An autonomous buoy system for observing spring freshet plumes under landfast sea ice

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Abstract

An ice buoy system was developed to measure oceanographic properties of freshwater plumes that occur in Arctic coastal oceans under landfast sea ice during the spring freshet. By implanting such systems into sea ice weeks or months in advance of the freshet event, sensors can be located immediately underneath the sea ice layer in situ at depths that riverine freshwater will occupy later when the freshet arrives. This observing approach is modular, can accommodate a wide range of sensors, is designed intentionally for use in remote regions, and can be readily deployed in any nearshore region that can be accessed by snowmachine. The buoy system incorporates an integral floatation collar that allows it to continue sampling as the coastal ocean becomes progressively ice free in the months after the freshet event. Automated sampling and telemetry via a satellite data network provide near-real-time observations of the timing and character of under-ice freshet plumes. An assessment study was done with an array of these ice buoy systems, outfitted with basic hydrographic and optical sensors and deployed in advance of the 2018 and 2019 freshets in landfast sea ice near the mouths of three coastal rivers in Stefansson Sound, Alaska.

The spring freshet is a significant annual event in many coastal regions of the Arctic Ocean. During the freshet, rivers transport recently melted snowpack from the adjacent landmass into the coastal ocean over a period that lasts from a few days to a month or more. How the arriving freshet interacts with coastal Arctic waters is difficult to observe, partly because its timing is hard to predict given year-to-year differences in weather over the adjacent watersheds. An additional complication is that the freshet typically arrives while coastal Arctic regions are still covered by sea ice from the prior winter (Walker et al. 2008; Lesack et al. 2013). The arriving riverine freshet forms a plume that flows on top of but also directly underneath the landfast sea ice layer, both flooding the ice surface and contributing thermally and mechanically to its degradation. Several studies have obtained insight into the hydrographic and biogeochemical character of these under-ice freshet plumes through boreholes augered through the overlying ice layer, via direct sampling and short-term instrument deployments (Ingram and Larouche 1987; Macdonald and Carmack 1991; Dittmar and Kattner 2003; Krell et al. 2003; Granskog et al. 2005a,b; Alkire and Trefry 2006; Weingartner et al. 2017). Beyond the basic challenge of timing on-site sampling to coincide with the arriving freshet, such a manual observing approach is also highly dangerous given the hazards associated with working in and transiting across flooding or degrading sea ice.

These observational challenges, combined with the inherent difficulty of accessing nearshore field sites over much of the Arctic margin during the ice season, suggest that new autonomous sampling approaches should be explored for obtaining better insight into spring freshet dynamics in the coastal Arctic Ocean. Recent advances in oceanographic sensing, autonomous datalogging, and data telemetry can each contribute to improve autonomous observing of spring freshet waters directly beneath coastal landfast sea ice, especially for situations where direct manual sampling is unsafe or ill-advised. In principle, sensors and dataloggers can be implanted in nearshore sea ice in the late winter or early spring to measure ice-ocean properties in advance of, during, and after the freshet arrives in subsequent weeks. One drawback with this approach is that the freshet itself contributes significantly to the breakup of sea ice, almost guaranteeing that any implanted sensor system will be lost or damaged which in turn risks the loss of any collected data stored onboard. This risk of loss also scales observational costs with the number of sites to be studied, which increases expense when broad- or fine-scale observations are desired. Another observational challenge is that many sensors that might be useful in such polar, through-ice,
weeks- to months-scale studies may themselves have not yet been tested for robustness or failure modes in such scenarios. These combined risks argue for autonomous sensing approaches that are effectively disposable, that can carry low-cost sensors appropriate for under-ice environments, and that can telemeter any collected data in near-real-time.

This contribution describes technical, operational, and logistical considerations behind a new autonomous ice buoy approach for observing spring freshet dynamics in ice-covered coastal oceans. This approach is designed for use in remote regions, is adaptable to a wide range of sensors, can be deployed with minimal field support, and can continue sampling in open water conditions after ice breakup. It uses a low-cost satellite channel to telemeter data in near-real-time and includes geolocation capabilities to track each buoy’s location after ice breakup. It requires minimal fabrication or technical skills compared to other potential solutions for ice-based autonomous ocean sampling. Initial assessments in a near-shore lagoon system in Stefansson Sound, Alaska, provided insight into the advantages and challenges with using such a buoy-based approach to observe hydrographic and other properties of under-ice freshet plumes.

