

Seasonal ice mass-balance buoys: adapting tools to the changing Arctic

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ABSTRACT. Monitoring the local mass balance of Arctic sea ice provides opportunities to attribute the observed changes in a particular floe's mass balance to specific forcing phenomena. A shift from multi-year to seasonal ice in large portions of the Arctic presents a challenge for the existing Lagrangian array of autonomous ice mass-balance buoys, which were designed with a perennial ice cover in mind. This work identifies the anticipated challenges of operation in seasonal ice and presents a new autonomous buoy designed to monitor ice mass balance in the seasonal ice zone. The new design presented incorporates features which allow the buoy to operate in thin ice and open water, and reduce its vulnerability to ice dynamics and wildlife damage, while enhancing ease of deployment. A test deployment undertaken from April to June 2009 is discussed and results are presented with analysis to illustrate both the features and limitations of the buoy's abilities.

THE IMPORTANCE OF MASS-BALANCE MEASUREMENTS

The mass balance of the Arctic sea-ice cover, which incorporates both thickness and extent of ice, is widely recognized as an indicator of climate change. Observations consistently indicate that the sea-ice cover is undergoing dramatic change. Satellite microwave (Comiso and others, 2008; Stroeve and others, 2008), satellite altimeter (Kwok and others, 2004), submarine sonar (Rothrock and others, 2008; Kwok and Rothrock, 2009) and mooring-based profiling observations (Melling and others, 2005) collectively have shown that both extent and thickness of Arctic sea ice have declined dramatically over the observational records. While general circulation models have predicted that sea ice may decline rapidly in response to climate change, the observed declines have been more dramatic than anticipated from the models (Stroeve and others, 2007). A complex array of interrelated factors have been found to contribute to this decline, including: ice-albedo feedback (Perovich and others, 2007, 2008), cloud feedbacks (Francis and Hunter, 2006; Kay and others, 2008), increased ice export (Kwok, 2009), advection of ocean heat from lower latitudes (Schauer and others, 2004; Woodgate and others, 2006) and atmospheric circulation patterns (Hilmer and Jung, 2000; Rigor and others, 2002). The relative impact of these factors is of high importance for improving climate model predictions and is therefore a topic of significant current research.

One variable which can help to quantify directly the impact of the thermodynamic factors on ice loss is the local mass balance of the ice. The local mass balance is simply the amount of ice growth in the winter and the amount of surface and bottom melt in the summer occurring on a specific floe. Changes in local mass balance reflect the integration of all the terms in the surface heat budget and ocean heat flux on a single piece of ice, tracking an ice floe's journey through both space and time. Measuring the local mass balance with high temporal frequency provides information on the timing, location and rate of changes in ice mass balance. When this information is coupled with

meteorological and oceanographic measurements it provides evidence that can be used to connect measured anomalies in forcing factors to their impacts on the ice mass balance.

THE ICE MASS-BALANCE BUOY

Over the past decade, autonomous ice mass-balance buoys (IMBs) have been deployed in the sea-ice cover, most recently as part of an International Polar Year effort to develop a component of an Arctic Observing Network. The buoys measure snow depth, ice thickness, ice growth, surface melt and bottom melt, as well as a temperature profile through the ice, air temperature, barometric pressure and ice drift. The buoys are an in situ, autonomous measurement system capable of delineating thickness changes between the top and bottom of the ice. By doing so, the buoys provide a unique insight into the sources of change (Richter-Menge and others, 2006). Results from these buoys are published in near real time to the web (<http://IMB.crrel.usace.army.mil>) and have been featured in several reports on the state of the Arctic sea ice (<http://nsidc.org/arcticseaicenews/2008/-082508.html>; http://www.arcus.org/search/seaiceoutlook/2008_outlook/downloads/monthly-reports/july/Perovich_etal-16-july-outlook.pdf). More importantly, the results have been used to conduct research on many processes affecting the ice cover.

The data collected by the current IMBs can be grouped into four primary categories: ice drift, meteorological observations, ice mass balance, and atmosphere-ocean-ice temperature profiles. Drift data, which are uploaded into the International Arctic Buoy Program for distribution, have been used to correlate ice motion to atmospheric pressure fields (Rigor and others, 2002), validate satellite ice-drift and age estimates used to build the US National Ice Center sea-ice charts (Maslanik and others, 2007; Nghiem and others, 2007) and reconstruct ice-drift paths for sea-floor sediment studies (Pfirman and others, 1997). Air-temperature and barometric pressure data, which are distributed through the World Meteorological Organization Global Telecommunication

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System, have been used in climate variability studies (Rigor and others, 2000; Polyakov and others, 2003) and for weather forecasting efforts. Temperature profiles have been used to evaluate and improve QuikSCAT retrievals of melt and freeze-up dates (Nghiem and others, 2007) and calculate year-round ocean heat flux to the ice (Morison and others, 2002; Krishfield and Perovich, 2005).

The star of the IMB data, however, is the mass-balance information. These data, provided by the acoustic range-finders positioned above and below the ice surface, give year-round high-resolution measurements of the accumulation and melt of snow and the growth and melt of ice. The majority of references that use the IMB data examine these mass-balance data, focusing on melt rate at the top and bottom surfaces of the ice. These two very powerful observations have proven quite useful for building understanding of processes affecting the ice today. For example, mass-balance observations have been used to attribute observed changes in the modal thickness of ice in the vicinity of the North Pole to advective rather than thermodynamic processes (Giles and others, 2008), to attribute changes in ice thickness measured during aerial thickness surveys (Haas and others, 2008) and to validate Ice, Cloud and land Elevation Satellite (ICESat) freeboard retrievals (Kwok and others, 2007). Synthesizing the mass balance with reanalysis products has enabled the attribution of dramatic ice retreat in the Beaufort Sea, Arctic Ocean, during 2007 and 2008 to solar heating of open water and established a strong correlation between ice concentration and bottom melt, illustrating the role of local heating due to ice-albedo feedback in recent ice retreat (Perovich and others, 2008).

