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Toward an integrated coastal sea-ice observatory: System components and a case study at Barrow, Alaska

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ABSTRACT

The morphology, stability and duration of seasonal landfast sea ice in Alaska's coastal zone is changing alongside large-scale ice thinning and retreat. The extent and complexity of change at the local level requires an integrated observing approach to assess implications of such change for coastal ecosystems and communities that rely on or make use of the sea-ice cover. Barrow, Alaska is an example of a community that experiences and utilizes a broad range of sea-ice types and conditions. The local population is increasingly forced to adapt to less stable sea ice, loss of multiyear ice and a shorter ice season. We are working toward an integrated coastal ice observatory to monitor landfast and adjacent pack ice and to maximize the usefulness of information to the community. The observatory includes: (1) satellite remote-sensing datasets distributed in near real-time; (2) a coastal sea-ice radar and webcam that monitor ice movement and evolution; (3) a mass-balance site that provides temperature profiles and thickness information for ice and snow; (4) sea-level measurements; (5) periodic ice thickness surveys using direct drilling and electromagnetic induction sounding; and (6) a program of regular, undirected observations by Iñupiat sea-ice experts. We examine two significant landfast ice breakout events off Barrow in spring of 2007. During these events, Barrow's subsistence whaling community partook in a successful hunting season observing and responding to these breakout events and their impacts on ice stability. Using local expert knowledge to parse geophysical datasets obtained from the observatory has provided deeper insight into different approaches for assessing ice stability, and integrating information on ice growth, origin, morphology, and dynamics, as well as winds, weather, and currents.

1. Introduction

In the Arctic, coastal sea ice is important from a number of perspectives. As a geologic agent, it plays a vital role in the sediment budget and nearshore dynamics of the coastline (Reimnitz et al., 1994). The landfast ice cover and adjacent stretches of open water serve as important biological habitats (Ainley et al., 2003). Landfast ice also serves as a platform for a broad range of activities by both coastal residents (Nelson, 1969; George et al., 2004; Nichols et al., 2004) and industry (C-Core, 2005). In summer, sea ice continues to benefit coastal communities during hunting and boating, while at the same time representing a significant hazard to commercial shipping. All of these factors are important in northern Alaska, where landfast ice is present along the coast from October through July and where pack ice can drift inshore throughout the summer (Mahoney et al., 2007a).

Over the past three decades the arctic sea-ice cover has experienced significant thinning and reductions in summer minimum ice extent, with the lowest coverage ever observed in September 2007 (Rothrock and Zhang, 2005; Stroeve et al., 2008). North of Alaska in the Chukchi and Beaufort Seas, the summer ice edge has retreated northward and the duration of the open water season has increased (Shimada et al., 2006). Landfast ice forms later in the season and is generally less stable than in the past (George et al., 2004; Mahoney et al., 2007b). To support active responses and adaptation to these changes, observations must be relevant to a broad assortment of user groups. (Hutchings and Bitz, 2005; SEARCH, 2005; NAS, 2006). National ice services typically provide graphical information on the regional– and large-scale distribution of ice types and sea-surface temperature determined from remote sensing imagery, as well as regional sea-ice advisories (see, e.g., Partington and Bertoia, 1999). However, local communities and specific stakeholder groups typically require observations at higher resolution as well as of additional variables (Hutchings and Bitz, 2005; Eicken et al., in press).

Despite the importance of ice observations to arctic coastal communities and industry, few sustained measurement programs or observatories are in place today. This gap has motivated science to look toward the most sustained and thorough observations of coastal sea ice that have been carried out over centuries—observations by coastal users of the ice cover, such as the Iñupiat and Yupik Eskimo of Alaska and the Inuit of northern Canada (Boas, 1885; Nelson, 1969; Lowenstein, 1981). Accordingly, Barrow, Alaska was chosen as the

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location for a pilot coastal sea-ice observatory (see Fig. 1), which began in the late 1990s and continues in an effort to increasingly provide an integrated approach to observing. Barrow was chosen for several other important reasons, including:

(1) a sea-ice environment that encompasses most major ice types and processes important in arctic Alaska,
(2) the importance of sea ice as a platform for subsistence activities and in the context of marine traffic and planned oil and gas development activities,
(3) the substantial expertise and information needs of the local community of several thousand people,
(4) the existence of significant research infrastructure and logistic support through the Barrow Arctic Science Consortium (BASC), that is built on a long history of collaboration between the Iñupiat Eskimo of northern Alaska and visiting scientists (Norton, 2001), and
(5) the extensive body of ancillary datasets resulting from both past and ongoing scientific research as well as the scientific need and capacity for coordinated observations.

In the context of ocean observing systems, the term ‘integrated’ is not always used consistently and is typically meant to imply that the system extends across the range of relevant scales and that data from the different system components are integrated, e.g., through assimilation into a nowcast or forecast model (Schofield et al., 2002; Chave et al., 2006). In this study, ‘integrated’ refers to an observing system that (1) combines different approaches to obtain data and information spanning the relevant scales, from point-based to regional, (2) interfaces local knowledge and observations with geophysical approaches to assess the state and evolution of the sea-ice cover, and (3) is driven by the local Iñupiat and scientific community's information needs in the context of observing and understanding cryospheric change. Therefore, the two primary goals of the Barrow sea-ice observatory are to monitor key geophysical sea-ice properties and to respond to the needs of local ice-users.

Section 4 of this paper will demonstrate this integrated approach by examining how seemingly disparate observations collected during spring 2007 are combined to examine causal relationships associated with two landfast ice breakout events (i.e., the detachment of landfast ice). These particular calving events were observed by the community and played a role in determining how hunters used and interpreted the stability of the ice cover during whaling season. A basic understanding of which variables are potentially involved in these types of events, along with local observations and expert testimony, allow us to develop a framework for analysis, sub-sample various data streams, and work toward coherent cause and effect explanations and development of forecasting approaches for unsafe or unstable ice conditions. Because these observed dynamic events happen at a particular place and time, issues of scale and context can be addressed in regards to the community relevance of observations. This is particularly helpful given that it is often a great challenge for scientists to grasp the entirety of the information shared when local ice-experts discuss their local knowledge. The nature of this exchange between targeted science and a body of knowledge that encompasses a much broader perspective often leads to unexpected discoveries that extend beyond the initial vision of the scientist. With the interaction of these different knowledge bases that are coincidently observing the local ice cover, this observatory is working toward an approach that fosters a potential for these unexpected discoveries.

The foundation of this observatory is built on several years of collaboration with the Barrow community and maintained though partnership with the Alaska Ocean Observing System (AOOS)—a

