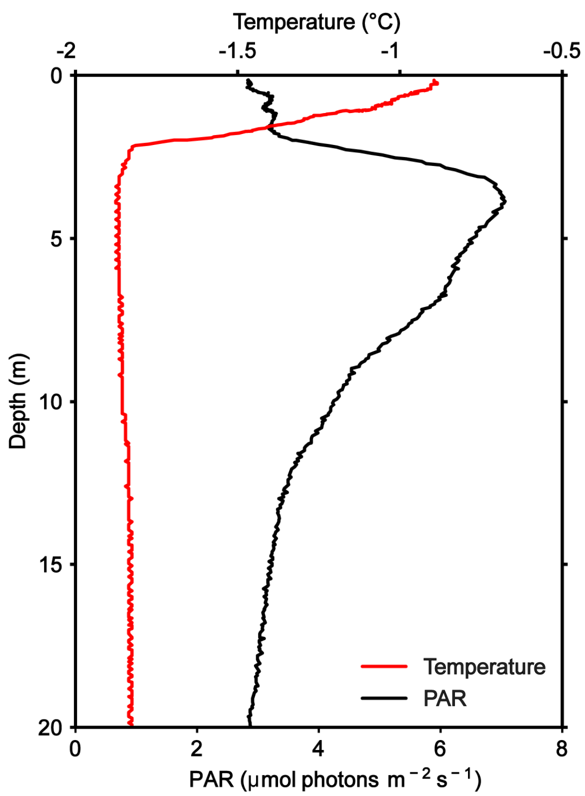

Fig. 4. The vertical profile of temperature (red) and PAR (black) on 17 July when Buoy-2 was released from the anchor.

C. *Assessment*

While the prototype was successful in meeting the basic requirements of an under-ice buoy, the design had several

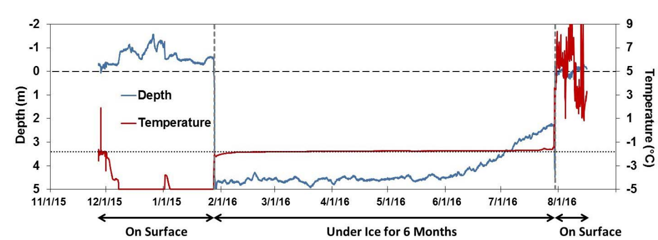

Fig. 5. Plot of depth (blue) and temperature (red) for Buoy-1. Vertical dashed lines indicate times when the buoy became submerged (1/28/16) and when it surfaced to transmit data to shore (7/30/2016). The horizontal lines indicate the sea-surface (dashed) and the freezing point of seawater (dotted) with salinity of 33 (–1.81°C).

drawbacks. Satellite tags were shown to be an effective method during initial development, but not for long-term use due to per-unit-cost ($4,300 per tag). The compact design of satellite tags, while advantageous for marine mammal applications, limited the available power, endurance, and potential sensors when evaluating long-term (1+ year) under-ice applications.

The most successful element of the prototypes were their survivability. The spherical shape of the buoy and protected antenna proved to be incredibly robust, as Buoy-1 survived two ice retreat seasons and one ice advance season in the Chukchi Sea.

III. Generation 2

A. Design

The second generation of under-ice buoy was equipped with sensors to measure depth (±0.21 m accuracy), temperature (±0.01° C) , PAR (±3% accuracy), and tilt; as well as GPS and Iridium SBD modules. A number of cost-saving design features were utilized to achieve a cost per instrument of less than $3,000. Features included low-cost pressure housings, commercial off-the-shelf components, and custom analog-to-digital circuitry for sensors. Fig. 6 shows pictures of the assembled buoys and Table 1 shows a list of the major components, and sensors, as well as costs and descriptions of each.