CHALLENGE AND NEED

The seasonal ice cover has been a component of the Arctic ice cover throughout the observational record; however, changes in the Arctic are creating larger areas of this ice type. Owing to a variety of processes, including the summer amplification of the ice-albedo feedback and geometric constraints of the Arctic basin (Holland and others, 2006; Serreze and others, 2007), the observed reduction in summer sea-ice spatial extent over the satellite era is much greater than the reduction in winter sea-ice extent. As a result of this seasonally asymmetric ice decline, the perennial ice cover has been retreating faster than the seasonal ice cover. This has significantly increased the area of the seasonal ice zone, while decreasing the area of multi-year ice for which the current IMB systems are designed. In recent years, ice <1 year old has represented as much as 70% of the maximum winter ice extent in the Arctic, an increase from about 40% in 1985. With trends and predictions pointing to further reductions in perennial ice and the potential for a seasonally ice-free Arctic (Overpeck and others, 2005), the processes governing understudied seasonal ice are of growing importance. Data collection systems capable of operating in the seasonal ice zone are needed to help improve the accuracy of both sea-ice and global circulation models. The importance of extending surface-based observations into the seasonal ice zone has been widely recognized (ARCUS, 2005, 2008; J. Calder and others, unpublished information; C.M Lee and others, unpublished information). Meeting this challenge for ice mass-balance observations is the objective of this study.

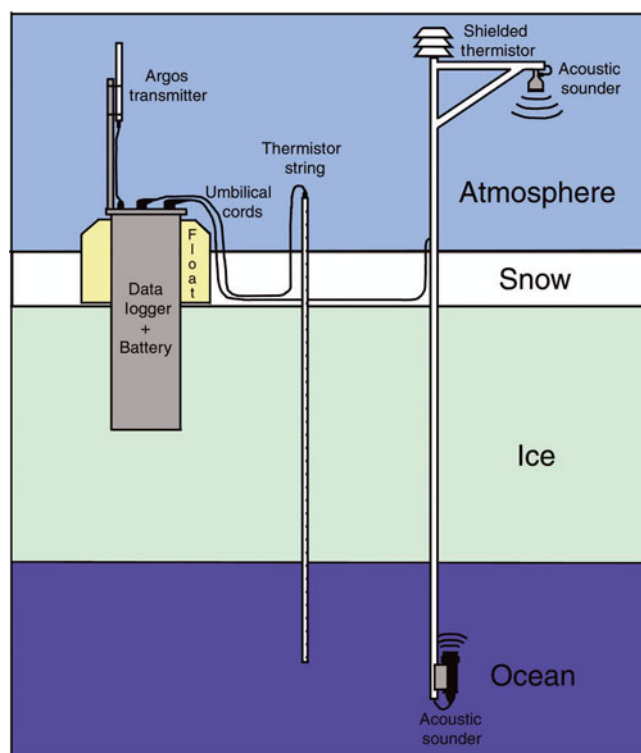


Fig. 1. Schematic of an ice mass-balance buoy (IMB).

An overview of the current IMB design is illustrated in Figure 1. The IMB consists of a central canister with two outlying sensor support structures. The central housing contains the data logger, batteries and satellite transmitter for the unit, as well as a barometer. An air temperature sensor may be located either here or on an outlying support structure, depending on the model. This central housing is deployed into a hole 25 cm in diameter and 1 m deep, which does not penetrate the ice. Deploying these components into the ice helps moderate the temperature extremes they are subject to. The outlying sensors are attached to two support structures which occupy holes drilled through the ice completely and are connected by umbilical cords to a central housing. One structure positions acoustic sonar units above and below the ice to track the surface and bottom position of the ice, while the other positions a string of thermistors to measure a profile of temperature through the snow, ice and upper ocean. These temperature profiles can be used to calculate ocean heat flux or can provide a backup to the acoustic sounders for locating the ice surface and bottom. The buoy is designed for ease of deployment with three common drill sizes and generally takes an untrained team of two individuals about 2 hours to deploy. Production cost of the buoys is approximately \$35 000, which, though inexpensive by arctic platform standards, still limits the size of the array.

While performing well in the multi-year pack (Richter-Menge and others, 2006), the current design of the IMB is not well optimized for the conditions it occasionally encounters in the marginal ice zone or might encounter during seasonal ice deployments. Many hazards encountered occasionally in the perennial pack are expected to be greatly amplified in the seasonal ice zone. These amplified hazards combine with several entirely new problems to shift the optimum design considerably. The multi-component design of the current