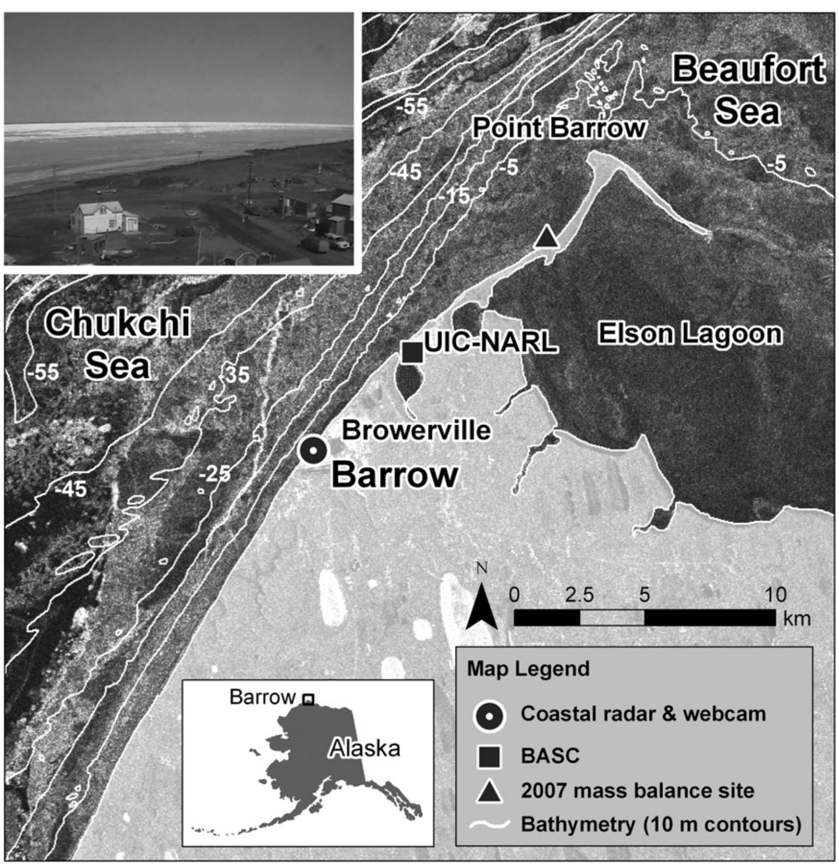

Fig. 1. Map of the Barrow sea-ice observatory overlaid on an ERS-2 SAR satellite image from 21 April 2007. Shown here are the coastline, bathymetry, and the fixed observatory components (coastal sea-ice radar, webcam, and the 2007 mass-balance site, which includes a sea-level gauge). The photo in the upper left corner is a sample webcam image from 6 June 2007, in which the landfast sea ice is clearly visible. The ice immediately off the beach is darker colored due to melt pond formation and the absence of snow.

component of the US Integrated Ocean Observing System (IOOS) that is establishing coastal ocean observing and forecast capabilities. With the implementation of the AOOS, a formal user needs meeting was held in Barrow in 2006. Over the years, the needs of the community of Barrow have also been assessed through collaboration with local Iñupiat ice experts and hunters (Huntington et al., 2001) and the North Slope Borough's Department of Wildlife Management. These exchanges have guided the early stages of the observatory's design, for example, through emphasizing the need for real-time measurements of sea level and potential floating ice surges. This guidance, along with continued efforts to seek input from community members, has led to a robust and evolving observatory that is capable of withstanding the challenging coastal ice environment (see Section 3).

2. Sea-ice conditions and subsistence activities at Barrow, Alaska

Landfast ice near Barrow forms in fall (typically November, but in recent years as late as December) through a combination of in-situ freezing and attachment of drift ice brought inshore by wind or currents (Shapiro, 1975; Mahoney et al., 2007b; Kenneth Toovak, public testimony, 2000; Joe Leavitt, unpubl. obs., 2006). Starting in the 1990s, the northward summer ice edge retreat has impacted the distribution of multiyear ice in nearshore waters (Drobot and Maslanik, 2003). In recent years very little multiyear ice has been present at the time of freeze-up (George et al., 2004; Andy Mahoney and Hajo Eicken, unpubl. obs., 2005–2008). Over the course of winter and spring, the landfast ice is subjected to accretion, breakout and deformation events (Shapiro, 1975; K. Toovak, public testimony, 2000; Mahoney et al., 2007a) that result in a complex agglomeration of ice types and ages (Arnold Brower, Sr., unpubl. obs., 2007; J. Leavitt, unpubl. obs., 2007, Mahoney et al., 2007a). In spring, offshore ice motion typically results in the formation of flaw leads (open water and new ice) along the edge of the landfast ice, generally between 1 and 10 km distance from shore. By mid-June large stretches of landfast ice breakout or decay in place, with the eastern Chukchi Sea coast being free of landfast ice by June 18 ± 13 days (Mahoney et al., 2007b).

The observatory focuses on the stability and morphology of the local landfast ice, which is intricately linked to the subsistence activities of the Iñupiat community of Barrow. Sea ice is used as a platform for harvesting marine mammals, including seals and whales. In spring, during the bowhead whale harvest, as many as 200 or 300 people may be engaged in various activities on a stretch of landfast ice extending approximately 10 km to either side of town and up to 10 km offshore to the edge of the landfast ice. Transport of personnel and supplies to camps at the flaw lead takes place on a network of trails that are built on the ice starting in March or early April. When a crew successfully strikes a whale, dozens of people using block and tackle haul it onto the ice for butchering (Eicken et al., in press). The whaling season ends in late May or early June. In recent years the end of the season has been determined as much by lack of ice stability as by the passing of the whale migration (J. Craig George, pers. comm., 2006).

Ice breakout events are a hazard during whaling as they can take whaling camps out to sea, requiring community rescue efforts. Community concern for breakout events is reflected in the extensive body of local and traditional knowledge on this topic (J. C. George et al., unpubl. manuscript). This knowledge, along with other sources of information including weather forecasts and satellite imagery, is used by those on the ice to minimize risk. Elders and local ice experts report that winter breakout events were exceedingly rare in the mid- to late 20th century (George et al., 2004; K. Toovak, public testimony, 2000), but the lack of a stable ice cover and the increase in landfast ice breakout events during the past 15 years (Mahoney et al., 2007b) has proved challenging to local residents. This increase in breakout occurrence has changed the risk management environment for on-ice activities and may be one factor that has contributed to less productive spring whale hunts in recent years (J. C. George, pers. comm., 2005).

3. Components of the observing system

This section will describe the various components of the observatory used to target a broad understanding of ice stability and related processes. Table 1 summarizes the observed parameters and the associated spatial and temporal scales of observation.

3.1. Satellite remote sensing

The observatory uses an assortment of satellite-derived data, including SAR (Synthetic Aperture Radar) and AVHRR (Advanced Very High Resolution Radiometer)/MODIS (Moderate Resolution Imaging Spectroradiometer) visible and thermal IR data. SAR data, obtained from both the Radarsat and ERS-2 (European Remote Sensing Satellite-2) platforms, are primarily used to distinguish ice types (i.e., multiyear versus young or first-year ice) and to monitor ice concentration and extent. Mahoney (2006) developed a methodology to define the edge of the landfast ice as the furthest seaward location in the landfast ice zone where ice remains attached over the course of three consecutive SAR scenes (approximately 20 days). AVHRR/MODIS data are also used to assess ice extent and concentration, as well as to monitor albedo (to assess melt pond coverage and coastal flooding) and sea-ice surface temperature.

AOOS receives raw and partially processed satellite data through the Alaska SAR Facility and through Geographic Information Network of Alaska (GINA). AOOS then corrects any geo-referencing errors in the images, locally archives, and displays these on the Internet for public access. AOOS also collects existing data products from multiple web sites providing a single data access point. For example, AOOS displays sea-ice concentration maps from AMSR-E (Advanced Microwave Scanning Radiometer), FNMOC (Fleet Numerical Meteorology and Oceanography Center) and GFS (Global Forecast System) as well as MODIS sea-ice extent. AOOS provides links to the existing NWS sea-ice charts, forecasts and analyses, and makes available a data inventory of all sea-ice products. AOOS staff worked with NASA over an eighteen month period to gain clearance for AOOS to provide SAR data (Radarsat-1) for the Barrow and North Slope region. This pilot project successfully delivered high resolution sea-ice imagery into 2008. Additional remotely sensed data include cloud cover from AVHRR visible and sea-surface temperature (SST) from AVHRR and MODIS. AOOS is working with sea-ice experts to create custom data products

Table 1
Components of the Barrow sea-ice observatory and observed sea-ice and related parameters.

Component	Observed parameters and processes	Spatial scale [m]	Temporal scale[a]
Satellite imagery	Landfast ice stabilization, landfast ice extent, lead occurrence, ridging, multiyear ice concentration	10^1–10^4	d–a
Coastal radar	Ice drift, landfast ice stabilization, ridging, landfast ice breakout events	10^1–10^3	min
Coastal webcam	Presence of first ice, melt pond formation, snow cover, breakout events, open water	10^1–10^2	min
Mass balance site	Ice thickness, snow thickness, water-ice-snow-air temperature profile, relative humidity, ice salinity	10^0–10^1	min
Sea-level measurements	Tidal, storm surges, and wind driven sea-level fluctuations,	10^1–10^4	min
Ice thickness and topography surveys	Ice thickness and surface elevation	10^1–10^3	mo–a
Local observations	Key events in the annual evolution of the ice cover, dynamic events, etc.	10^1–10^3	d–a

[a] min = minute, h = hourly, d = daily, mo = monthly, a = annually.

for its 'Barrow Page', a dedicated site for commonly-requested data products. As part of its forecast improvement effort, AOOS compares modeled hindcast sea-ice concentration data with observational data (Johnson et al., 2007), and reports any significant differences back to the modeling community.