TABLE I. List of Major Components for Generation 2 Buoys

Component(s)[a]	Cost[b]	Details
Trawl Float (Pressure Housing)	$33	12" ABS Trawl Float; 27.5 lb. nominal buoyancy
PAR Sensor	$364	Skye Instruments TAG-PARQ Sensor; ±3% accuracy, 0 to 2000 μmol m^{-2} s^{-1}
Temperature Sensor	$10	Custom NTC Thermistor Probe ±0.01°C accuracy, -5°C to +70°C
Pressure Sensors	$125 ea	Two Keller PA-4LD Pressure Sensors; 4.5 cm accuracy (at 0°C), 0 to 30/100 m
Iridium Module and Antenna	$330	RockSeven RockBLOCK Mk2 Iridium 9602 Module
Burn Wire Release	$165	Sub-Sea Sonics TR-45 Timed Release; 40 lb. Max. Load, 170 Day Limit
Micro-Controller	$38	Arduino MEGA 2650
Battery Pack	$56	Custom 9V, 28A-h Alkaline Pack
GPS Module and Antenna	$35	Alpha Micro PA6H Module
PCB Assembly	$350	Custom PCB Assembly
Mechanical Assembly	$1,100	Custom Machining for Load-Reducing Mechanism and Sensor Integration
TOTAL	**$3,000**	Total cost (Note: not all components are listed in this table)

a. Only major components listed

b. Approximate costs

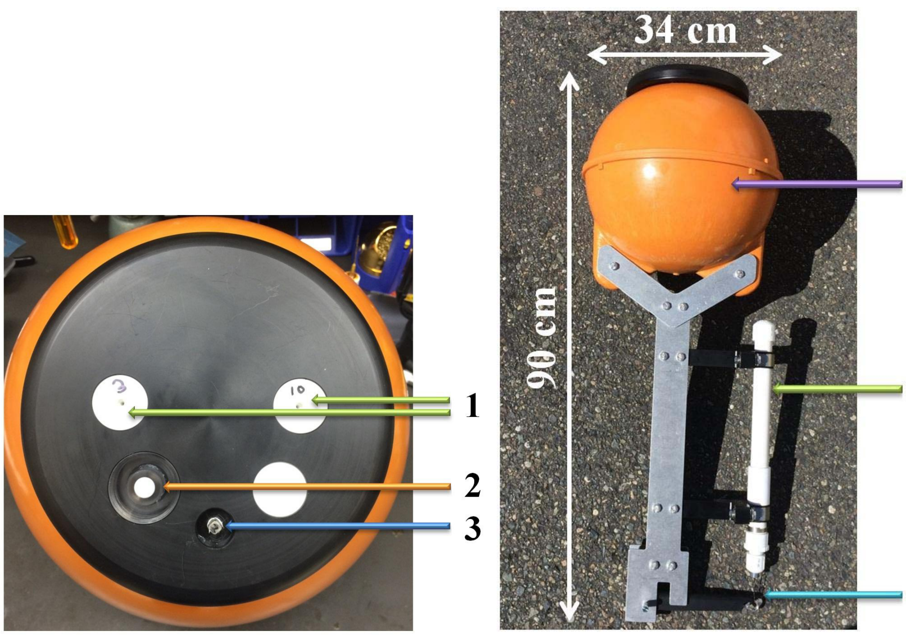

Fig. 6. Left: Under-ice buoy as viewed from above showing (1) pressure sensors, (2) PAR sensor, and (3) temperature sensor. GPS and Iridium antennas are embedded under the cap to prevent them from being damaged by ice. Right: Under-ice buoy as viewed from side showing (4) pressure housing, (5) "burn wire" timed release, and (6) load-reducing mechanism. Diameter of housing is 34 cm and height from top of buoy to bottom of frame is 90 cm.

B. Deployment (2017)

In September 2017, five Generation 2 under-ice buoys were deployed in the Bering Sea approximately 30 km southeast of St. Matthew Island in 68 m of water (Fig. 7). Historically, sea ice arrives at this location in December and persists into May. From February to March, average areal ice concentration exceeds 65% [8]. Noting this, the buoys were programmed with release dates between 20 February and 15 March 2018. The expectation was that the instruments would surface under thin, first-year ice and be transported southward by the prevailing winds. The buoys were expected to emerge from the ice within a few weeks as the leading edge of the ice encountered warmer water to the south and melted. Unfortunately for this experiment, for the first time in the satellite era (starting 1972), there was no ice at the deployment site during winter. In fact, the most notable aspect of the 2017 to 2018 winter sea-ice extent was the persistently low ice extent in the Bering Sea [5].

Because of the absence of ice at the site, four of the five buoys (Buoys 4–7) surfaced in open water. They transmitted complete sets of data via Iridium SBD within 8–12 hours of surfacing. It is unknown why the other buoy (Buoy-3) failed to transmit any data. All four of the successful buoys continued to drift at the surface in the Bering Sea for several months, transmitting SBD messages with at least an 80% transmission success rate in seas ranging from 2 to 7 on the Beaufort scale, as determined by wind speed in the region.