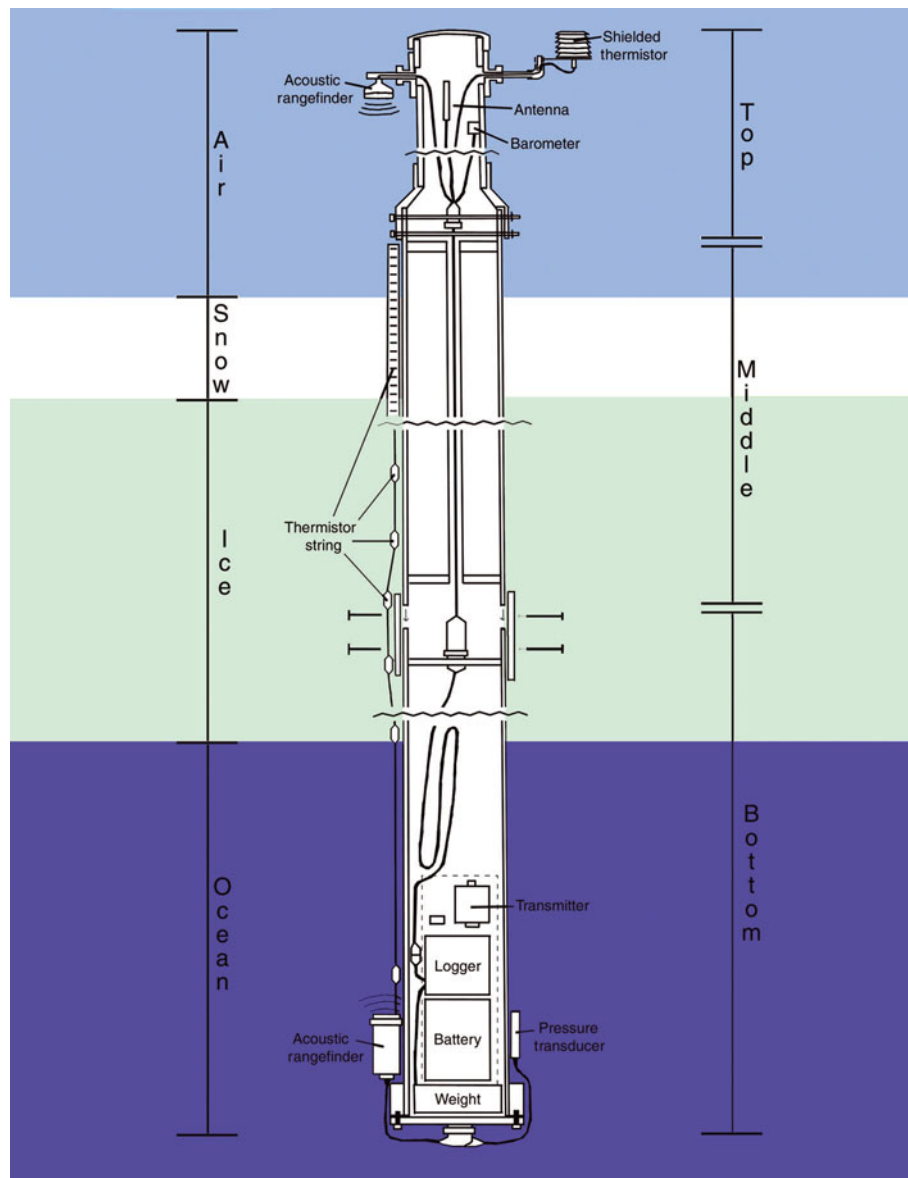


Fig. 2. Schematic of the new seasonal ice mass-balance buoy (SIMB).

IMB, connected by umbilical cords, is one example. The design has the notable advantage of removing the sensors from the area of ice that might be influenced by the properties of the central canister, but exposes the system to greater risks of being rended apart by ice dynamics or wildlife damage. The increased dynamics and higher wildlife densities associated with the seasonal ice zone make the decentralized design less desirable. Placing all instruments on a single housing, on the other hand, presents the challenge of ensuring that the housing does not significantly affect ice conditions near it, necessitating that the buoy hull be reduced in size and altered in material make-up.

The central canister and outlying support structures of the IMB also depend on the integrity of the ice cover for the support that keeps the instruments positioned correctly. While perennial ice cover can ensure the necessary integrity, neither perennial ice which has entered a marginal ice zone nor thinner seasonal ice can be counted on to provide this support. Therefore, the seasonal IMB (SIMB) must be capable of keeping itself upright without ice support. Further, delineating surface and bottom melt using sonic rangefinders positioned above and below the ice requires

that the buoy remain fixed to the ice vertically. Operation in thin ice enhances the risk of the system becoming detached from the ice and slipping, thereby repositioning the rangefinders and thermistor string in relation to the ice and removing the ability to delineate top and bottom melt from the data. Further modifications to reduce the likelihood of slippage and diagnose or correct for such a slip are therefore highly desirable additions.

The end-of-melt season condition in the seasonal ice zone is generally expected to be open water. Any system that is to survive in these conditions must be completely waterproof and float with a known orientation. Even a buoy that can survive floating in open water upright has uncertain odds of freezing back into the ice in the autumn. Risks include freezing of salt spray on the upper buoy, causing the buoy to tip over, and drifting up against the edge of remaining ice floes, where the buoy is more likely to be destroyed by dynamics on the floe's next collision. With a shorter anticipated lifespan in this harsher environment, both reducing costs and enhancing ease of deployment are desirable to leverage resources available to monitor the seasonal ice zone.

OBJECTIVES

Data collected with the IMBs have proven extremely useful. In order to extend these measurements to the seasonal ice zone, the following goals must be targeted by a new system:

1. Minimal dependence on ice for support.
2. Survivability and unaffected operation in thin ice and open water.
3. Reduction in vulnerability to damage by wildlife or mechanical ice motion.
4. Return of quality-control data to diagnose and correct for potential tilt or slippage.
5. Easy deployment by untrained individuals, with minimal equipment.
6. Cost reductions wherever possible.

THE SEASONAL ICE MASS-BALANCE BUOY

The result of our design process is the SIMB (Perovich and others, 2009) depicted in Figure 2. The SIMB has been designed around a single 15 cm diameter spar-buoy type hull which contains, protects and positions the sensors. External wires are reduced to an absolute minimum. The hull floats with a strong righting moment which enables it to position the sensors accurately in relation to sea level, even when completely detached from the ice and floating in open water. The hull is made almost entirely from off-the-shelf PVC components, greatly reducing its cost and matching the thermal properties of the ice. All outer surfaces of the hull are white to minimize solar absorption and preferential melt around the hull. The design is modular, shipping in three sections which fit within typical air express size cut-offs and allow helicopter transport for deployment. The top section (labeled on the right of Fig. 2) both protects the wires and serves as a support tower for the transmitting antenna, air-temperature sensor, barometric pressure sensor and the downward-looking acoustic sounder used to locate the snow or ice surface. The middle section serves to provide buoyancy, support the top section and provides an attachment point for the thermistor string passing through the ice. The bottom section houses the data logger, satellite transmitter and battery, provides an attachment point for the underwater sensors and contains ballast which provides a righting moment to the buoy. The total height of an assembled buoy is 5.5 m, with the top 2 m above the ice surface. Unused hull space is filled with closed cell foam to reduce the likelihood of sinking in the event of a leak and to eliminate convection currents which might otherwise transport energy through the ice within the buoy hull.