3.2. Coastal sea-ice radar and webcam

Near-shore ice is monitored (operating range 11 km) with a Furuno FR-7112 10 kW, X-band (3 cm, 10 GHz) marine radar with a 1.65 m open array sweeping every 2 s. This radar is positioned close to the shoreline, 22.5 m above sea level on a building in downtown Barrow (71°17′33″N, 156°47′17″W). A Xenex XC2000 digital controller allows full remote operation from the University of Alaska Fairbanks (UAF). The radar backscatter map, produced with each sweep of the array, reveals ridges, floe edges and other roughness elements not in the shadow of other such features. Areas of flat sea ice or calm open water do not generate sufficient backscatter for detection (Mahoney et al., 2007b). One full scan is recorded and archived locally every 90 s. The data is then transferred via ftp to Fairbanks at five minute intervals, geo-located, and archived by AOOS.

Coastal sea-ice radars provide important information on the movement, deformation and stability of the coastal ice cover, as shown by Shapiro (1975) for the Barrow region and Aota et al. (1988) in northern Japan. Such radars are ideal for bridging the gap between point-scale, local, and regional data. Relative to satellite imagery, coastal sea-ice radars improve temporal and spatial resolution when monitoring the evolution of the landfast ice, assessing ice stability, and characterizing ice breakout events (Mahoney et al., 2007b). Radar images are used for tracking long- and short-term changes in morphology of landfast ice, and additionally provide information on dynamics of offshore ice. When analyzed alongside wind records, this data also provides useful yet rudimentary information about currents. Daily 24-hour animations of the radar maps are provided on the Internet (at www.gi.alaska.edu/BRWICE or ak.aoos.org) for those interested in short term processes such as deformation and breakout events.

Shapiro (1975) and Mahoney et al. (2007b) demonstrated that variations in backscatter from landfast ice targets (radar reflectors) up to an hour prior to an ice breakout event might serve as an early warning system for the community. These precursory observations are characterized by a rapid and localized change in backscatter response without motion of the reflector, causing features in the image to flicker (Shapiro, 1987; Mahoney et al., 2007b). It has been suggested that the rising and lowering of landfast ice, which produces the change in radar reflectors, dislodges the ice and allows it to detach from the remaining landfast ice (Mahoney et al., 2007b). However, our current understanding of this phenomenon is not sufficient to implement an automated early warning system. In its present state, the observatory is collecting and interpreting data that, ideally, will lead to improvements in the identification of such precursor events (see Section 4).

Mounted immediately beneath the radar is a webcam (AXIS 211A network camera with a heated outdoor housing) that overlooks the landfast ice (or coastal ocean during the ice-free period in summer) in the NNW-direction. The primary aim of the camera is to establish a long-term visual archive of key dates in the seasonal evolution of the local sea-ice cover near Barrow. Key dates include the onset of fall ice formation, formation of a stable ice cover, onset of spring melt, appearance of melt ponds, beginning of ice break-up in early summer, and removal or advection of sea ice during the summer months. As with the radar, webcam images are recorded locally and made available online for near-real-time viewing of ice conditions.

3.3. Sea-ice mass balance site and sea-level gauge

An automated mass balance site is installed annually in growing, undeformed landfast first-year ice in a small embayment SW of Pt. Barrow in the Chukchi Sea (see Fig. 1). Local ice experts and analysis of SAR imagery confirm that the bathymetry and coastline in this area result in stable ice with breakout not prior to ice decay in June. At this location the ice is homogeneous. It forms primarily through in-situ freezing rather than advection and deformation and provides ice and snow data representative of level, undeformed ice. The distance from the coastal road is sufficient to prevent contamination by traffic-generated dust that can increase ice albedo and accelerate melt. Because this site is separated from bottom-fast ice inshore by tidal cracks and is several hundred meters from grounded ridges offshore, variations in local sea level due to tides and surges can be measured from the vertical motion of the ice.

Fig. 2 shows components of the mass balance site. Snow depth is measured with a Campbell SR50 sonic ranger fixed to a mast extending through the ice. Upward- and downward-looking underwater acoustic altimeters (Benthos, PSA-916) are fixed to the under-ice continuation of the mast. Ice thickness is calculated as the distance between the upper ice surface at the time of installation and the bottom of the ice. Instantaneous local sea level is calculated as the distance from the initial upper ice surface to the sea floor. Vertical temperature profiles through water-ice-snow-air are measured at 10 cm intervals with thermistor strings. Air temperature and relative humidity are measured 2 m above the ice with a shielded Campbell CS500 sensor. Dielectric permittivity measurements were made in 2006 and 2007 using Stevens Water Hydraprobes to assess their use for automated salinity measurements (Backstrom and Eicken, 2006; Pringle et al., in press). Data are logged with a Campbell CR10X data logger, transmitted via FreeWave Radio to BASC and transferred via ftp to UAF where they are processed, posted on the web and archived at AOOS. This fully automated process results in data and plots of temperatures, snow and ice depths, and sea level updated typically an hour after measurement. Such sites operated from l2 February–10 June 2006, 25 January–9 June 2007 and 7 February–17 June 2008. These dates were dictated by the time at which the ice became securely landfast and by melt-out and final break-up.

3.4. Ice thickness surveys

Ice thickness surveys are conducted at key times during the ice growth season to obtain information on the morphology of the ice and potential anchor points, such as grounded ridges. In addition to the single-point mass balance data, thickness surveys map variations in ice thickness and type. A Geonics EM-31 electromagnetic induction (EM) device determines the apparent conductivity of the half-space below the instrument by generating a primary electromagnetic field at 9.8 kHz and comparing this to the secondary field generated by induced eddy currents in the seawater underneath (Haas, 2003). Here, thickness values are obtained by applying a semi-empirical inversion equation derived for growing first-year arctic sea ice (Haas et al., 1997). Such

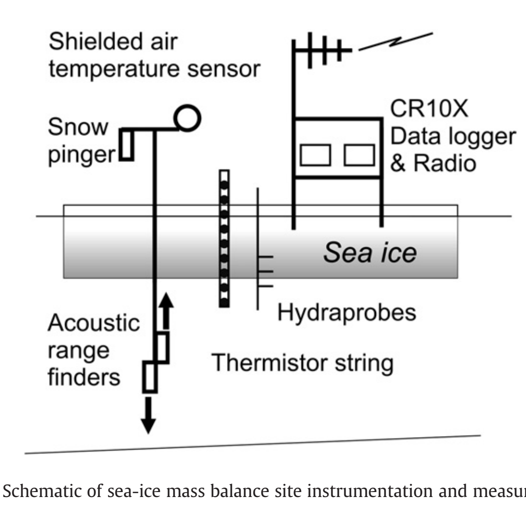

Fig. 2. Schematic of sea-ice mass balance site instrumentation and measurements.

measurements on sea ice have been validated by Kovacs and Morey (1991), Haas et al. (1997), and Eicken et al. (2001). The lateral resolution is on the order of the EM coil spacing of 3.66 m. Measurements in level ice have been found to be accurate within 10 cm of the true value averaged over the instrument footprint (Haas, 2003). The EM-31 and a geodetic DGPS receiver, which measures surface elevation to within centimeters and geo-references the measurements, are either towed on a sled or carried depending on the length and trafficability of the transect. Measurements are made at two to 10 m intervals depending on the mode of travel (i.e., snow machine versus walking). Snow depth is also measured manually along transects to correct the derived depths for true ice thickness, which are then validated against depths measured directly from drilling.