In Fig. 8, all four time series of temperature are plotted and the release time of each buoy is indicated by a dotted vertical line. These data provide a snapshot of subsurface conditions many months before other observations from ships and moorings in the region became available. Note that while there are moorings in the vicinity, they do not transmit in real time and would not be recovered until September 2018. Also shown in Fig. 8 are bottom temperatures for two years (2008/2009 and 2016/2017) from a nearby, long-term mooring, M5 (59.91°N, 171.73°W). (Details of the mooring can be found in [8].) Note

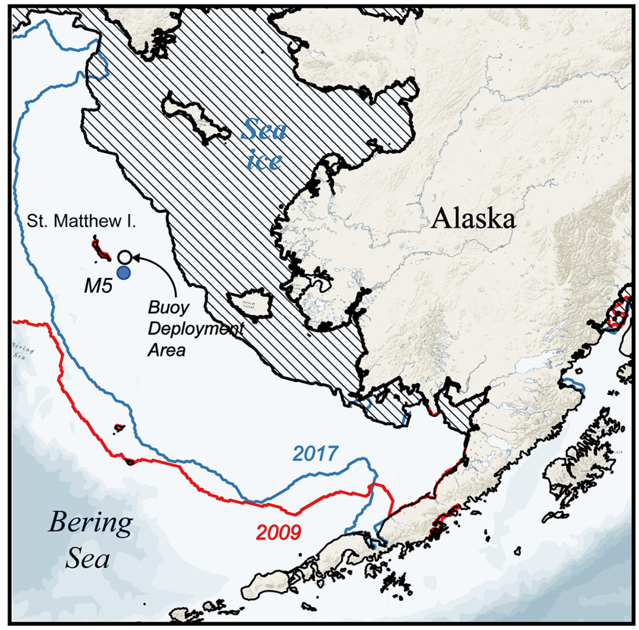

Fig. 7. Map showing the locations of the 2017 under-ice buoy deployment location (circle) and the M5 long-term mooring. The hatched area shows 2018 ice extent from Multisensor Analyzed Sea-Ice Extent (MASIE). Maximum ice extent in 2018 was the lowest on record in the Bering Sea. Maximum ice extent for 2017 (blue line) and 2009 (red line) are shown for comparison.

that 2008 and 2009 were cold years with extensive ice, while 2016 was the warmest year on record with no ice on the southern shelf. The year 2017 was colder with ice arriving late. The maximum ice extent in 2009 and 2017 is shown in Fig. 7.

The general patterns in the three time series shown in Fig. 8 are similar. In late summer, the water column is two-layered, with a warmer, fresher surface layer overlaying a colder, more saline bottom layer. As the warm surface waters are mixed downward by fall storms, bottom temperatures increase and the water column becomes well mixed. For these three time series,

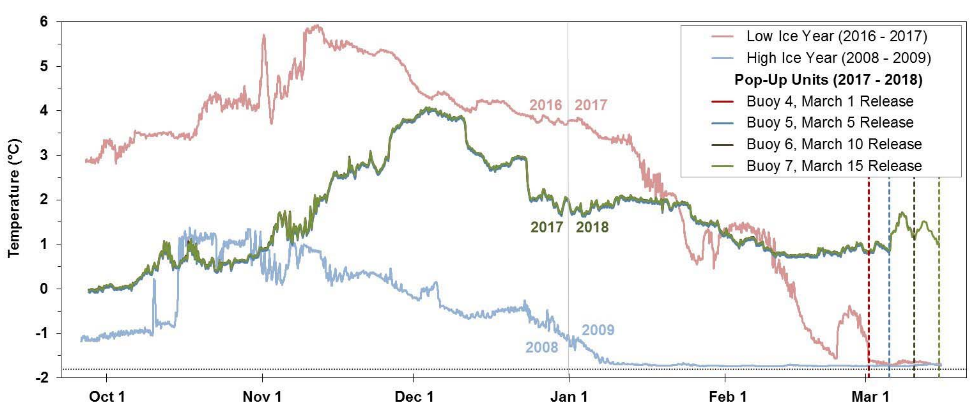

Fig. 8. Plot of seasonal bottom temperatures near St. Matthew Island in the Bering Sea. Data from 2008/2009 (pale blue) and 2016/2017 (pale red) are from a long-term mooring (M5). Data from 2017/2018 (darker colors) are from four buoys anchored north of the M5 mooring. These buoys were sequentially released beginning in early March. Vertical dashed lines indicate times when the buoys were released (color-coded to match the time series of each unit in Fig. 9). The grey horizontal line is the freezing point of seawater with a salinity of 33 (–1.81°C).