**Use materials and procedures**

The observational approach described here involves an ice buoy system comprising three main subunits: an above-ice surface float assembly, a datalogger and telemetry assembly affixed above the float, and a subsurface spar assembly below the float to which under-ice sensors can be attached (Fig. 1). This three-piece design is somewhat arbitrary but represents a configuration that simplifies logistics with shipping equipment to Arctic regions, that can be preassembled in a manner that eases transport into the field, and that requires only minimal tools and time to assemble once on site.

**Surface float assembly**

A float assembly was designed around an off-the-shelf mooring buoy (Taylor Made Sur-Moor taper buoy, 24” diameter, #46724) that allows these ice buoy systems to continue sampling over the full course of the freshet event and afterward, once sea ice has broken up and the buoy becomes free-floating in open water during early summer. These mooring buoys have an axial hole through which a 36” length of stock 2½” threaded aluminum pipe was inserted as a center structural member. A stock 2½” threaded pipe flange was fitted to the top of the pipe and fitted to a machined ½” thick aluminum plate with mating holes drilled to match those on the flanged bottom of the datalogger housing that sits above (see next). In the section of pipe that protruded below the float, three ¼” through holes were drilled for bolting the subsurface strut directly to the pipe. This pipe-centered structural solution was required because the inner diameter of the float’s central hole is slightly too narrow to accommodate standard 1–5/8” strut channel, which would have simplified this design considerably. A different float with a slightly larger central hole would allow for different designs that use strut channel throughout for structural elements. Cables carrying power to and data from each subsurface sensor are routed upward through this central pipe and mated to bulkhead connectors (SubConn Micro Circular series, MacArtney) clustered in the center of the bottom plate of the datalogger housing. Given the inner diameter of this stock pipe, it was possible to arrange these three standard connectors on the datalogger’s bottom plate so that they all fit within the internal diameter of the pipe, providing additional protection in the field.

**Datalogger assembly**

The datalogger assembly in these buoy systems serves three key functions: (1) powering and sampling the various sensors integrated into the system, (2) transmitting the resulting data via a satellite data network, and (3) storing the data onboard.
for potential future download if desired. These requirements do not require complex electronics and can in principle be met by off-the-shelf or even hobbyist microcontrollers. For convenience, for our initial prototypes we modified a general-purpose datalogger framework designed earlier for very-low-power polar ocean observing applications (Laney 2017). The core microcontroller (AVR XmegaD3, Atmel) is from a family of devices widely used both in research- and hobbyist-grade microcontroller applications. That feature, and writing the firmware in C, enables easy use and reuse of openly available code for supporting the more complex tasks such as correctly performing the Iridium transmission protocols and storing data on removable cards (Fig. 2). The datalogger firmware includes several operational parameters that a user can set in advance, or alternatively in the field by communicating with the system via a diagnostic host serial port connector on the top of the datalogger housing. If parameters are programmed on shore prior to transport into the field, a pigtail with an indicator LED can be simply attached to this port once on site to initiate start-up and assess basic initial operation without requiring a computer to communicate via the host port.

**Housing**

For these initial prototypes, the datalogger electronics and battery pack were contained in a custom waterproof canister made from an 18" long, 5" internal diameter, and stock aluminum pipe of 1/4" wall thickness. A cover plate welded to the bottom of the pipe provided mounting holes to attach the datalogger assembly to the float assembly below. This plate also included a centered cluster of three threaded holes to accommodate standard oceanographic bulkhead connectors (SubConn Micro Circular series, MacArtney). A removable cover plate on the top of the housing included multiple threaded holes for mounting the Iridium antenna, for a gland for the GPS cable, for a pressure relief valve to vent any released battery gases, and for the diagnostics port bulkhead connector. The top cover plate was sealed with dual piston O-rings and secured to the housing by four external rods to enable easy internal access in the field when necessary. The entire housing was painted with marine-grade epoxy paint. Although a custom design, this housing represented a best-choice option given the design tradeoffs that were considered when designing these initial buoy prototypes such as cost and simplicity, robust use and failure modes, and logistics for deployment and use in the field (Table 1). A custom or off-the-shelf plastic housing would have been a cheaper solution and lighter to transport into the field and deploy, but risk of cracking and breakage was a significant concern given the low ambient temperatures expected in late winter and the rough conditions expected once ice break up began and buoys become free-floating.