The instrument package is very similar to that on IMBs. Sonic rangefinders located above and below the ice surface monitor ice mass balance by tracking changes in the locations of the free surfaces. The buoy incorporates a thermistor string for measuring a profile of temperatures through the atmosphere–ice–ocean boundary. The string is designed for service in the seasonal ice zone, with nodes spaced every 10 cm along a 3 m string. The buoy positions the string so that the highest node is 60 cm above the ice surface and the remaining nodes penetrate through the snow and ice and into the ocean below. Buoy coordinates are calculated from Doppler shifts in the satellite transmissions

to within a few kilometers, but the potential for adding a GPS exists. New to the SIMB is an underwater pressure sensor, which provides information on the changes in mass balance of the entire floe (Untersteiner, 1961) and allows the buoy to be monitored for slippage in relation to the ice during thin ice conditions. Readings of the basic meteorological data from the air-temperature and barometric pressure sensors are taken and transmitted out on an hourly basis, while ice temperatures and mass-balance data are collected and sent only every 4 hours. Buoy position is calculated from each transmission set received. Prototype system costs were only slightly lower than IMB costs due to substituting some sensor components. Further substitutions are being tested for deployment this summer, which may reduce costs further.

DEPLOYMENT

As with IMBs, site selection is critical for ensuring that the point data that an SIMB can collect are representative of the surrounding ice cover. A level undeformed floe of first-year ice is the preferred deployment location. Finer-scale site selection will also improve the buoy's odds of collecting valid data through the summer months. Because the SIMB's surface-locating acoustic rangefinders are unable to differentiate liquid water surface from solid ice surface, pond formation around a buoy can mask ice ablation. Furthermore, solar heating and convective heat transfer by the water in a pond can cause objects frozen into the ice to melt out sooner. Previous studies have shown that areas of ice covered by deeper snow dunes are strongly anti-correlated with melt-pond locations in summer and are therefore the preferred deployment sites, just as hummocks between ponds are the preferred location for IMB deployment on multi-year ice.

The SIMB ships in three sections and is designed for deployment by two individuals in under 1 hour. The bottom two sections are connected by fixed cables and can be folded but not separated. The top section is entirely separate, with wires that plug into the lower sections. The deployment procedure requires a single 25 cm diameter hole to be drilled in the ice. Subsequently, the two connected lower sections are raised vertically, with the bottom section right side up and middle section upside down. The bottom section of the buoy is lowered into the hole as the top of the middle section is walked away from the hole. When the bottom section has been lowered into the hole entirely, the middle section lies horizontally on the ice next to it. The middle section is then stood up, inserted into a pipe coupler affixed to the bottom section, and attached to the bottom section with several self-tapping screws. Finally, the top section is installed on top of this and also fastened into place with self-tapping screws. The design easily met our goal of a 1 hour deployment and was deployed by one individual in 17 min including drilling time. Deployment with two individuals is still strongly recommended.

The SIMB prototype was deployed in April 2009 in seasonal landfast ice just north of Barrow, Alaska. The location chosen was 1 km offshore on a flat undeformed pan of first-year ice approximately 1.6 km × 1.3 km in size. The site was also the location of a sustained field campaign which enabled monitoring of the buoy throughout the season and retrieval at the end of the test period. The ice conditions at the deployment site are believed to have been