Repeat thickness profiles are measured perpendicular to shore in multiple locations, including in the vicinity of the mass-balance site (see Fig. 1). As measurements are made along the Barrow coastline where whale hunting crews establish trails from the shore to the landfast ice edge, the thickness transects are often performed on these trails. Use of these pre-established trails not only allows for greater collection of data and spatial coverage but also makes thickness data more relevant to the whaling community, who are concerned with the state of the ice along their trail system. The majority of measurements are made toward the end of the ice growth season to obtain an estimate of maximum ice thickness for mass budget analysis. Additional transects, such as those detailed in Section 4.4, are performed at times of year or in locations where ice stability is in question or to support satellite and/or coastal remote sensing efforts.

In addition to these measurements, ice cores are taken when ice thickness approaches the seasonal maximum to obtain a record of salinity profiles, ice stratigraphy (as a means to assess the ice-accretion processes that govern ice growth in that particular year), and for analysis of the (water) isotopic composition. These data provide additional insight into the growth history of the ice (Pfirman et al., 2004).

3.5. Local observations by Iñupiat sea-ice experts

Collaborations with local sea-ice experts provide point source observations from an ice-user's perspective. Because Iñupiat ice experts follow the seasonal evolution of the ice cover, making note of specific deformation events and the distribution of key features such as grounded ridges or multiyear ice floes, their observations greatly assist in assessing ice stability. Two local sea-ice experts, Arnold Brower, Sr. and Joe Leavitt, have provided detailed observations of Barrow's near shore sea-ice environment as well as general guidance for scientific field research campaigns. Brower and Leavitt have acquired their expertise through subsistence activities, including hunting bowhead whales and ice seals, which require ongoing evaluation and sharing of knowledge regarding the local sea ice, currents, and weather. Both have extensive experience working with researchers in Barrow and elsewhere in the Arctic and are familiar with attempts to interface local observations with physical western science (Gearheard et al., 2006). Brower (2006–2007) and Leavitt (2006–2009) kept near-daily written journals of sea-ice and related observations. More frequent observations were made during periods of change in the ice cover or at times most relevant to activities on or near

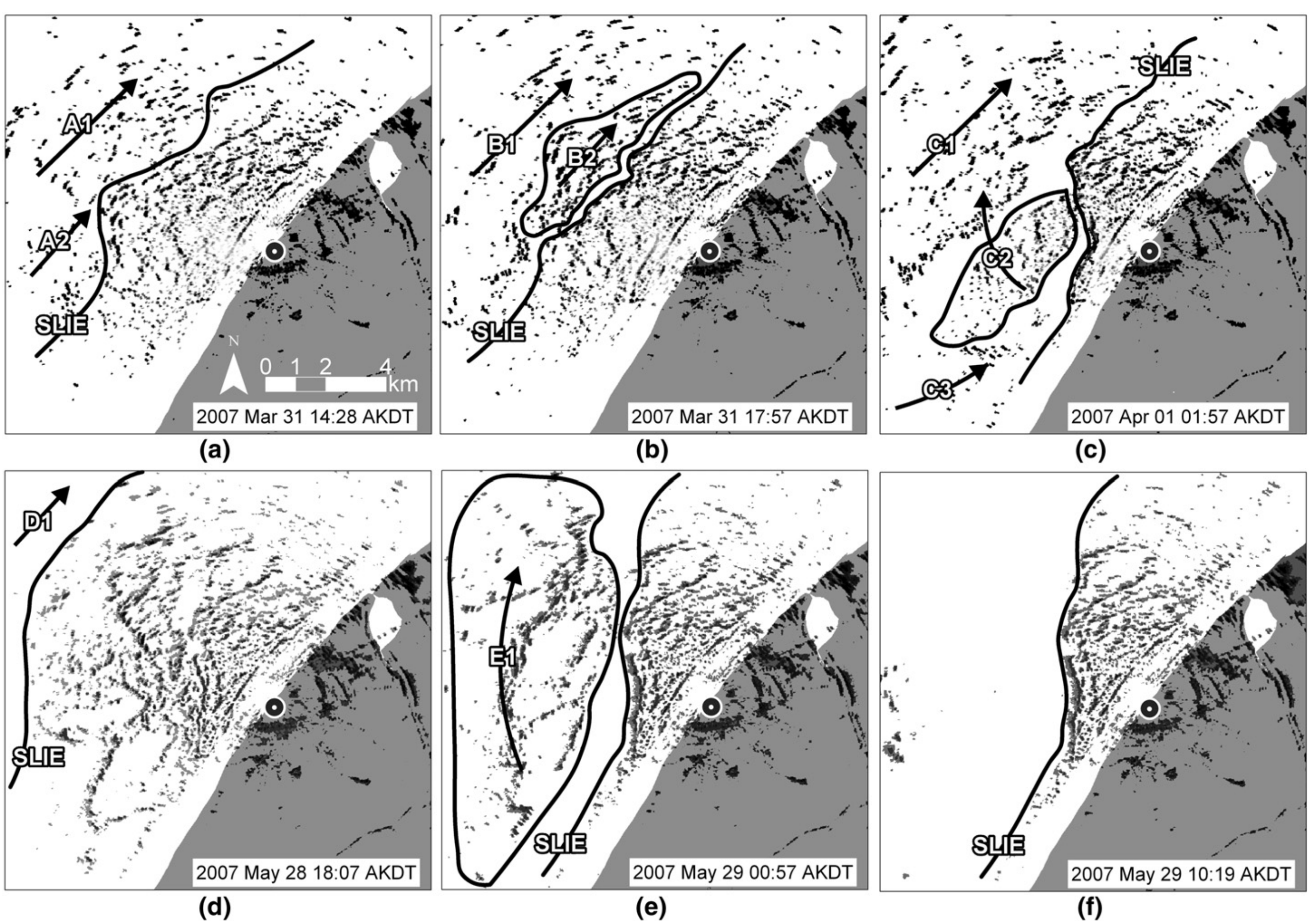

Fig. 3. Radar backscatter images illustrating the late-March (images a to c) and late-May (images d to f) breakout events. The areas of solid gray are land, the circles near the image centers mark the radar location and solid heavy lines represent edges of ice areas of interest. SLIE denotes the seaward landfast ice edge determined from SAR. Arrows A1, B1, C1 and D1 indicate the direction of pack ice movement beyond the SLIE. See Section 4.1 for discussion of all other arrows.

the ice, especially those related to whaling. Their sea-ice observations were thus often made in the context of what they and others in the community were doing on the ice (e.g., scouting for potential ice trail locations, traveling on the ice to access local trapping areas, etc.).

An independent review of these written local observations is not adequate to fully interpret and utilize the information in these records. Rather, a back-and-forth communication between our research team and local observers is required to extract the most relevant information and avoid misinterpretation. In addition to these two formal collaborations with Brower and Leavitt, various interviews are conducted with other experienced members of the community, especially in our efforts to thoroughly summarize the state of the local sea-ice cover for a given year.

Recent years have seen increasing discussion of the depth and extent of this type of knowledge (Huntington et al., 2001; Krupnik and Jolly, 2002; Fox, 2003). Many studies highlight the potential of such observations for tracking, understanding, and adapting to climate change in the North (Huntington, 2000; Berkes, 2002; Nichols et al., 2004; Chapin et al., 2004; Laidler, 2006). However, significant challenges exist in how such information is used in conjunction with geophysically derived data. It is crucial to understand not only what is being observed but also why and how these observations are being made; context is important, especially as longer-term records of local observations are maintained.

4. Case study: ice breakout events during the 2006/07 ice season

To illustrate the integration of various components of the observatory, two landfast ice breakout events observed in spring 2007 immediately offshore of Barrow were examined. While these events represent typical landfast ice calving, they are important as they provide a spatial and temporal framework in which to integrate observations for the purpose of understanding the processes that drive and control breakout events. Furthermore, these events had implications for how the community used the local sea-ice environment and assessed risks during the spring bowhead whaling season.