this occurred in mid-October 2008, early November 2016, and early December 2017. At these latitudes the water column begins to cool (net heat flux into the atmosphere) sometime in September. Once the water column becomes well mixed, cooling is evident in the bottom temperatures. The arrival of ice cools the surface water to –1.7 °C and it can take a week for this colder, fresher water to be mixed to the bottom. The arrival of ice is evident in the two M5 time series (early January 2009 and early March 2017). The absence of sea ice in 2018 resulted in bottom temperatures in early March to be approximately 2.8 °C warmer than usual. These changes in bottom temperatures are known to have dramatic effects on the ecosystem of the Bering Sea [9, 10].

The vertical profiles (Fig. 9) provided snapshots of the water column during a time when no other in situ measurements were available. At first the water column was well mixed. This was followed by an intrusion of warmer water on the bottom and cooling of the near-surface water. To remain stably stratified, the near-surface water must have been fresher than the deeper water. PAR provided little unexpected information; for instance, there was no discernable light signal at the bottom (68 m).

C. Assessment

Although the instruments did not surface under ice as desired, their functionality and low-cost design proved successful. The major innovations in the Generation 2 buoys were the custom sensor package and software, implementation of burn-wire releases, and the addition of GPS and Iridium SBD modules.

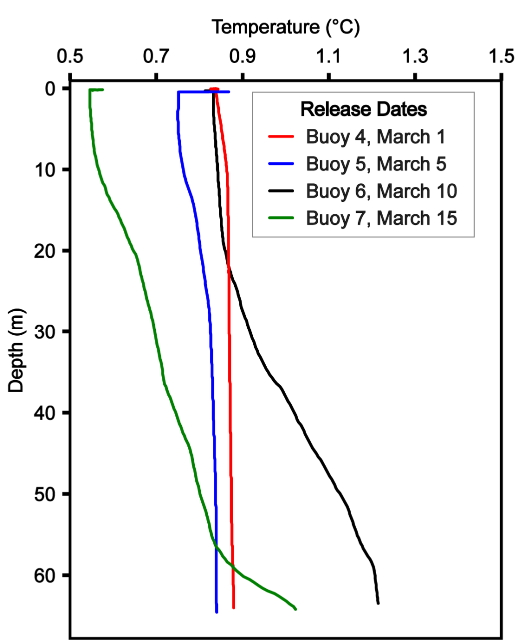

Fig. 9. Vertical profiles of temperature from each of the under-ice buoys. Note that at the surface the buoys were exposed to the air.

The custom sensor package and software provided high-quality data and a reliable sampling routine. Utilizing burn-wire releases with the main instruments having independent clocks provided accurate timing for release and a dependable method for profile collection. The high success rate of SBD transmissions, even in open seas with moderate to heavy sea states, demonstrated that the buoys' protected antennas still provided dependable satellite communication.

IV. Generation 3: On-Going/Future Development

A. Design Improvements

Based on the lessons learned from Generation 2 under-ice buoys, a number of improvements have been integrated for Generation 3 buoys, which will be deployed over winter 2018/2019. These improvements, discussed in detail below, will leverage the under-ice buoys' unique capabilities to access and monitor conditions under first-year sea ice common in the Bering and Chukchi seas. Fig. 10 provides a section view of a 3-D model for Generation 3 under-ice buoys; Table 2 lists the major components and sensors, as well as costs and descriptions of each.

TABLE II. List Of Major Components For Generation 3

Component[a]	Cost[b]	Details
Trawl Float (Pressure Housing)	$33	12" ABS Trawl Float; 27.5 lb. nominal buoyancy
PAR Sensor	$364	Skye Instruments TAG-PARQ Sensor; ±3% accuracy, 0 to 2000 μmol/m^{-2} s^{-1}
Temperature Sensors	$67 ea	US Sensor NTC Thermistor Probes; ±0.01°C accuracy, -5°C to +70°C
Pressure Sensor	$117	Keller PA-4LD Pressure Sensors; 4.5 cm accuracy (at 0°C), 0 to 100 m
Iridium Module and Antenna	$330	RockSeven RockBLOCK Mk3 Iridium 9603 Module
Burn Wire Release	$750	DBV Technology Burn Wire Release; 40 lb. Max. Load, 170 Day Limit
Micro-Controller	$38	Arduino MEGA 2650
Battery Pack	$95	Custom 9V, 42A-h Alkaline Pack
GPS Module and Antenna	$35	Alpha Micro PA6H Module
PCB Assembly	$350	Custom PCB Assembly
Mechanical Assembly	$600	Custom Machining for Load-Reducing Mechanism and Sensor Integration
Fluorometer (Optional)	$1,600	Turner Cyclops Fluorometer
TOTAL	**$3,000**[c]	Total cost (Note: not all components are listed in this table)

a. Only major components listed

b. Approximate costs

c. Total does not include the optional fluorometer.