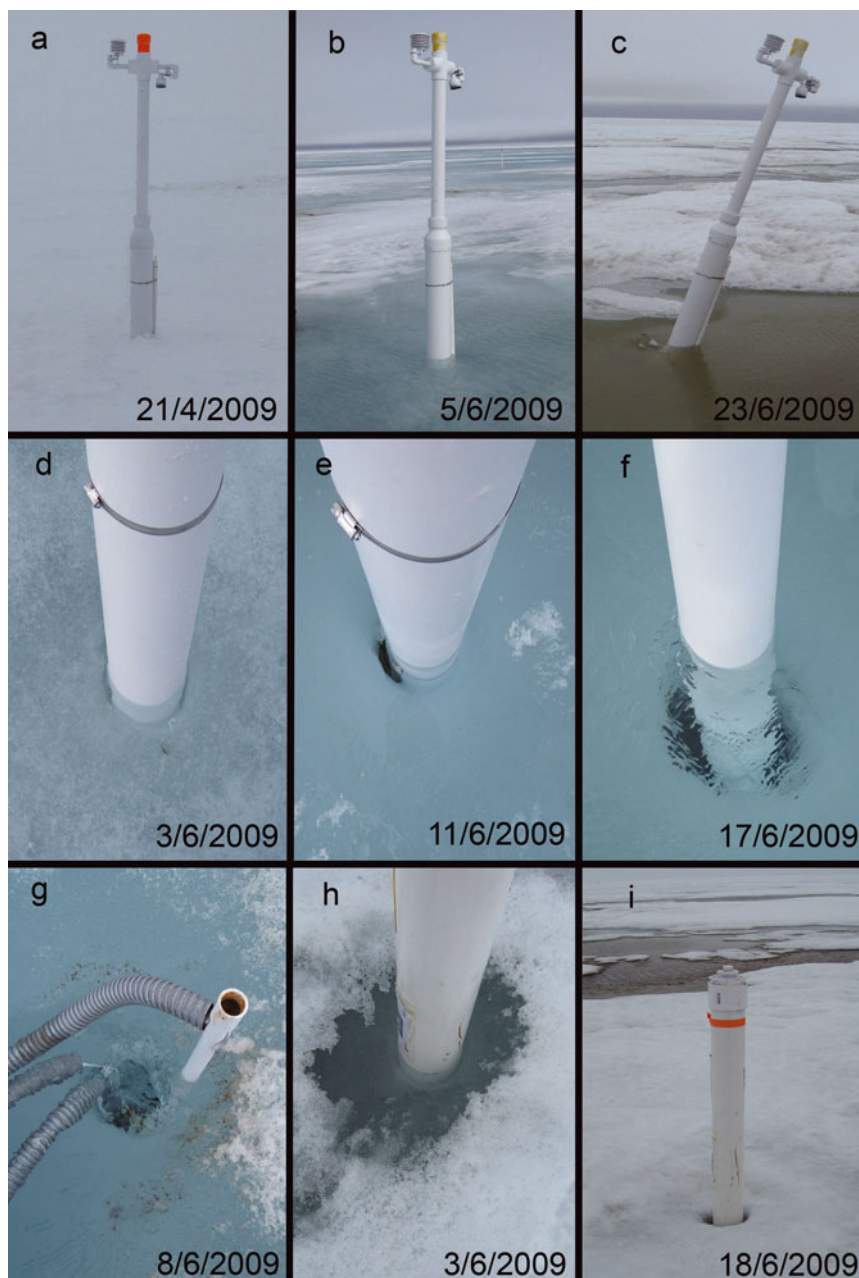


Fig. 3. Photos of SIMB test deployment. Note dates (day/month/year) in all of the images. The top row shows the buoy shortly after deployment (a), still operating unimpaired in the melt season (b), and tilted due to very strong coastal currents after melting out (c). The second row shows close-ups of a well forming around the buoy due to preferential solar heating (d), which leads to a hole forming through the ice draining meltwater (e), and the buoy melting free entirely (f). This behavior is believed to be caused by deployment in a melt-ponded area. For comparison, a thermistor string of the same design used in the IMBs, also deployed in a ponded area, melted out even sooner (g), and a mock-up hull deployed in an unponded area did form a small melt well in the early melt season (h), but was still solidly frozen in with only a 2–3 cm wide and 6 cm deep well formed around it at the end of the field season (i).

comparable to those offshore in the first-year pack ice of the Chukchi Sea, Arctic Ocean. Ice thickness in the deployment hole was 1.34 m with snow cover of 0.14 m while the average ice thickness measured over a nearby 200 m transect was 1.19 m with snow cover of 0.22 m. Note that by deploying the buoy in a location of thinner snow cover between snow dunes, our site selection was in conflict with the preferred site selection. The prototype buoy was intentionally deployed in an area of thinner snow cover in an effort to monitor what would happen to the buoy if located in a melt pond. A second buoy hull without instruments was deployed at a location of deeper snow adjacent to the prototype to monitor differences and test the

hypothesis that a buoy would remain fixed to the ice significantly longer in un-ponded ice.

RESULTS

The buoy test deployment lasted from 21 April to 23 June 2009, encompassing the end of the winter growth season and approximately the first half of the melt season before the buoy was retrieved. A series of photos of the deployment is shown in Figure 3. As expected, a pond did form around the buoy on 3 June 2009, the first day of ponding on the floe. Shortly after the onset of ponding, the ice on the south side of the buoy began to melt preferentially due to solar heating

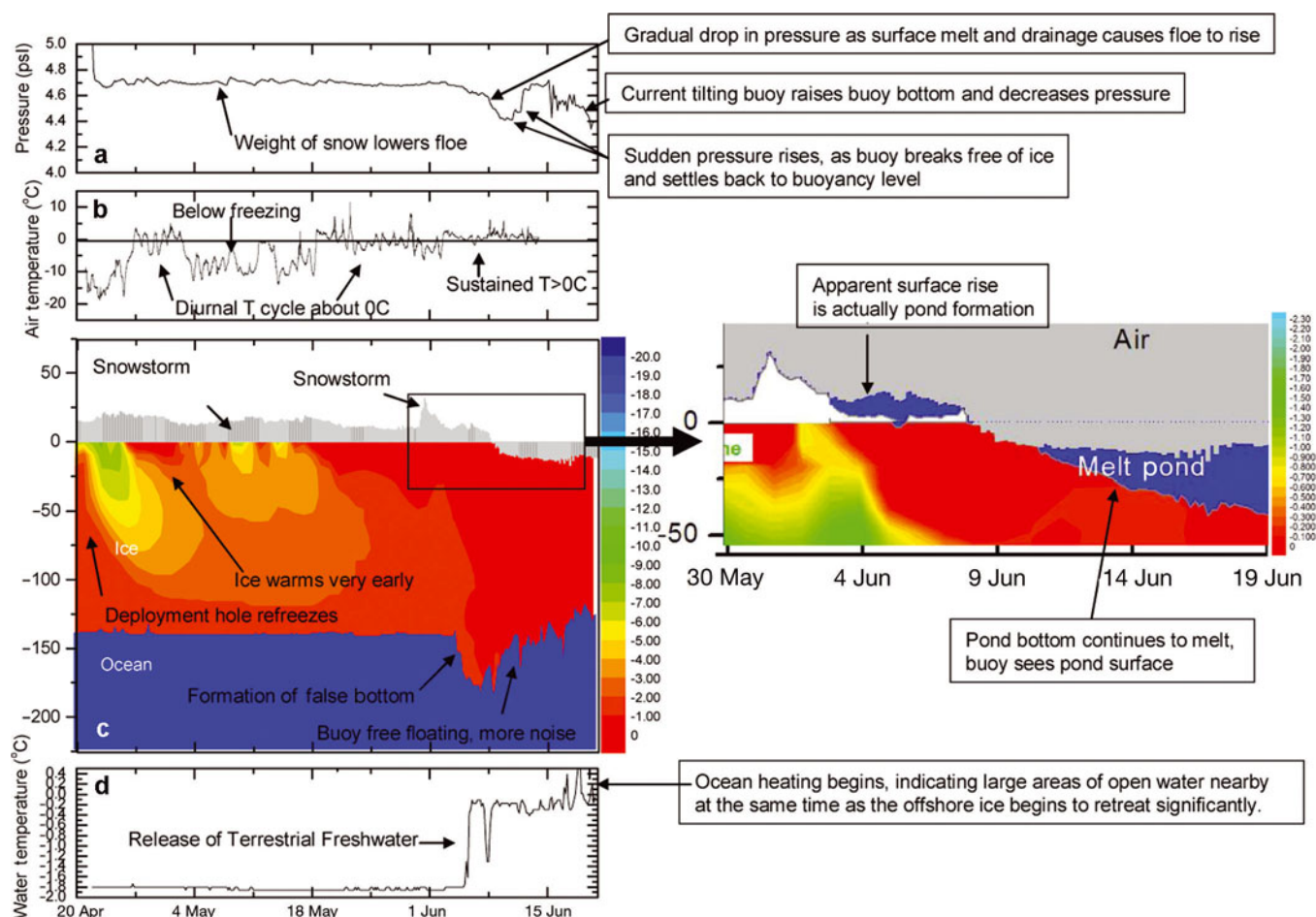


Fig. 4. Results from SIMB deployment. (a) Water pressure measured at the bottom of the buoy, which indicates movement of the buoy in relation to sea level. (b) Air temperature and (d) water temperature 0.5 m below the bottom of the ice. (c) Evolution of the top and bottom surfaces of the ice, as well as temperature profiles within the ice, shaded according to the color bar on the right. (a–d) are plotted on the same x-axis scale, shown at the bottom. A tick mark is 7 days. A number of interesting data features are labeled.