4.1. Coastal sea-ice radar and SAR satellite imagery capture ice breakout events

On 31 March 2007 the sea-ice radar captured a breakout event of an apron of landfast ice immediately off Barrow's coast. Animations of radar scenes show interaction with the nearby pack-ice, large-scale fracture, rotation about an apparent anchor point, detachment, and subsequent replacement of this ice in the landfast zone. The entire event lasted 13 h. A second breakout event occurred on 28 May 2007, with the breakout line apparently along the ice edge left by the first event. Animations of these two events are available at http://www.gi.alaska.edu/BRWICE/. Fig. 3 shows the sequence of key stages of these breakout events, which can be summarized as follows:

- Pack-ice drifting in a northeast direction (see arrow A2 in Fig. 3a) collided with and destabilized the landfast ice by breaking away a section of approximately 8 km^2 of the seaward landfast ice edge (SLIE) (see B2 in Fig. 3b). Strong radar returns along the new SLIE suggest the presence of high, presumably grounded, ridges along the breakout line.
- Next, a fracture developed with the clockwise rigid-body rotation of a portion of the landfast ice of approximately 10 km^2 (see C2 in Fig. 3c). During this detachment the radar received increased backscatter from targets along the new temporary SLIE, which is indicated by the relatively dark reflectors to the right of the detaching ice in Fig. 3c. As this piece of ice rotated and created open water in its wake, drifting ice quickly replaced the detached ice and came into position along the landfast ice (see C3 in Fig. 3c).
- Between 1 April and 28 May, conditions (see Sections 4.2 and 4.4) allowed for both drifting ice and new ice growth to contribute to an extended SLIE in the area where the first breakout occurred (see Fig. 3d). On 28 May at 22:18 local time, the radar observed a rapid detachment of ice (see Fig. 3e) that resulted in the SLIE reverting back to approximately the same position as immediately after the first event (compare the SLIE in Fig. 3f and c).

Further investigation (see Section 4.3) revealed that the ice edge following the first breakout event was defined by an elevated ridge line. With sails of up to at least 3 m in height, the ridges were thick enough to be grounded on the seafloor, with water depths along the ridge line ranging from 10 to 30 m. While some pack ice temporarily attached itself to the landfast ice along this ridge for 8 weeks and 2 days before the second breakout event, the ridge itself remained in place and stationary throughout much of the remaining ice season. It was observable in SAR images from Radarsat and ERS-2 during this time. The bright line of backscatter indicated by “A” in the April 21st SAR scene in Fig. 4a shows newly-formed ice parallel to this ridge (see

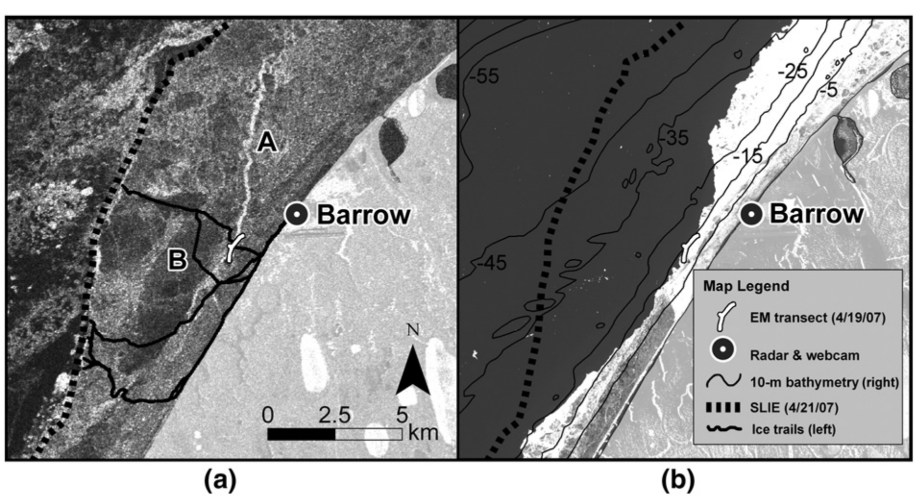

Fig. 4. (a) ERS-2 SAR image from 21 April 2007 of Barrow's coastal ice. The dotted line represents the seaward landfast ice edge (SLIE), “A” indicates a bright line of backscatter in a N–S orientation resulting from new ice at the attachment area and “B” indicates a flat pan of ice brought in following the late-March breakout. The black lines represent ice trails used by hunters in May to access hunting camps at the ice edge. (b) ALOS AVIR-2 image from 8 June 2007 of Barrow's coastal ice. The dotted line represents the SLIE from 21 April 2007, shown in Fig. 4a. The area between the dotted line and the clearly visible landfast ice edge represents ice that had broken away during the 28 May breakout and in the several days that followed. The EM thickness transect measured on 19 April 2007 (see Fig. 7) is also shown here in both figures.

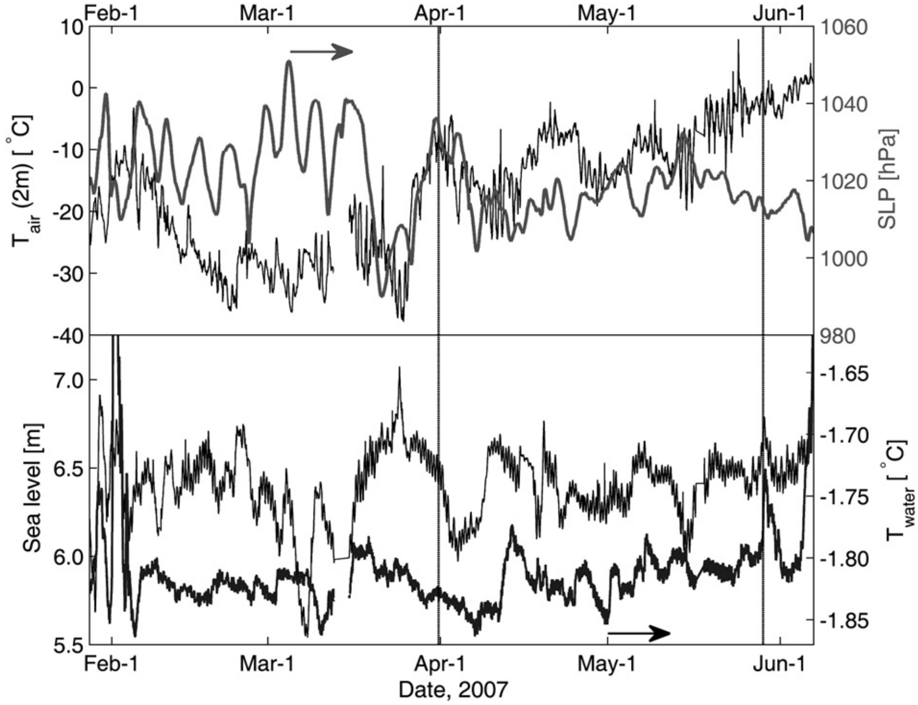

Fig. 5. Timing of 2007 Barrow breakout events with weather conditions. Dashed vertical lines indicate the breakout events. Top: air temperature 2 m above ice surface (light curve, left axis) and sea-level air pressure (heavy curve, right axis). Bottom: Sea level (light line, left axis) and water temperature (heavy line, right axis) at mass balance site. Water temperature is the mean of 5 thermistors, 1.45 to 1.85 m below the upper ice surface.

discussion in Section 4.3). Fig. 4b reveals the ridge to be still present later in the season on 8 June 2007. This ridge finally deteriorated during the melt season.

4.2. Weather and ice conditions preceding and during ice breakout events

A good description of the state of the atmosphere, ocean, and ice throughout the season comes from the mass balance site measurements and weather data obtained from NOAA data records for Will Rogers Memorial Airport in Barrow (approximately 2 km southeast of the breakout location). These conditions correlate with the March and May breakout events. Fig. 5 shows sea-level air pressure (SLP) from NOAA records and the air temperature, sea level and water temperature from our mass balance site. Fig. 6 shows wind speed and direction.