**Batteries**

A battery pack provided power for the datalogger and all peripheral sensors, with the batteries placed internal to the datalogger housing and thus situated above the sea ice in the air, not underwater. The latter approach would likely confer some increase in the system’s operational lifetime when air temperature is below ocean temperature, as all battery technologies exhibit shorter lifetimes with decreasing temperatures. However, placing batteries in separate subsurface housings is more complicated technically and those housings would be difficult if not impossible to access in the field once they become frozen into sea ice. Because it is generally more feasible to revisit systems deployed in coastal landfast sea ice than in open ocean pack ice, we designed the overall buoy system so that as much of the system as possible was situated above the ice in case later servicing or reconﬁguring were required. We designed the entire buoy system to operate with standard alkaline-zinc/manganese cells for several reasons. Such cells perform adequately at our anticipated air temperatures (typically above –20 °C in this region) and they are readily available, considered nonhazardous for transport, and unlike some other battery technologies can be readily disposed of after use without special procedures. Our prototypes involved three stacks of five high-capacity 1.5 V D cells (Panasonic LR20XWA) wired in parallel in a diode-OR conﬁguration, purchased pre-made from a standard vendor (DigiKey). We anticipated that three stacks of these particular cells would

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**Fig. 2.** System architecture. Open boxes indicate components internal to the datalogger housing. Light shaded boxes indicate components mounted externally to the housing top. Dark shaded items are sensors affixed to the strut in the current study. Stippled boxes represent available ports unused in the current study.
be adequate given our anticipated operational lifetimes, anticipated ambient air temperatures during the deployment window, and the temperature performance characteristics of these cells. Longer observational lifetimes can be achieved simply by adding additional stacks, as the system is not inherently space-limited with respect to battery payloads. In principle these systems could be operated with multiple combined power sources, such as solar cells or wind turbines if necessary, to sustain higher power demands that those we required for our field study.

**Data sampling and telemetry**

The datalogger board used in these prototype ice buoys provides nine independently powered sensor ports that accommodate up to seven serial-output user-chosen sensors and up to two analog voltage-output sensors, with the latter also providing twin logic lines for setting sensor gains. Sensors in this buoy system can be placed external to the datalogger, for example, in the ocean, in the ice, or above the ice, or alternatively internal to the datalogger housing if preferable such as for inertial or tilt-roll sensors. The specific sensors used in this spring freshet assessment study (Fig. 2) are all off-the-shelf oceanographic units that could be directly interfaced to this datalogger. These included a miniature conductivity-temperature module (DST CT), two optical sensors (Cyclops-7U and -7T for fluorescent dissolved organic matter [FDOM] and for optical backscatter [OBS], respectively; Turner Designs), and an upward-looking acoustic ranger to monitor ice ablation over time (Airmar Echorange SS510). Only with the Star Oddi CTD were additional electronics needed to interface its logic-level serial lines to the RS232-levels expected by the datalogger board. For simplicity we accomplished this using the manufacturer-supplied logic level converter module, placing it inside the datalogger housing. Other off-the-shelf modules can in principle similarly be incorporated easily into this datalogger system, for example to provide other interfaces commonly used with relevant ocean or ice sensors such as the 1-Wire bus used by Jackson et al. (2013) to profile sea ice temperatures. This approach minimizes the need for new custom electronics or for major changes to the datalogger’s firmware to accommodate different observing needs. All sensors are individually powered and separately fused in case any single sensor shorts or fails, for example, if a subsurface power and data cable is severed by sea ice or if an above-ice cable or sensor is damaged by weather or by interference by bears. The Iridium modem and the GPS receiver are each interfaced through separate, dedicated, independently powered serial ports.

Sampling of sensors in this system follows a sequential process coded into the datalogger’s firmware (Fig. 3). Upon initial power-up, the datalogger attempts to connect to the Iridium satellite network and if successful, interrogates the network to determine time and date in case the system’s internal clock has failed or drifted. The datalogger then performs an initial

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**Table 1.** Example design elements relevant to Arctic nearshore use of buoys in landfast sea ice. Possible decision trade-offs are noted in the bottom row.

| Manufacturing | Field deployment | Supply chain | Environmental impact |
|---------------|------------------|--------------|----------------------|
| Robust to survive ice-out and later beaching or grounding. | Preassembly and ease of field assembly. | Modular for transport by small planes, vans, snow machine. | Trackable for later recovery. |
| Use of technologies and materials supportable in remote communities. | Resistant to vibration during transport by sled. | Batteries that require no special shipping considerations. | Nonhazardous batteries for ease of disposal. |
| Possible design choices or alternatives | Serviceable on return visits to site. | Components that are available in remote regions. | Use of materials that can be repurposed in remote coastal communities. |
| Metal vs. plastic housing. | Transport to field site semi-assembled vs. fully assemble on ice. | Batteries that are easy to purchase and ship but low performance, vs. better performance but difficult to buy and ship. | Hazardous batteries vs. disposable batteries. |