and water convection. By 8 June 2009, the well forming along the south side of the buoy became deep enough to connect through the ice, allowing meltwater to drain to the ocean along the buoy. The hole widened rapidly until the buoy melted free on 11 June 2009, demonstrating rather dramatically the issues caused by deployment in a melt pond. Another mass-balance site, of a similar design to the IMBs, deployed on the same floe also happened to be deployed in a location which later became a melt pond. There, the thermistor string also melted preferentially, allowing meltwater to penetrate on 7 June 2009 and melting out entirely on 8 June 2009. This suggests that the deployment location in a melt pond, rather than the new buoy design, was responsible for the rapid melt-out of the instruments. The mock-up buoy deployed through deeper snow also supports our finding that the deployment location, rather than the hull change, was responsible for affecting the surface conditions. The mock-up hull deployed on unpounded ice also experienced some preferential melting around it, but the melt well never grew more than a few centimeters deep and the hull was still solidly frozen into place when it was removed on 24 June 2009, with no apparent effect on the mass balance 2–3 cm from the hull.

The melt-pond deployment of the prototype allowed us an opportunity to observe how well the SIMB survives when free floating. One immediately obvious issue, which can be

observed in the photos of Figure 3, is that the SIMB began to tilt shortly after melting out, reaching a tilt of 15° at one point late in the melt season. The tilt was caused by strong ocean currents under the shorefast ice in the location of Barrow, often tilting the buoy in a direction opposite to that expected from surface winds. Current forces in this location were significant enough that it was difficult to stand the buoy back upright. Forces of the magnitude seen in Barrow are considered unlikely in the floating pack.

The underwater pressure sensor demonstrated its utility as a quality-control device by showing both the point when the buoy broke free of the ice and became free-floating and the effects of this tilt (Fig. 4a). Though the pressure sensor did enable correction for the slippage as the buoy broke free and began floating, it was impossible to know from these data alone that the pressure drops later in the season were caused by buoy tilt. However, the tilt was measured manually twice daily, allowing us to correct the data with simple trigonometry and illustrating another potential for data quality control. The next model will incorporate a two-axis inclinometer so that similar corrections will be possible for remote buoys.

Results from the buoy test deployment at Barrow, corrected for tilt, are plotted in Figure 4. The results provide a detailed time series of the evolution of the ice conditions from prior to the onset of melt through the loss of more than

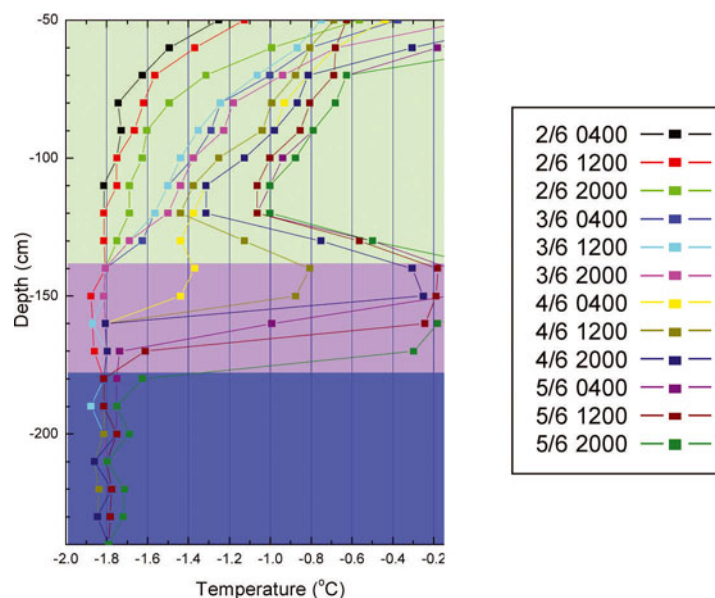


Fig. 5. Temperature profiles showing the intrusion of a freshwater layer under the ice which results in the formation of a false bottom. Time period is 2–5 June 2009. The x-axis is temperature and the y-axis is the position of the thermistors in relation to the surface of the ice. The thermistors that are within the ice at the start of this period are in the green shaded area and those that are in the ocean are in the purple and blue shaded areas. The purple shaded area, where water temperatures warm suddenly on 4 June, is the area that is filled with fresh water. The lower thermistors, in the blue shaded area, remain in saline water at -1.8°C .

half of the ice mass and allow us to learn a significant amount about the ice. Figure 4a shows the water pressure at the bottom of the buoy and indicates changes in the buoy's position in relation to local sea level. Figure 4b shows air temperature and Figure 4d shows the water temperature 0.5 m below the bottom of the ice. The snow (gray) and ice (colored for temperature) evolution during the course of the melt season is illustrated in Figure 4c. Figure 4a–d are on the same timescale shown at the bottom, with 7 days between tick marks. In Figure 4c, we can see that snow depth begins to decline in late April during an anomalous warm spell, which is reflected in the air-temperature readings. Snowmelt then pauses until mid-May as temperatures return closer to climatic averages, but ice temperatures do not decline significantly again. As snowmelt resumes in mid-May, the ice is already warmed to above -3°C . A late-season snowstorm temporarily interrupts melt in the closing days of May before melt sets in for the season on 2 June, when air temperatures transition from diurnally cycling around the freezing point to a regime of sustained temperatures above freezing. The snow surface appears to rise between 2 and 3 June, but this in fact represents the flooding of the surface with meltwater from adjacent areas, something which would have been difficult to discern had we not been on site to watch the buoy. Pond depth was measured manually throughout the season and is added in blue to the inset plot of Figure 4. The pond depth coloring throughout the season illustrates the error in measurement which could be caused by the buoy being placed in a melt pond, and emphasizes the need for deploying the SIMB in locations unlikely to flood. The pressure data suggest that, though the surface drops significantly from 30 May to 8 June, the floe rises only a small amount. This indicates the formation of melt ponds on the floe, as the meltwater produced has not left the surface. On 8 June, coinciding with the onset of pond drainage observed at the site, pressure readings show that the floe rose rapidly, and the sonic rangefinder showed that

the surface dropped about 30 cm in 2 days, enabling the diagnosis of melt-pond drainage.

