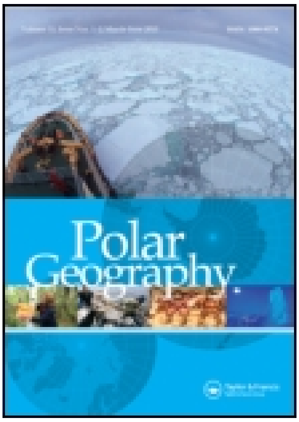

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Matthew L. Druckenmiller [a], Hajo Eicken [b], J.C. "Craig" George [c] & Lewis Brower [d]

[a] National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA

[b] Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA

[c] North Slope Borough Department of Wildlife Management, Barrow, AK, USA

[d] North Slope Borough Department of Search and Rescue, Barrow, AK, USA
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Trails to the whale: reflections of change and choice on an Iñupiat icescape at Barrow, Alaska

MATTHEW L. DRUCKENMILLER[a]*, HAJO EICKEN[b], J.C. "CRAIG" GEORGE[c] and LEWIS BROWER[d]

[a]*National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA;*
[b]*Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK, USA;*
[c]*North Slope Borough Department of Wildlife Management, Barrow, AK, USA;*
[d]*North Slope Borough Department of Search and Rescue, Barrow, AK, USA*

Shorefast ice, present along Alaska's Arctic coastline from late fall through early summer, provides a platform for subsistence hunting by coastal indigenous communities. At Barrow, Alaska, Iñupiat hunters build trails each spring across the shorefast ice to connect the community to the adjacent lead where they hunt migrating bowhead whales. Building on efforts initiated by Alaska's North Slope Borough and in collaboration with the Barrow Whaling Captains Association, a systematic ice trail mapping and surveying project was developed in spring 2008. Using electromagnetic induction sounding, ice thickness surveys were completed along trails just prior to whaling. Semi-directed interviews with hunters addressed the impact of ice conditions on the hunt, choice of trail and hunting locations, and safety concerns. Four years of results (2008–2011) have shown that (1) tracking of local ice conditions along ice trails reveals the interannual variability of the shorefast ice thickness distribution, (2) documenting trail building and hunting strategies provides a baseline for how the community copes with variability, and (3) developing information resources for the community facilitates interaction with hunters and maintains project relevance to environmental challenges facing the community.

Introduction

In the Arctic, coastal indigenous peoples possess an unparalleled familiarity with sea ice as it provides a physical pathway and platform for accessing many of their most important food sources. For nine Iñupiat communities in Alaska (Figure 1), the traditional springtime hunt of the bowhead whale remains an important part of their subsistence culture. Aside from the communities of Gambell and Savoonga on St. Lawrence Island and Little Diomede, most traditional spring whaling in Alaska is done from the outer shorefast ice edge. Shorefast ice is seasonally anchored along the coast due to either ice freezing to the seafloor near the shoreline or deformation ridges grounding in shallow waters, typically <20 m deep (Barry *et al.* 1979; Mahoney *et al.* 2007a). Along Alaska's northern coastline with the Chukchi and Beaufort Seas, shorefast ice remains in place from approximately early-November through mid-July (Mahoney *et al.* 2007a). Between late-March and early-April, ice trails—expressions of traditional knowledge, risk assessment, and hunting

*Corresponding author. Email: druckenmiller@nsidc.org

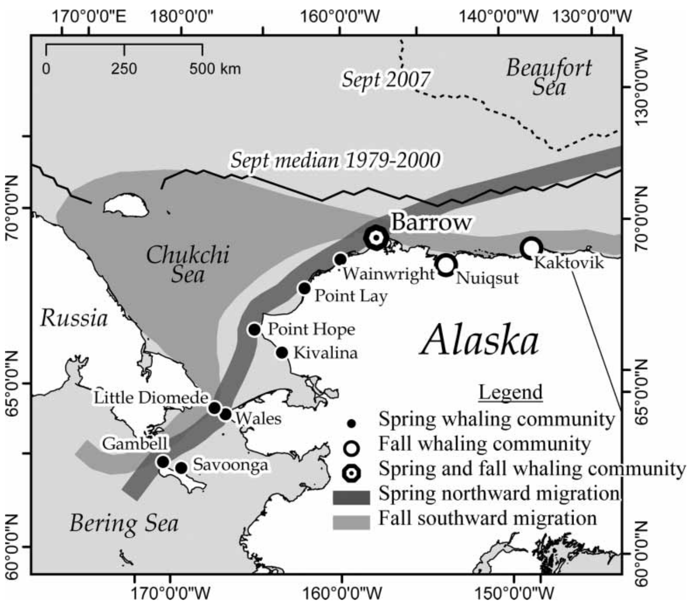

Figure 1. Alaska's indigenous whaling communities, whale migration, and summer sea ice extent. Barrow is the only community to practice both spring and fall whaling. Moore and Reeves (1993) and Quakenbush *et al.* (2012) provide the approximate migration path for the Bering-Chukchi-Beaufort bowhead whale stock. The September median (1979–2000) and the September 2007 ice extents are derived from passive microwave satellite imagery and obtained from the National Snow and Ice Data Center.