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**Fig. 3.** Operational sequence for these buoys, initiated at power up.
sampling sequence that involves collecting housekeeping data on battery levels and other system status indicators. The system then sequences through each attached sensor: powering it, configuring it if necessary (for example to set gains adaptively, as was done here with the two optical sensors), receiving its data, powering the sensor off, and adding that data into the full data record being prepared for satellite transmission. The firmware included contingencies for skipping any individual sensor in this sequence which might result from failure over the course of the deployment. Sequential sampling of sensors in this manner minimizes the instantaneous load placed on the battery pack at any given instant.

Once all sensors are sampled and if an Iridium link was detected at startup, the full data record is telemetered off the datalogger via the Iridium Short Burst Data (SBD) network using an Iridium 9602 miniature modem. Iridium’s SBD service provides two-way transport for messages: both Mobile Originating and Mobile Terminated, and data costs for Iridium SBD service are comparable to a cell phone plan. For the amount of data collected in our assessment study during any given wakeup event, a single 330-byte SBD data packet was sufficient for transmitting the entire data record in plaintext. The Iridium antenna was a fixed-mast design (AT1621-142, AeroAntenna Technology) placed at the highest point above the datalogger housing but close enough to its body to minimize any anticipated bending or breaking due to interference by bears. Once the Iridium transmission is completed, or if failure occurs after three retries, the datalogger then sets a wakeup timer for the next sampling event, computed from a user-specified sampling interval (in hours, stored in the datalogger’s nonvolatile memory) that is aligned with midnight Universal Time. The datalogger then puts itself into a very-low-power sleep mode to await the next wakeup event at which point the sampling sequence begins again.

Geolocation

For studies conducted in landfast sea ice like ours, ice buoy locations are not expected to change appreciably before or at the onset of the freshet event. So, geolocation may not be an important design element in the weeks leading up to the freshet event. However, later in the spring and early summer, these buoys become free-floating after ice breakup and are likely to wash ashore nearby along the coastline or, in our study area in Stefansson Sound, on barrier islands within the region. Having each buoy self-report its location was therefore essential for retrieving any beached buoys later in the year when the area could be accessed by boat. Recovery is beneficial, not only to re-use recovered equipment in any future field seasons but also to minimize the amount of abandoned equipment along shorelines that local communities use for subsistence hunting. The Iridium network provides rough geolocation information associated with each transmission detected by the satellite network, but these data are not precise enough for easy retrieval of beached systems. Therefore, a weatherproof serial-output GPS module (Garmin 18x LVC) was attached externally to the top cover plate of the datalogger housing, to be powered and polled at each sampling event with locational information incorporated into the transmitted data packet.

Subsurface spar assembly

Sensors to be placed in the water column below the sea ice layer are affixed to a subsurface spar assembly that is bolted to the projecting section of the central structural pipe, immediately below the float assembly (Fig. 1). For our prototype systems, this spar was a length of standard 1–5/8" stainless steel strut channel. The necessary total length of the spar can be roughly estimated in advance of arriving on site in the field, for example, from prior knowledge of seasonal ice thickness, and shorter sections of spar can be brought into the field and assembled into longer lengths using standard strut channel couplers as needed to achieve any length desired. Sensors can be placed at any location along the spar, at spacings either determined ahead of time or chosen in the field based on the actual ice thickness measured at a given deployment site. In principle, systems can be deployed anytime in the sea ice season, even early in the year during periods of increasing ice thickness, provided that any sensors near the ice-ocean interface can survive potential freeze-up.

For ice conditions expected in our study region in late spring, we selected 10’ lengths that can be readily carried into the field on sleds towed by snow machine. Such lengths would be sufficient earlier in the season given historical ice thicknesses in Stefansson Sound, except perhaps for areas with substantial ice ridging where additional lengths may be needed. An added benefit of using strut channel is that its U-shaped cross section provides a natural cavity to route cables for added protection, which we accomplished in our deployments using electrical tape. Another benefit in remote regions is that such strut channel may be readily repurposed in local communities, which reduces waste of any buoy components that may be recovered at the end of a given field study. The off-the-shelf mooring buoys that are used for floatation in this system are another design element that could find ready reuse in coastal communities.