The bottom position of the ice stays relatively constant from the deployment time in mid-April to 4 June due to anomalously warm spring temperatures preventing further ice growth. Very interestingly, the profile appears to show rapid bottom ice growth on 4 June. This coincides with a jump in water temperature, which was likely caused by the release of fresh water from the dam in the town of Barrow several kilometers down the coast. We believe that this fresh water caused the development of a false bottom of the ice which did not decay until several days later. Figure 5 shows a series of temperature profiles from the lower ice and ocean every 8 hours from 2 to 5 June which helps support this explanation. The profiles in the ocean are vertically uniform at -1.8°C prior to 4 June (yellow) when the profile begins to show warmer likely fresher water intruding under the bottom of the ice. The warmer water layer is about 0.5 m thick and the measured ice bottom is seen to jump downward to where the warmer and colder water interface. After the false bottom decays on 9 June, bottom melt resumes more expected behavior. The additional noise in this area of the melt season is caused by the fact that the buoy is free-floating and the twice daily tilt corrections were not adequate. Just as in the IMBs, the interpretation of thermistor data just below the ice–air interface is difficult after the ice becomes isothermal, due to the potential for preferential melt around the string and potential for ponding. Used with care, however, the temperature profiles provide some useful information throughout the summer. Here we used lower thermistors to watch as water temperatures, shown in Figure 4d, begin to spike above 0°C after 17 June, likely reflecting the large areas of open water just up-current from the buoy deployment location. The high water temperatures were reflected in rapid decay of ice, necessitating our removal of the buoy from the floe to conclude the test deployment.

GENERALITY

A key concern when using local mass-balance data to attribute regional change is the generality of the measurements. By distributing an array of over 100 mass-balance measurement sites over a 100 km² area and monitoring them for a full year, the 1997/98 Surface Heat Budget of the Arctic Ocean (SHEBA) experiment showed that the growth and ablation rates taken at an individual point are, in fact, indicative of the melt rates on similar ice types of the surrounding area (Perovich and Richter-Menge, 2006). As long as representative ice is chosen, buoy results can be extrapolated to the region.

A similar, albeit smaller-scale, exercise was conducted on the floe where the SIMB was located to track surface melt. Ablation was monitored at 30 ablation stakes, and an initial and final transect of total ice thickness was taken. Average ice ablation at the stakes was 32 cm. The buoy measured a surface ablation of 15 cm because of the return from the pond surface. Manually adding the pond depth would result in an ablation of 41 cm. This is not unexpected because ice at the bottom of ponds ablates more rapidly than bare ice, but again emphasizes the importance of site selection and avoiding ponded locations. Thickness transects were measured with an EM31 electromagnetic sensor at the start of the melt season, and at the time of removal a 200 hole thickness transect was drilled along the same line. All snow melted and average ice thickness decreased from 1.19 m to 0.90 m for total ablation of 29 cm. At the buoy, ice thickness declined from 1.34 m to 0.85 m for an ablation of 49 cm, almost entirely due to enhanced surface melt at the bottom of the pond.

CONCLUSIONS AND ONGOING WORK

Accurate in situ measurements of local ice mass balance have proven to be a powerful tool for determining the impact of various forcings on the observed ice loss. Existing autonomous platforms provide an inexpensive alternative to ice camp or ship-based time series ice mass-balance measurements. The SIMB holds promise for extending these capabilities into the seasonal ice zone, complementing and extending the capabilities of the existing IMB network. The key developments of this prototype remove the buoy's dependence on the ice cover for support, provide quality-control data to correct uncertainties in instrument position which may occur in particularly thin ice, and significantly reduce the vulnerability of instruments to damage by wildlife or ice dynamics, while reducing the per unit costs. A successful test deployment has allowed us to identify and address minor issues with the prototype and make several improvements. The prototype and the first two production buoys being developed at the time of writing will be deployed in the drifting pack during spring and summer of 2010. Results will be available on our website at <http://imb.crrel.usace.army.mil>.