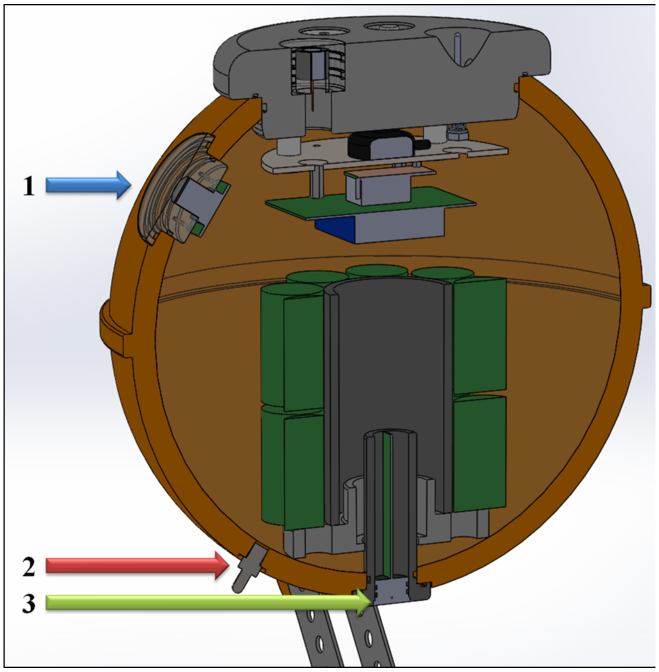

Fig. 10. Section view of 3-D model for under-ice buoy showing Generation 3 improvements, including (1) camera, (2) sea surface temperature probe, and (3) fluorometer.

A Turner Cyclops fluorometer was integrated into the system and will provide measurements of chlorophyll fluorescence: an indicator of phytoplankton biomass. These data will be used to better understand the timing and extent of under-ice phytoplankton blooms [1, 2]. The fluorometer is an optional sensor. Because of its relatively high cost, the buoys are designed so that it can be easily removed. One under-ice buoy equipped with fluorometers will be deployed in August 2018 from the USCGC *Healy* and a second in October 2018 from the NOAA Ship *Oscar Dyson*.

Once free of the ice, thermistors mounted on the top of the buoy no longer record sea surface temperature (SST). To continue obtaining valuable SST measurements after the buoys are free of ice and drifting in open water, a SST probe was integrated on the underside of the trawl float. The probe is approximately 18 cm below the waterline, which is comparable to SVP drifters [11]. NOAA's under-ice buoys will provide a unique opportunity to obtain accurate SST measurements in the Arctic in the weeks and months following sea-ice retreat. These data can be used to aid in ground-truthing satellite estimates in a region where SST measurements are scarce.

A low-cost serial camera module has also been added for situational awareness and to assess the spatial patterns of ice-associated algae. The microCAM-III is a low-power module and includes an on-board JPEG compression chip that dramatically reduces the amount of data that must be transmitted via SBD, while still providing full-color images (160 × 128 to 640 × 480 resolution). An earlier version of the microCAM-III was selected as the optimal solution for cubeSat (http://www.cubesat.org/) missions based on many factors including price, power consumption, simple interface, wide operating temperature range, and compression capabilities [12]. These are also driving factors in NOAA's low-cost under-ice buoys, making the microCAM-III an ideal choice for this application.

Lastly, an improved burn-wire release mechanism was needed to extend the duration from deployment to release beyond 170 days. This is especially critical for deployments in the Chukchi Sea, where research cruises typically occur in the ice-free or low-ice months of August and September, but release of the under-ice buoys may not be desired until May or June. A new burn-wire mechanism, developed by DBV Technology will be tested in the Chukchi Sea during the 2018–2019 deployments. The additional cost of the new release mechanism is negated due to its higher load limit, eliminating the need for the load-reducing mechanism used on Generation 2 buoys.