Deployment of these systems in our assessment study involved on-shore preassembly of the miniature conductivity-temperature module and the two optical sensors, all within a common 6” length of standard precut rectangular cross section aluminum channel (8” x 2”), using off-the-shelf mounting hardware. Once in the field, this module was bolted to the subsurface spar at locations dictated by the thickness of ice measured through the boreholes drilled at each individual deployment site. The fourth subsurface sensor (the upward-looking acoustic ranger) was placed further down the strut to ensure that this sensor was initially located at least 50 cm away from the ice bottom to range correctly (Fig. 1). This fourth sensor was mounted to the strut using a standard strut channel bracket that was machined slightly to hold this
sensor. Cables to connect all sensors to the datalogger were fabricated with standard oceanographic connectors and pig-tails (SubConn Micro Circular series, MacArtney) and neoprene cable, using inexpensive adhesive-lined shrink tubing where splices were needed. All cables were fabricated long enough to accommodate sea ice thicknesses greater than usually expected in our study region. When assembling in the field, extra cable was looped and secured to the spar.

**Assessment study**

We assessed this new ice buoy design in a spring freshet plume study within the coastal lagoon system of Stefansson Sound, Alaska, in 2018 and 2019. In late spring of both years, we deployed an array of these buoys bracketing the outflows of three rivers that feed this region: from east to west the Shaviovik, the Sagavanirktok, and the Kuparuk. The deployments were timed so that these buoy systems and under-ice sensors would be implanted several weeks in advance of the anticipated onset of the spring freshet. For our 2018 field season, we designed and fabricated the initial ice buoy prototypes, assessed their performance in the laboratory, and shipped five systems in late April by commercial air (FedEx) to Fairbanks, Alaska, and then on to Deadhorse, Alaska, roughly 400 mi by van. The stopover in Fairbanks was used to assess Iridium throughput and dropout at higher latitudes than could be examined at the location of fabrication (Woods Hole, Massachusetts, 41.5°N). During the time of this study, the Iridium network was managed such that certain satellites in the constellation were put in power-saving mode while over the poles to extend the lifetime of the Iridium network until newer satellites could be added to the constellation. For users at high latitudes, this required additional attention to Iridium connection protocols in order to handle dropouts and retries correctly. We reassessed Iridium throughput and made necessary modifications to firmware once upon arrival in Fairbanks (64.8°N) and then later in Deadhorse (70.2°N) before deploying buoys in the field. Buoy deployments in 2019 were similar in overall execution but involved two trips to Stefansson Sound: one in late April to initially deploy systems and a subsequent one in late May to address technical issues with some of the systems. Fortunately, this second 2019 visit coincided with the onset of that year’s freshet event which provided a unique opportunity to assess deployment approaches and functionality of these buoy systems while the sea ice was in the process of being flooded by the arriving freshet.

Field deployment involved shoreside preassembly and preparation of the sensor clusters and associated cabling, as well as final tests for Iridium connectivity. Partially assembled buoys were towed on sled by snowmachine to predetermined sites within the Stefansson Sound lagoon system. Once arriving on site, surface snow was cleared by shovel and two overlapping ice holes were drilled using a standard 8” diameter auger. With these initial prototypes, two overlapping holes were needed to accommodate the particular assemblies we fabricated to hold the CT and optical sensors. Other configurations with physically smaller sensor assemblies might require only a single hole. While the holes were being augered, the buoy subassemblies were mated together using stainless steel hardware. Ice thickness was then measured through the augered holes and used to determine the distances along the spar to bolt the sensor modules so that they would be located at the correct depths in the water column after the buoy is seated on the ice. For our study, the topmost cluster carrying the CT and optical sensors was affixed to the strut such that these sensors were ~15 cm below the ice-ocean interface on the day of deployment. At the time of year, these buoys were deployed (late April/early May) further ice growth was not expected and we anticipated only minimal bottom ablation of the ice layer in the few weeks before the freshet’s arrival. Thus, sensors placed this close to the ice bottom were unlikely to be subsequently encased in new sea ice and likely to remain at depths appropriate for sensing the arriving freshwater plume as it rode on top of the denser ocean water immediately beneath the sea ice layer. Once fully assembled, the buoys were hand-lowered into the ice hole and allowed to freeze in. If pre-assembled and deployed in this way, a team of four people using two snowmachine-towed sleds can carry two full buoy systems and associated deployment equipment (e.g., ice augers and shovels) and safety equipment (e.g., survival gear, satellite phone, and firearms) in a single trip onto the ice. With one person serving as bear guard, a buoy system can be deployed by the remaining three through ~1–2 m of ice in less than 1 h of arrival on site.