The March breakout event followed a week-long period of warming from approximately −30 to −10 °C in air temperature associated with a rebound in SLP following extended low pressure during

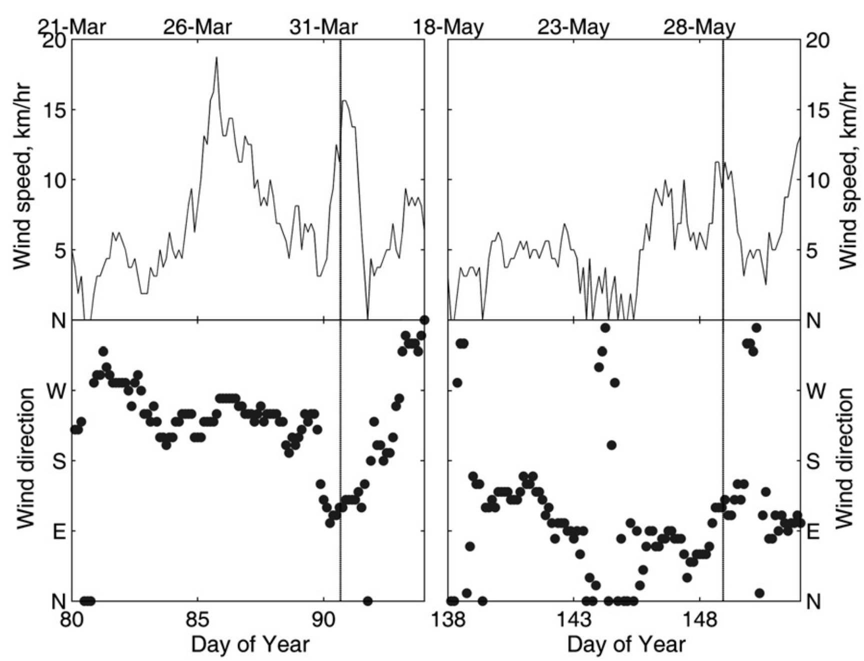

Fig. 6. Wind speed (top) and direction (bottom) from Will Rogers Airport, Barrow before and after the two breakout events. By convention, wind direction is the direction from which the wind blows. Dashed vertical lines indicate the breakout events. (Source: NOAA Local climatological data, Will Rogers Airport, Barrow.)

mid-to-late March. The under-ice water temperature showed no significant change at the time of the breakout. (This contrasts with strong warming events in both late January and early February due to the inshore advection of warm shelf water, and during the melt season in May and June.) Sea level was relatively high for about three weeks during and after the period of low SLP in March. The most noteworthy feature here is the sea-level peak on 26 March (day 85). This coincided with a pronounced peak in wind strength during a sustained period of westerly- to south-westerly winds (see Fig. 6), and a small and gradual decrease in water temperature. Ekman dynamics dictate that the direction of induced surface currents in the ocean will be to the right of the wind forcing. For example, in an ideal case, a wind blowing from west to east forces the upper ocean to move southward, raising sea level along the SW-NE trending coastline at Barrow. Therefore, this period of elevated sea level may in part be due to wind-driven, inshore advection of cooler, off-shore water. This is particularly likely for the sea-level peak on 26 March. Such inshore forcing may have disturbed ice keels anchoring the fast ice to the seafloor, thereby preconditioning the ice for subsequent breakout while momentarily holding it in place. While not visible in this plot, breakout occurred just prior to low-tide, so off-shore tidal flow may have played a role.

Fig. 6 shows the 31 March breakout followed an abrupt, almost 180° shift in wind direction and a daylong increase in wind speed. For more than 10 days prior to the breakout, the prevailing winds were primarily west and southwest (between inshore and along-shore). By early morning 31 March (day 90), the winds shifted to the southeast—almost exactly offshore—and the breakout occurred near the peak in increasing wind speed. The initial direction of ice motion toward the northwest (Fig. 3a) supports the idea that the southeasterly wind had a large effect on ice detachment. The radar data also suggest that interaction and coincident displacement of weakly grounded or ungrounded landfast ice with incoming offshore pack ice (arrow C3 in Fig. 3c) played an important role in the breakout.

A similar analysis of the 28 May event again shows breakout at the onset of strong SE winds. This breakout followed a week of weaker winds from the north and east and coincided with a pronounced increase in water temperature and sea level. The latter suggests inshore advection of warmer offshore water, also seen in late January in Fig. 5, but with solar heating likely contributing to the warming at this late stage of the season. Advection of warm water affects grounded ridges through ablation and de-stabilization (Mahoney et al., 2007b), potentially priming the ice for breakout under conducive

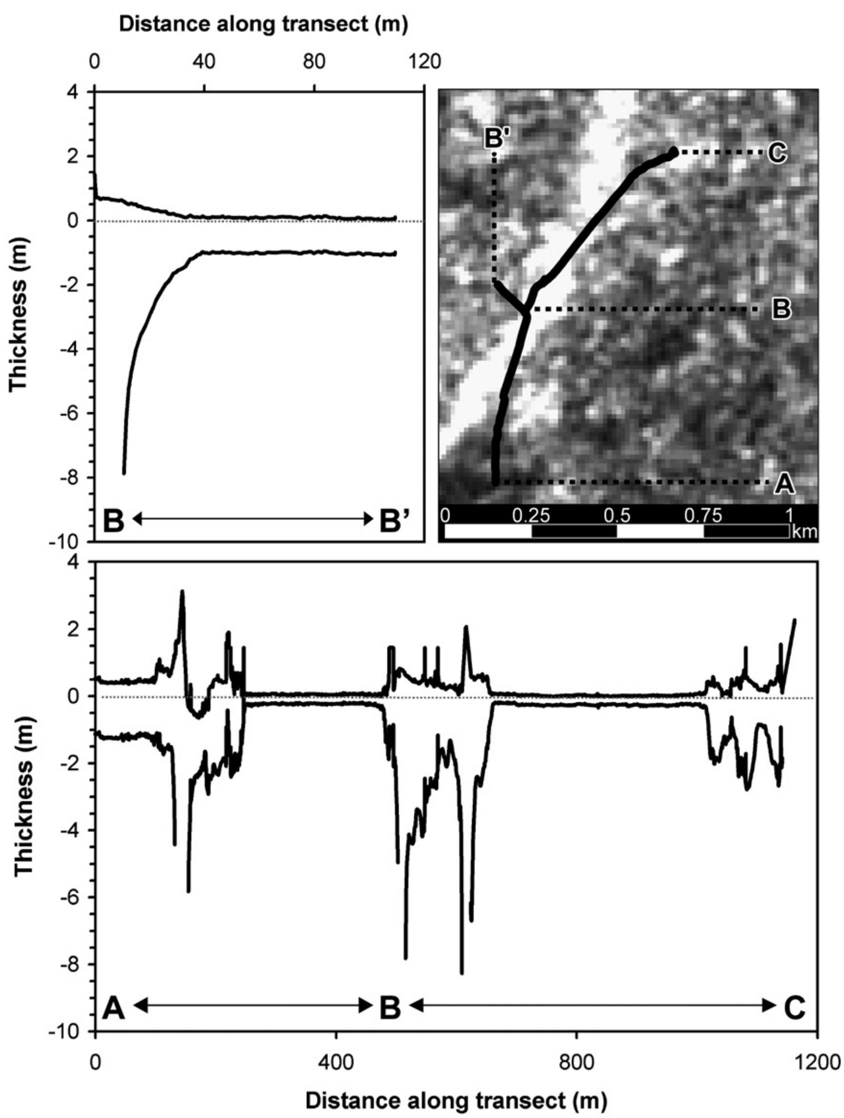

Fig. 7. Ice thickness and surface elevation profiles from 19 April 2007 obtained using EM sounding and DGPS, respectively. The map of the transect in the upper right is overlaid on a SAR image from 21 April 2007. The bright pixels in this image represent the young saline ice that formed following the 31 March breakout event (see Section 4.1 and Fig. 4a). The location of transect shown here is also shown in Fig. 4a and b. Missing data at ridge keels are due to EM measurement values outside the bounds of the empirical equation used to calculate ice thickness from apparent conductivity.