B. *Future Endeavors*

NOAA's under-ice buoys are only one element of a wide network of observing systems for assessing and monitoring changing conditions in the Arctic. These buoys provide a tool for expanding measurements in the harsh environment of the Arctic. Their innovative and relatively inexpensive design provides opportunity for near-surface measurements and greater spatial sampling to complement moorings, ice-tethered instruments, and autonomous vehicles.

In order to fully assess physical, biological, and chemical conditions under sea ice, a more extensive sensor suite and improved vertical resolution are necessary. However, many sensors, such as conductivity, oxygen, and nitrate, are too expensive to integrate into these instruments. Opportunities for integrating new low-cost sensors and developing a low-cost buoyancy engine are currently being explored.

Acknowledgment

This work would not have been achieved without the dedication and commitment of many personnel from NOAA Research and our Cooperative Institute, the University of Washington Joint Institute for the Study of Atmosphere and Ocean. From the drawing board to the field; these successful field missions are made possible through dedicated administration, engineers, technicians, researchers, communications teams, private partnerships, and the officers and crews of the NOAA Ship *Oscar Dyson* and the USCG Cutter *Healy*. This is Contribution No. EcoFOCI-0908 to EcoFOCI, 2018-0166 to JISAO, and 4823 to PMEL.

References

[1] K. R. Arrigo, D. K. Perovich, R. S. Pickart, Z. W. Brown, G. L. Van Dijken, K. E. Lowry, et al., "Massive phytoplankton blooms under Arctic sea ice," Science, vol. 336, pp. 1408, June 2012.

[2] C. Horvat, D. Jones, S. Iams, D. Schroeder, D. Flocco, and D. Feltham, "The frequency and extent of sub-ice phytoplankton blooms in the Arctic Ocean," Science Advances, vol. 3, e1601191, March 2017.

[3] E. Post, U. S. Bhatt, C. M. Bitz, J. F. Brodie, T. L. Fulton, M. Hebblewhite, et al., "Ecological consequences of sea-ice decline," Science, vol. 341, pp. 519–524, August 2013.

[4] C. M. Lee, J. Thomson, and the Marginal Ice Zone and Arctic Sea State Teams, “An autonomous approach to observing the seasonal ice zone in the western Arctic,” Oceanography, vol. 30, pp. 56–68, June 2017.

[5] P. J. Stabeno, S. Bell, N. A. Bond, D. Kimmel, C. W. Mordy, and P. Sullivan, “Distributed Biological Observatory Region 1: Physics, chemistry and plankton in the northern Bering Sea,” Deep-Sea Res. II, unpublished.

[6] P. Stabeno, N. Kachel, C. Ladd, and R. Woodgate, “Flow patterns in the eastern Chukchi Sea: 2010–2015,” J. Geophys. Res., vol. 123, pp. 1177–1195, February 2018.

[7] Toole, J.M., R.A. Krishfield, M.-L. Timmermans, and A. Proshutinsky, “The ice-tethered profiler: Argo of the Arctic,” Oceanography, vol. 24 pp. 126–135, 2011.

[8] P. J. Stabeno, E. Farley, N. Kachel, S. Moore, C. Mordy, J. M. Napp, et al., “A comparison of the physics of the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem,” Deep-Sea Res. II, vol. 65–70, pp. 14–30, June 2012.

[9] P. J. Stabeno, J. T. Duffy-Anderson, L. B. Eisner, E. V. Farley, R. A. Heintz, and C. W. Mordy, “Return of warm conditions in the southeastern Bering Sea: Physics to fluorescence,” PLoS ONE, vol. 12, e0185464, September 2017.

[10] J. T. Duffy-Anderson, P. J. Stabeno, E. C. Siddon, A. G. Andrews, D. W. Cooper, L. B. Eisner, et al., “Return of warm conditions in the southeastern Bering Sea: Phytoplankton–fish,” PLoS ONE, vol. 12, e0178955, June 2017.

[11] G. Reverdin, S. Morisset, H. Bellenger, J. Boutin, and N. Martin, “Near–sea surface temperature stratification from SVP drifters,” J. Atmos. Ocean. Tech., vol. 30, pp. 1867–1883, August 2013.

[12] K. Khurshid, R. Mahmood and Q. ul Islam, "A survey of camera modules for CubeSats - Design of imaging payload of ICUBE-1," 6th International Conference on Recent Advances in Space Technologies (RAST), Istanbul, 2013, pp. 875–879.