Buoy systems in 2018 were activated by connecting the datalogger to its internal battery which could be done either on shore prior to transport to the deployment site or at any time later. In 2019, systems were activated by connecting a hard-wired pigtail with an indicator LED to the diagnostic connector on top of the datalogger housing. Blink codes through the LED provided users with an indication of power-up and sampling status, useful in the field. Power-up initiated a single data sampling event and immediate telemetry of those data through the Iridium network. For sites close enough to shore where cellular data service was available, buoy function could be ascertained with roughly a 1-min latency by checking email for incoming Iridium messages transmitted by the buoy and relayed by the Iridium network. Because buoy data packets are sent in plaintext, performance of individual sensors in each buoy system could be ascertained immediately. Once the systems performed their initial sampling protocol, attempted to connect to the Iridium network, and transmitted the resulting data packet through the network using a limited number of retries, a timer was then set for later wake-up. The systems then went into low power sleep mode to await subsequent wake-up. In this study, we programmed each buoy to wake at 6 h intervals synchronized to Universal Time midnight and programmed all buoys to increase this interval to
1 d if they lasted into August of that year, in order to conserve battery power and to maintain the ability to self-report locational information if still adrift or unrecovered by that time of the year. Once each buoy was determined operational it was left to freeze in and continue sampling autonomously and indefinitely, until the battery was depleted or the system was otherwise rendered inoperable.

Deployments in 2018 occurred in April, several weeks in advance of the freshet event and early enough in spring so that weather and ice conditions provided for safe fieldwork. Of the five buoys that were deployed, one failed immediately (K1; Fig. 4a) and eventually transmitted only a single message ~53 d after deployment. The remaining four systems continued operating throughout the 2018 freshet event, surviving subsequent ice-out and continuing to sample for 2–4.5 months albeit with data transmission failures increasing over time, possibly due to changes in antenna orientation as these buoys broke out of landfast sea ice (Table 2). Once free from landfast ice, two of these buoys drifted locally within the lagoon system and eventually beached on the coast (SN1) or on a nearby barrier island (KS1; Fig. 4a). These two systems were recovered later in August by small boat during the open water season. The remaining two buoys both drifted out of the lagoon system once released from landfast ice (Fig. 4b). One (N1) was recovered at sea by another research group who spotted it floating free off the village of Kaktovik, to the east of our study area. Because each buoy transmitted its location every 6 h, we were able to infer the at-sea recovery of buoy N1 by its subsequent apparent rapid transit toward and into Kaktovik. The other buoy ejected from the lagoon system (S1) also drifted eastward past Kaktovik after ice breakup, moving toward the Canadian border before reversing direction to follow the shelf break westward. The onboard external GPS module failed during this time but the buoy’s location as reported by the Iridium network indicated its last known position roughly 285 km northwest of Utqiaġvik, Alaska, in the Chukchi Sea. This buoy remains unrecovered.

Ice buoys for the 2019 field season included a number of technical modifications to assess possible improvements to the initial design, such as the diagnostic pigtail described above. These modifications involved the use of 3D printing to fabricate battery packs and internal support struts for the datalogger and the addition of a pressure-relief safety valve on the datalogger housings. Internal struts made by 3D printing with polylactic acid were especially fragile in the low-temperature, high-vibration environments of deploying these systems from snowmachine-towed sleds and failed mechanically. These 2019 buoys were also deployed in late April, well in advance of the anticipated onset of the spring freshet, but enough buoys experienced some level of technical issue with these various exploratory design modifications to warrant a revisit in late May. Fortunately, this revisit coincided with the onset of that year’s spring freshet event which provided an opportunity to assess our design with respect to buoy servicing and deployment in near-flooding ice conditions. All four of these 2019 buoys survived ice-out and were recovered later in the year by small boat or by foot from shore, after eventually beaching in the region (Fig. 4c).