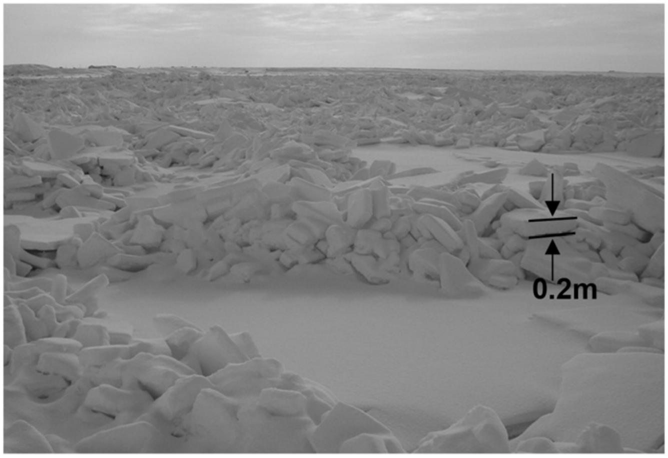

Fig. 8. Rubble field and ridges created by deformation event immediately following the 31 March breakout event. The view is looking approximately south from the top of one of the highest ridges.

winds from the SE. Furthermore, unlike the March breakout, interaction with the offshore pack played no role in this breakout event.

4.3. Ice thickness and distribution of potential anchor points

On 19 April 2007, EM thickness transects were performed in the area where the late-March breakout event occurred (see 'B' in Fig. 4a.) The thickness transects crossed the breakout line sampling ice that was landfast prior to the March breakout and ice incorporated immediately after it. The primary objectives were to characterize the features observed in both the sea-ice radar and SAR imagery and to obtain thickness data that could be compared to the measurements at the mass-balance site, thus providing a basis to infer where the ice originated. The EM ice thickness profile, which consists of two segments—A to C and B to B', is shown in Fig. 7. The average thickness of the level undeformed ice along the profile A to C was 0.29 m, indicating that it froze in place following the breakout and deformational events of late March. Deviations between thickness drilling and EM-derived values ranged between 5 and 14 cm, which can be attributed to the difference in footprints (5 cm for drill versus several meters for EM-31) as much as the accuracy of the measurements. The EM and DGPS data revealed ridges along this profile with sail heights ranging from 1.5 to 3.1 m. Pressure ridges, and accordingly, keel depths are often underestimated using EM measurements by up to 30% (Haas, 2003); therefore it is important to assess whether ridges are grounded using a ratio of keel depth to sail height (e.g., a ratio of 4.4 for first-year ridges; Timco and Burden, 1997). Given that the water depth in this region ranges from approximately 10 to 17 m, it is likely that at least one of the largest three keels was grounded on the seafloor, if only over a short distance.

Seaward of both ridges that formed during the first breakout event and the newly formed ice represented by the bright line in the SAR image of Fig. 4a, level ice thickness along the profile B to B' was about 1.65 m. This pan of ice was thicker than level ice at the mass-balance site (1.3 m around the same date). This difference can be attributed to the pan ice forming elsewhere and being incorporated into the landfast cover through advection following the breakout event.

The thickness of ice blocks in the ridges and rubble along the EM transects were also measured. Some blocks of seaward ice lifted onto the incoming ice sheet were between 0.85 and 1.05 m thick, slightly thinner than ice at the mass-balance site at the time of the breakout (1.25 m). Most of the ridges and rubble formed during the deformation event immediately following the breakout consisted of blocks 0.20 to 0.58 m thick, as seen in the photograph of Fig. 8. Based on the ice movement apparent from the radar, the incoming parent ice sheet that deformed during this deformation event was most likely thin ice that had grown for less than one month due to the freezing of flaw leads to the southwest of this location, and driven into the area by the northeast coastal current (*qaisagniq* in Iñupiaq). Remnants of this ice are apparent as uniform areas of low-backscatter in the SAR scene (see area "B" in Fig. 4a).

4.4. Local observations and community use of the ice

Uisauniq, the Iñupiaq term meaning "to be separated or cut off during an ice separation", is a central concern to those hunting or traveling on the landfast sea ice. (J. C. George et al., unpubl. manuscript). Many coastal arctic communities possess extensive local and traditional knowledge on this subject and utilize this knowledge throughout the year as they evaluate the local landfast ice conditions (George et al., 2004). The Iñupiat identify a range of mechanisms that may act to detach a section of the landfast ice. These theories include, but are not limited to, the nearby pack ice acting as an abrasive chisel against the landfast ice, ice deterioration by offshore under-ice currents perpendicular to the ice edge, and rapid changes in sea level (George et al., 2004; J. C. George et al., unpubl. manuscript).

Table 2 summarizes the observations made by Leavitt that are relevant to understanding the ice and weather conditions and forcing under which the two ice breakout events in spring 2007 took place. The event on 31 March happened approximately one week before whaling crews began the annual task of clearing trails through the deformed landfast ice to provide access to the open lead in order to establish camps for the bowhead whale hunt. The event on 28 May took place just days after the final whaling crews pulled off the ice at the conclusion of the hunt.

Table 2
Sequence of events pertaining to the breakout events as observed by Joe Leavitt (unpublished journal of sea-ice observations, 2006/07).

Date	Event
28 February	It looks like low terrain first-year ice to the west.[a]
25 March	Young ice is piling up with a south wind all along the coast about 1/2 mile out. Pressure ridges piling up in front of Napa.[b]
27 March	It is rough terrain to the west with high piles of ice past 1/4 mile to 5 mi out. A couple of high piles to the North. No sign of open water. Skies are clearing.
29–31 March	There was an opening 1/2 mile from shore in front of the gravel pit, although it closed with west winds. There is now smoother ice, flat spots, and changed pressure ridges.[c]
1–5 April	Not too much activity with leads closing with west winds.
3 May	The ice is still well off shore down south. It is all first-year ice on the Hollywood trail. We must watch the tide because there are no grounded pressure ridges and it is all low terrain ice.[d]
25 May	All whalers are now off the ice. The quota is done for this year.
28 May	There is a big crack only 1/2 mile out. The ice is moving out and the broken off pieces are going to the NE with *Qaisagniq*.[e]
29 May	Open water is 3/8 mile out. Shore ice is still stable and no melt water is on top yet.

[a] "to the west" refers to the ice in the area of the breakout events.
[b] "Napa" refers to a commercial store located in Browerville (see Fig. 1).
[c] "gravel pit" refers to the coastal region immediately SW of Barrow.
[d] The "Hollywood trail" refers to a trail used for whaling located in the southern reach of the area that broke-out on 31March (see trails and area "B" in Fig. 4a).
[e] Qaisagniq refers to a current traveling in a NE direction off Barrow.

Leavitt indicated that ice in the region of the 31 March breakout event was composed of low terrain first-year ice and experienced little ridging until 27 March, a few days prior to the breakout. He noted that open water appeared near shore and then closed with a west wind. Since the breakout took place in the middle of the night, Leavitt did not witness the actual event.

Following the formation of new ice after the 31 March breakout, many of Barrow's whaling crews established their camps in this region (see Fig. 4a) despite the fact that ice failure was a clear risk based on the thickness (A. Brower, Sr., pers. comm., 2007). The thickness of this new ice was approximately 0.29 and 0.65 m on 19 April and 9 May, respectively. This region, where many of the whaling trails and camps were located, was held in place by a few "key" ridges (J. Leavitt, pers. comm., 2007). Wesley Aiken (public testimony, 2007), a Barrow elder and experienced whaling captain, noted that the "new thin ice piling up in April was 'lucky' because it made [the landfast ice] stable at the lead for whaling." Favorable winds certainly added to this perception of stability. Neither Leavitt, A. Brower, Sr., nor the Airport's wind records (see Fig. 6) reported any significant west winds between 14 April and 27 May, the period in which most of the whales were harvested in this area. Although a westerly current was acting on the ice, the lack of a west wind allowed the lead to remain open and prevented northeast-drifting ice from colliding with the landfast ice. A. Brower, Sr. noted that a strong west wind could have "folded" this ice. These experienced hunters staged their efforts in this area for two reasons: (1) whales were being seen and were accessible (Harry Brower, Jr., pers. comm., 2007), and (2) the ice and weather conditions did not present any clear warnings that a breakout (*uisauniq*) was likely to occur (A. Brower, Sr., pers. comm., 2007).