strategy—are built across the shorefast ice to connect the communities to adjacent leads where they camp and wait for the migrating whales.

Barrow, with a population of approximately 4,000, is the largest Iñupiat community in Alaska and strategically positioned for hunting bowhead whales. The village sits just 15 km south of the northernmost point in Alaska—Point Barrow. In spring, the whales, which over-winter in the Bering Sea, begin their eastward migration toward summer feeding areas in the Beaufort Sea (Moore and Reeves 1993). The annual development of a persistent flaw lead system along Alaska's Chukchi coast (Eicken *et al.* 2006) provides a reliable and efficient travel corridor for the whales, typically guiding them within striking distance of Barrow's hunters. Over the last ten years Barrow has landed around 10 bowhead whales each spring, more than any other whaling community in Alaska.

The bowhead whale is one of many natural resources that comprise the Native's subsistence diet at Barrow and other Alaska whaling communities. Ice seals (bearded, ringed, and spotted), walrus, beluga whale, polar bear, caribou, waterfowl, and fish also contribute (Braund and Moorehead 1995); however, the spring hunt for the bowhead whale is perhaps the most culturally significant and labor-intensive subsistence activity. A hunter establishes his- or herself as a whaling captain only after the appropriate resources are acquired (skin boat, bomb lance, ice cellar, several snowmobiles and sleds, etc.), a whaling crew is recruited, and the proper instructions are learned by all involved. The whaling crew is more than just those at the hunting camp; it also includes everyone who performs the sewing, cooking, and other necessary preparations. As a result, bowhead whaling provides an important structure for social behavior and organization (Bodenhorn 2003).

The dynamic local ice environment at Barrow presents significant challenges to whaling crews who rely on shorefast ice as a platform for travel, camping, and butchering 10–60+ ton whales (George *et al.* 2004a; Norton and Gaylord 2004; George 2009; Druckenmiller *et al.* 2010). Along with weather, ocean currents, and whale behavior, ice conditions largely determine where, when, and how the hunters travel, assess safety, and make decisions related to the hunt. The inherent danger and risk associated with operating from such an ephemeral and evolving icescape shapes a holistic, and accordingly highly nuanced, body of local and traditional knowledge (Krupnik and Jolly 2002; Lowenstein 1980; Nelson 1969).

In addition to the dramatic pan-Arctic retreat of perennial sea ice extent over the last three decades (Comiso *et al.* 2008), studies reveal many changes in Arctic sea ice that are important on regional and local scales. These include a later onset of freeze-up (Mahoney *et al.* 2007a; Markus *et al.* 2009), decreases in multi-year ice (Maslanik *et al.* 2007), and general reductions in the annual mean sea ice concentration in the coastal regions (Wendler *et al.* 2010). After the mid-1970s, hunters along Alaska's Chukchi coast also began observing ice conditions unlike those experienced in previous decades (Krupnik and Jolly 2002; Norton 2002; Druckenmiller 2011). These changes include a progressive decrease in the abundance of old ice, shorefast ice forming later in the year, and reduced stability of shorefast ice.

Dating back to the Point Barrow Expedition during the first International Polar Year (1881–1883) (Murdoch 1892), Barrow has maintained a long history of local people interacting and partnering with researchers (Albert 1988, 2001; Bee and Hall 1956; Brewster 1997). As a more recent example, the Barrow Symposium on Sea Ice in 2000 was a three-day gathering of over 30 participants, mostly whaling captains and scientists, to explore potential areas for collaborative sea ice research and understanding (Huntington *et al.* 2001). Local experts expressed a strong interest in seeing research address questions related to shorefast ice safety and accordingly expressed support for research focusing on shorefast ice break-out events, which take place when large sections of shorefast ice detach and drift away from the coast. Throughout history such events have resulted in loss of life to hunters and/or major rescue efforts (George *et al.* 2004a). Since 2000, several research projects have focused on break-out events near Barrow (Druckenmiller *et al.* 2009; George *et al.* 2004a; Mahoney *et al.* 2007b). It was in light of these types of hazards that the suggestion to map the community's ice trails emerged, in part, to establish a more direct and identifiable link between the observations made by hunters and those made by scientists.