When recovered, only two of these buoys showed any substantial physical damage from being implanted in the sea ice: for example, bent struts and/or severed cables. To ensure the best data quality, these sensors and cabling would typically not be reused for subsequent observational studies. The
Iridium transmission statistics of these nine buoy systems, as well as diagnostic information that was embedded in each transmitted data record, provided information on the longevity and reliability of this ice buoy design and on failure modes unforeseen in the initial design stage (Table 2). The single transmission sent by the failed 2018 K1 buoy, roughly 53 d after deployment, indicated that battery voltage had dropped substantially, suggesting an electrical failure in the unit. The longest-lasting buoy systems from our 2018 deployments (S1 and SN1) transmitted messages with near-perfect Iridium reliability for 142 and 136 d, respectively. The 2018 buoy with the lowest reliability in transmitting data (N1) exhibited decreasing percentages of transmissions compared to the number expected, progressively over its 3-month lifetime. The N1 buoy also reported the weakest average Iridium signal strength of all buoys tested in this study, beginning with the day it was deployed and suggesting a modem or antenna issue that arose during transport into the field. Coastal sea ice conditions were different in 2019 than in 2018 and all 2019 buoys were released from the ice and beached earlier in the season. Thus, deployment lifetimes appear shorter even though all four buoy systems transmitted data regularly and reliably between deployment and beaching. Low voltages reported by the 2019 K1 buoy at the end of its lifetime suggest that anomalous battery drain was responsible for the dramatic drop in percent transmissions seen in this buoy’s third month in service. Beyond assessing the performance of these ice buoy systems overall, an important secondary goal was to evaluate the specific low-cost oceanographic sensors used in this study in order to identify failure modes when used in such challenging, under-ice observational scenarios. For our intended study, the required accuracy and precision of certain parameters, such as salinity and temperature for identifying a riverine plume intruding into the coastal ocean, encouraged us to use substantially less complex and expensive sensors than are typically seen in oceanographic research. In principle, this lessens cost and mitigates risk of loss, but only if these lower-cost sensors provide data of adequate quality and reliability. In our assessment study, certain sensors did show concerning levels of failure, in particular the conductivity channel of the miniature CT sensors which were uniformly poor in these deployments. Unfortunately, with minimal built-in diagnostic capabilities, it is difficult to draw firm conclusions about the specific failure modes of these or other sensors. Analyses from these deployments indicated that at some periods during the freshet, the water column directly beneath the ice layer contained intermittent frazil ice (Okkonen and Laney, in press) which may have contributed to poor sensor performance. Replacing these inexpensive sensors with more expensive traditional ones would not necessarily result in better data if the failures were due to freezing. Yet even accounting for anticipated failures in at least some of the deployed buoy systems or with individual sensors, the observations we collected using this ice buoy approach provided new insight into the hydrographic and optical properties of the arriving riverine freshet plumes.

The arrival of riverine freshet waters can be seen clearly in time series of temperature, optical backscattering, and dissolved fluorescent matter under the landfast ice a function of time (Fig. 5). Interestingly, the optical characteristics of the arriving freshet plumes exhibited changes over time, for example in the relationship between the two measured optical properties (FDOM, interpreted as a proxy for dissolved organic matter, and OBS, interpreted as a proxy for particulate matter) seen before, during, and after the onset of the freshet (Fig. 5c, shaded boxes). Biofouling was anticipated to be negligible at this time of the year, given that deployment occurred after the main ice-algal growth season in otherwise cold, low-biomass Arctic waters. This was confirmed later in the summer during

| Buoy | Lifetime (d) | Messages | Average signal strength | Final voltage | % received 0–30 d | % received 31–60 d | % received 61–90 d |
|------|--------------|----------|------------------------|---------------|------------------|-------------------|-------------------|
| 2018 K1 | 0 | 1 | 5.0 | 10.0 | 0 | NA | NA |
| 2018 KS1 | 91 | 362 | 5.0 | 14.8 | 100 | 100 | 97 |
| 2018 S1 | 142 | 562 | 5.0 | 14.8 | 97 | 100 | 98 |
| 2018 SN1 | 136 | 523 | 4.9 | 14.5 | 99 | 99 | 99 |
| 2018 N1 | 85 | 233 | 4.7 | 14.7 | 76 | 63 | 0 |
| 2019 K1 | 78 | 277 | 4.9 | 12.5 | 102 | 99 | 0 |
| 2019 KS1 | 46 | 177 | 5.0 | 15.2 | 101 | NA | NA |
| 2019 S1 | 80 | 285 | 4.9 | 14.7 | 100 | 98 | 0 |
| 2019 N1 | 87 | 285 | 4.9 | 14.5 | 101 | 99 | 0 |
the recovery of systems that had washed up along regional shorelines which showed no appreciable biofouling of the sensor faces. A detailed interpretation of the variability seen in these data records is outside the scope of this methodological assessment, but the absence of biofouling in all recovered buoys suggests that the observed changes in under-ice optical properties were actual and not artifactual of the sensor. Our ability to recover these buoy systems after ice-out, due to the onboard geolocation information, was essential for us to confirm this expectation.