The whaling crews eventually pulled out of this southern area (see the trails in Fig. 4b) before the 28 May breakout event as they noticed the ice being worn dangerously thin by snow machine traffic and also detected wave motion lifting the thin ice (H. Brower, Jr., pers. comm., 2007). Observations of previously refrozen cracks melting to yield open water provided an additional indicator that it was too risky to remain in this area (A. Brower, Sr., pers. comm., 2007). A. Brower, Sr. noted that warm weather and current erosion to the under ice surface contributed substantially to this second breakout event.

4.5. Discussion

These coordinated observations of the breakout events in spring 2007 allow us to: (1) discuss the implications of how the landfast ice off Barrow stabilized and evolved throughout the 2006/07 season, (2) build toward a greater understanding of the mechanisms that cause winter or early spring breakouts in the landfast ice, and (3) evaluate how the community's use of the ice, an important proxy for understanding ice conditions, relates to various methods of assessing safety and stability.

Local hunters acknowledge that in order to understand how stable the ice cover is at any given time they must observe the entire ice season (George et al., 2004). This requires an ability to spatially and temporally organize observations of (1) ice ridging events and the distribution of potential anchor points, (2) areas where ice may extend from the landfast ice without being properly anchored, (3) hazardous thin ice potentially concealed by snow cover, and (4) where ice deterioration may be taking place, either through mechanical or thermal ablation. It is necessary to then apply an understanding of how relatively short-term and variable forcing interacts with the inherent stabilizing characteristics of the ice cover. Local knowledge as well as past studies, including an analysis of five separate breakout events since the 1980's by J. Craig George et al. (unpubl. manuscript), reveal that breakout events can be attributed to sea-level changes, strong winds, under ice currents, open water wave generation, and collision with drifting pack ice (George et al., 2004). For example, while camped at the edge of the landfast ice, hunters frequently check the strength and direction of under-ice currents, as well as monitor the water level in cracks near grounded ridges to assess how tidal fluctuations may disturb anchor points (K. Toovak, pers. comm., 2000; H. Brower, pers. comm., 2001; A. Brower, Sr., pers. comm.., 2007; J. Leavitt, pers. comm., 2007). The observing system's efforts to track and analyze the forces and instabilities leading to breakouts have ultimately been inspired by this approach; the ice's yearly history is carefully observed in order to assess stability at any given time.

Table 3 summarizes comments made by four separate local ice experts regarding the 2006/07 ice season. These observations and SAR images provide a consistent picture that the season was characterized by a lack of large ridges and thick multiyear ice. Both local and traditional knowledge (George et al., 2004; A. Brower, Sr., pers. comm., 2006) and recent glaciological studies (Mahoney et al., 2007a,b) point to the importance of anchor points such as ridges or thick multiyear ice floes in holding the landfast ice cover in place.

The entrainment of multiyear ice in the landfast ice cover is affected by the presence of near-shore multiyear pack ice during freeze-up. Fall freeze-up is occurring on average 16 days later now compared to the 1950s (Mahoney, 2006). Coupled with concurrent changes in multiyear ice, this is considered a major cause of the observed changes in the coastal zone. However, as offshore multiyear ice usually moves southward in fall, a later freeze-up need not imply a reduced incorporation of multiyear ice in the landfast ice zone. The northward recession of the multiyear ice edge in summer 2006 (NSIDC, 2006) was likely the controlling factor in the reduced multiyear fractions in the landfast ice cover in spring 2007. Local observations and webcam, radar, and satellite imagery confirmed that the onset of stable ice occurred late in the season in 2006/07. This may be partially attributed to a storm on 13 November that brought strong north-northwest winds of up to 40 mph (NOAA, 2006), disrupted freeze-up, and resulted in the season's first ice being broken-up and deposited on the shore. It was not until 2 January 2007 that Leavitt indicated that the landfast ice immediately off Barrow appeared to be established for the winter.

Analysis of the data presented in this case study indicates that the late-March breakout event was most likely caused by a sequence of: (1) mechanical action by drifting pack ice causing detachment of relatively few grounded ridges along the seaward landfast ice edge, and (2) stabilizing onshore winds shifting to strong offshore winds. The absence of precursor events, small-scale motion of ridges prior to breakout ("flickering", Mahoney et al., 2007b), also point to dynamic interaction with pack ice as opposed to bottom ablation that may have helped to un-ground or destabilize key ridges. Significant factors associated with the late-May breakout were: (1) a weakened attachment zone, (2) the onset of spring surface warming and solar heating, (3) an insufficient number of grounded ridges as observed by local ice experts,

Table 3
General observations of Barrow's 2006/07 ice season.

Observation	Source
Few ridges were formed in the landfast ice region off Barrow due to a lack of a west wind.	Joe Leavitt[a]
There was a lack of multiyear ice incorporated into the landfast ice. Whaling crews had to haul freshwater to their camps as opposed to melting multiyear ice.	Harry Brower, Jr.[a]
There was "low-profile" multiyear ice in the landfast ice off Barrow, as opposed to the "high-profile smooth hills of old ice" that people are used to seeing.	Arnold Brower, Sr.[a]
There was an "instability" in the landfast ice due to "young ice forming later in winter." Also, the pressure ridges were smaller.	Wesley Aiken[b]

[a] Personal communication, 2007.
[b] Public testimony, UNEP World Environment Day, Barrow, Alaska, 5 June 2007.

satellite imagery, and ground-based ice thickness surveys, and (4) ablation at the ice bottom enhanced by under-ice currents and the advection of warm water from the lead areas adjacent to the landfast ice edge. Despite conditions of thin, seemingly unstable ice between these two breakout events, the community was able to safely and productively use this ice in the absence of destabilizing environmental forces (e.g., an onshore westerly wind that may have caused pack ice to collide with the landfast ice). Data compiled during future breakout events over multiple seasons will lead to better understanding of how a lack of grounding ridges affects the ability of local experts and geophysical monitoring to detect early warning signs of ice breakouts.

5. Conclusions

This coastal ice observing system is being developed using a stepwise, multi-pronged approach and major components are currently in place. However, the system is far from delivering data and information in a format that fully meets user needs. The integrated approach outlined in this paper is ultimately working toward tracking and anticipating risks associated with events at the local scale. Risk is subjective; therefore, to move forward in this context, a continued partnership with the community is critical to ensure that data organization and the construction of causal explanations for these events are conducted at the interface with local knowledge.

Interfacing geophysical observations of sea ice with local Iñupiat knowledge has proven extremely helpful by providing detailed observations and explanations of interactions between ice, atmosphere, ocean, and land, as well as a holistic framework into which we may place our observations. Ellen Bielawski (1992), who researched Native knowledge systems in the Arctic, noted that “the key intellectual problem for research integrating indigenous knowledge and science is discovering categories for data collection that match the aboriginal and scientific worldviews.” Researching landfast ice stability and the mechanisms for spring breakouts provides such a shared category for data and information, and a method for strategically mining vast amounts of the geophysically derived data. At this “interface”, we are also learning to ask the right questions. To find answers to these questions research methods must often be adaptive to evolving ice conditions so as to make observations at scales relevant to the community's response to these conditions.

As ice trends in Alaska's arctic seas continue, we may expect decreasing summer minimum pack-ice, which will in turn have a large impact on the stability of the landfast ice which depends on the presence of multiyear ice as a stabilizing component (Norton and Gaylord, 2004). This observatory has proven important in assessing how changes in ice conditions impact human activity, and therefore may help address similar questions that exist in other arctic coastal environments. Furthermore, local-scale observations may significantly improve the products currently disseminated by the ice services by providing ground truth and more detailed information on ice thickness and type.

As national and international efforts work towards an Arctic Observing Network to monitor global climate change and arctic warming (NAS, 2006), it is important that the Barrow observatory supports sustained observations over a prolonged period of time, especially as it fills an important observational gap by monitoring the seasonal ice zone. One approach to meeting this objective is to work toward joint ownership between researchers and the community of Barrow. Although joint ownership has yet to be realized, current efforts that include the community in the research process and in the design of studies is bringing us a step closer to achieving this long-term goal.

Acknowledgements

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