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REFERENCES

- Arctic Research Consortium of the United States (ARCUS). 2005. *SEARCH: the study of environmental Arctic change: an interagency program to understand change in the Arctic and how it connects to global climate and society*. Fairbanks, AK, Arctic Research Consortium of the United States.
- ArRCUS. 2008. *Arctic observation integration: Workshops report*. Fairbanks, AK, SEARCH Project Office, Arctic Research Consortium of the United States.
- Comiso, J.C., C.L. Parkinson, R. Gersten and L. Stock. 2008. Accelerated decline in the Arctic sea ice cover. *Geophys. Res. Lett.*, **35**(1), L01703. (10.1029/2007GL031972.)
- Francis, J.A. and E. Hunter. 2006. New insight into the disappearing Arctic sea ice. *Eos*, **87**(46), 509.
- Giles, K.A., S.W. Laxon and A.L. Ridout. 2008. Circumpolar thinning of Arctic sea ice following the 2007 record ice extent minimum. *Geophys. Res. Lett.*, **35**(22), L22502. (10.1029/2008GL035710.)
- Haas, C., A. Pfaffling, S. Hendricks, L. Rabenstein, J.-L. Etienne and I. Rigor. 2008. Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat. *Geophys. Res. Lett.*, **35**(17), L17501. (10.1029/2008GL034457.)
- Hilmer, M. and T. Jung. 2000. Evidence for recent change in the link between the North Atlantic Oscillation and Arctic sea ice export. *Geophys. Res. Lett.*, **27**(7), 989–992.
- Holland, M.M., C.M. Bitz and B. Tremblay. 2006. Future abrupt reductions in the summer Arctic sea ice. *Geophys. Res. Lett.*, **33**(23), L23503. (10.1029/2006GL028024.)
- Kay, J.E., A. Gettelman, G. Stephens and C. O'Dell. 2008. The contribution of cloud and radiation anomalies to the 2007 Arctic sea ice extent minimum. *Geophys. Res. Lett.*, **35**(8), L08503. (10.1029/2008GL033451.)
- Krishfield, R.A. and D.K. Perovich. 2005. Spatial and temporal variability of oceanic heat flux to the Arctic ice pack. *J. Geophys. Res.*, **110**(C7), C07021. (10.1029/2004JC002293.)
- Kwok, R. 2009. Outflow of Arctic Ocean sea ice into the Greenland and Barents Seas: 1979–2007. *J. Climate*, **22**(9), 2438–2457.
- Kwok, R. and D.A. Rothrock. 2009. Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008. *Geophys. Res. Lett.*, **36**(15), L15501. (10.1029/2009GL039035.)
- Kwok, R., H.J. Zwally and D. Yi. 2004. ICESat observations of Arctic sea ice: a first look. *Geophys. Res. Lett.*, **31**(16), L16401. (10.1029/2004GL020309.)
- Kwok, R., G.F. Cunningham, H.J. Zwally and D. Yi. 2007. Ice, Cloud, and land Elevation Satellite (ICESat) over Arctic sea ice: retrieval of freeboard. *J. Geophys. Res.*, **112**(C12), C12013. (10.1029/2006JC003978.)
- Maslanik, J.A., C. Fowler, J. Stroeve, S. Drobot and H.J. Zwally. 2007. A younger, thinner Arctic ice cover: increased potential for rapid, extensive ice loss. *Geophys. Res. Lett.*, **34**(24), L24501. (10.1029/2007GL032043.)
- Melling, H., D.A. Riedel and Z. Gedalof. 2005. Trends in the draft and extent of seasonal pack ice, Canadian Beaufort Sea. *Geophys. Res. Lett.*, **32**(24), L24501. (10.1029/2005GL024483.)
- Morison, J.H. and 10 others. 2002. North Pole environmental observatory delivers early results. *Eos*, **83**(33), 357, 360–361.
- Nghiem, S.V., I.G. Rigor, D.K. Perovich, P. Clemente-Colón, J.W. Weatherly and G. Neumann. 2007. Rapid reduction of Arctic perennial sea ice. *Geophys. Res. Lett.*, **34**(19), L19504. (10.1029/2007GL031138.)
- Overpeck, J.T. and 20 others. 2005. Arctic system on trajectory to new, seasonally ice-free state. *Eos*, **86**(34), 309, 312–313.
- Perovich, D.K. and J.A. Richter-Menge. 2006. From points to Poles: extrapolating point measurements of sea-ice mass balance. *Ann. Glaciol.*, **44**, 188–192.
- Perovich, D.K., B. Light, H. Eicken, K.F. Jones, K. Runciman and S.V. Nghiem. 2007. Increasing solar heating of the Arctic Ocean and adjacent seas, 1979–2005: attribution and role in the ice-albedo feedback. *Geophys. Res. Lett.*, **34**(19), L19505. (10.1029/2007GL031480.)

- Perovich, D.K., J.A. Richter-Menge, K.F. Jones and B. Light. 2008. Sunlight, water, and ice: extreme Arctic sea ice melt during the summer of 2007. *Geophys. Res. Lett.*, **35**(11), L11501. (10.1029/2008GL034007.)
- Perovich, D., J.A. Richter-Menge, B. Elder and C. Polashenski. 2009. Buoy for automated data collection and transmittal. US Patent pending 12569966.
- Pfirman, S.L., R. Colony, D. Nürnberg, H. Eicken and I. Rigor. 1997. Reconstructing the origin and trajectory of drifting Arctic sea ice. *J. Geophys. Res.*, **102**(C6), 12,575–12,586.
- Polyakov, I.V. and 7 others. 2003. Variability and trends of air temperature and pressure in the maritime Arctic. *J. Climate*, **16**(12), 2067–2077.
- Richter-Menge, J.A., D.K. Perovich, B.C. Elder, K. Claffey, I. Rigor and M. Ortmeyer. 2006. Ice mass balance buoys: a tool for measuring and attributing changes in the thickness of the Arctic sea-ice cover. *Ann. Glaciol.*, **44**, 205–210.
- Rigor, I.G., R.L. Colony and S. Martin. 2000. Variations in surface air temperature observations in the Arctic, 1979–97. *J. Climate*, **13**(5), 896–914.
- Rigor, I.G., J.M. Wallace and R.L. Colony. 2002. Response of sea ice to the Arctic Oscillation. *J. Climate*, **15**(18), 2648–2663.
- Rothrock, D.A., D.B. Percival and M. Wensnahan. 2008. The decline in arctic sea-ice thickness: separating the spatial, annual, and interannual variability in a quarter century of submarine data. *J. Geophys. Res.*, **113**(C5), C05003. (10.1029/2007JC004252.)
- Schauer, U., E. Fahrbach, S. Osterhus and G. Rohardt. 2004. Arctic warming through the Fram Strait: oceanic heat transport from 3 years of measurements. *J. Geophys. Res.*, **109**(C6), C06026. (10.1029/2003JC001823.)
- Serreze, M.C., M.M. Holland and J. Stroeve. 2007. Perspectives on the Arctic's shrinking sea-ice cover. *Science*, **315**(5818), 1533–1536.
- Stroeve, J., M.M. Holland, W. Meier, T. Scambos and M. Serreze. 2007. Arctic sea ice decline: faster than forecast. *Geophys. Res. Lett.*, **34**(9), L09501. (10.1029/2007GL029703.)
- Stroeve, J. and 7 others. 2008. Arctic sea ice extent plummets in 2007. *Eos*, **89**(2), 13–14.
- Untersteiner, N. 1961. On the mass and heat budget of Arctic sea ice. *Arch. Meteorol. Geophys. Bioklimatol., Ser. A*, **12**(2), 151–182.
- Woodgate, R.A., K. Aagaard and T.J. Weingartner. 2006. Inter-annual changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004. *Geophys. Res. Lett.*, **33**(15), L15609. (10.1029/2006GL026931.)