Discussion and recommendations

To the best of our knowledge, this approach of implanting dataloggers in nearshore landfast sea ice to measure and telemeter underlying water column properties during the spring freshet is novel and addresses an unusually difficult challenge of observing spring freshet plumes in situ in ice-covered coastal oceans. Spring freshet interactions are of increasing interest in Arctic coastal systems as adjacent watersheds experience greater climate-driven changes that affect the riverine transport of freshwater, heat, and dissolved and particulate matter into the coastal ocean (Peterson et al. 2003; Terry et al. 2006; Spencer et al. 2015). Designing telemetering buoys suitable for use in nearshore landfast sea ice, such as in this spring freshet plume study, involves considerations that may be less relevant for buoy-based observing in open-ocean pack ice, for example, when designing systems such as those described by Jackson et al. (2013), Wang et al. (2014), or Hill et al. (2018). Our design also enhances the repurposing of research equipment after seasonal use, where we fabricated our systems out of materials such as strut channel and commercial floats that may be of value and use to local communities. Both strategies help to reduce the environmental and societal impact of abandoned or damaged research equipment in these sensitive areas. This is of particular importance in our Stefansson Sound study area where local communities use the coastline and barrier islands after ice-out each year for subsistence hunting. Recovery of equipment fosters better regional relationships and represents good stewardship. Other aspects of this ice buoy that are more related to aspects of deployment and technical performance similarly reflect design considerations that may be particularly relevant to use in nearshore landfast sea ice (Table 1).

Deployment of these prototype buoys over two field seasons provided valuable information for continued improvement of this design and approach. Certain mechanical aspects of these prototypes, such as the aluminum datalogger housing, were deliberately overengineered to increase robustness and reduce overall risk of failure in these initial assessments. We believe improvements can be made to the datalogger housing to use thinner-walled aluminum tubing and simpler fabrication approaches, which would reduce weight and cost while maintaining robustness during open-water conditions and subsequent beaching. In the same vein, the Iridium antenna used in these prototypes was chosen due to prior experience, but other lower-profile antennas may perform equally well and eliminate weak points for mechanical damage in the current design. Other specific sensors than the ones we used here could also be adopted in future deployments, for example, to provide more robust measurement of conductivity.

In terms of operations, our field assessment suggests that salinity measurements immediately under ice may be
unreliable with the sensors we used, and also that the freshet arrival may be adequately inferred from temperature alone. Given this core observing need for freshet studies, redundant temperature sensors are probably worth including in future designs if a more robust CT sensor cannot be identified. In principle, there are no inherent technical limitations on adding any other CT sensor to this ice buoy platform that can support real-time output. A second temperature sensor was actually present on our subsurface spar in these deployments, as a secondary sensor internal to the acoustic ranger. As this sensor was located well below the ice-ocean interface in order to enable accurate distance ranging, it was only valuable for measuring water temperature at depth and not in the layer of the arriving freshet. Although in our freshet study we did not measure temperature at depths within the ice layer itself, such information would be of value for assessing flooding of the ice layer by any freshet plume flowing on top of the ice. An array of temperature sensors similar to that described by Jackson et al. (2013) could in principle be fitted to the exterior of the float assembly’s center pipe to accomplish this, similar to the manner described by Polashenski et al. (2011). Such an array of temperature sensors would be trivial to interface to the datalogger as designed currently.

In terms of telemetry, the current design uses a simple retry algorithm to recover from Iridium transmission failures during any sampling event. More advanced retransmission strategies can be envisioned that could retain data from prior failed transmission attempts and strategically attempt to retransmit when an Iridium connection is next established. Given that the Iridium modem is the major draw on system power, any such strategies would need to be considered carefully in order to minimize the cost in battery life of attempting to retransmit data packets that fail initial transmission. However, the Iridium constellation and network currently are more robust than when these assessment studies were first conducted, and so a lesser need for retries might be expected. In our initial prototypes, we did not take advantage of the Iridium network’s Mobile Terminated capabilities that support sending messages to these buoys while deployed. However, such a capability could, for example, allow buoys to be reconfigured remotely to adjust sampling parameters throughout the course of any study. Such a capability can be added to this system if needed, for studies where it would be beneficial.

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