In the following spring of 2001, ice trail mapping began when J.C. George, a whale biologist with the North Slope Borough (NSB), collected hand-drawn sketches of trails and ice features from Warren Matumeak, an elder whaling captain. George worked with other community members to map the trails using handheld GPS (global positioning system) devices. Figure 2 presents a map based on both GPS tracks and Matumeak's sketches where he noted features and ice types that he considered important (e.g. "pressure ridges" as an indicator of ice anchoring strength, "smooth" versus "jumbled ice" as related to trafficability, and "multi-year ice" as a source of fresh drinking water). George kept a record of general trail

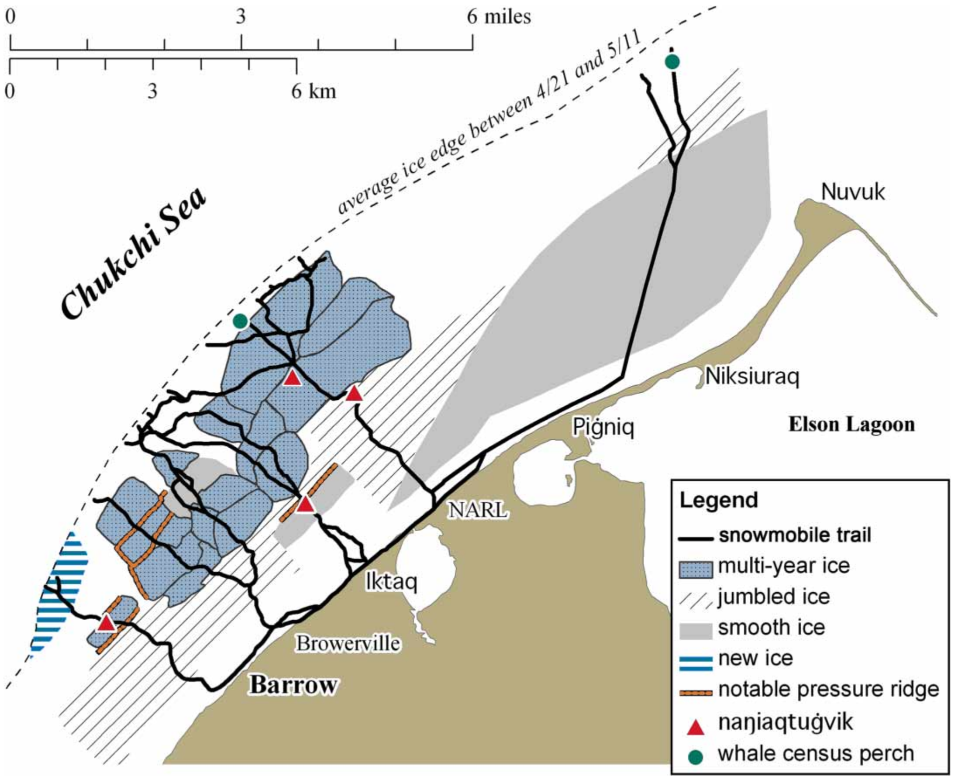

Figure 2. A reconstructed map of the 2001 ice trails using Warren Matumeak's sketches and GPS tracks. Naŋiaqtuġvik refers to a safe camp away from the ice edge.

locations through spring 2007, occasionally collecting GPS data; however a thorough and systematic trail mapping project did not emerge until spring 2008.

We hypothesize that the placement of ice trails reflects how ice conditions guide the community's use of ice and interaction with their local environment. In this paper, we focus on findings of the trail surveying project during its first four consecutive spring seasons, 2008–2011. To better understand the current state of ice conditions and efforts of the community to cope with interannual variability, we explore the benefits of combining geophysical-based monitoring with local knowledge and ice-use along the following themes: (1) tracking ice conditions; (2) documenting trail building and hunting strategies; and (3) developing information resources for the community.

This project is not the first to map ice trails used by indigenous peoples in the Arctic. In the Canadian Arctic, Tremblay et al. (2006), Aporta (2009), and Gearheard *et al.* (2010) have mapped trails used by the Inuit to access traditional hunting and fishing sites and to travel between communities. These projects have documented routes that extend for hundreds of kilometers, mostly over level undeformed ice. The work of Gearheard *et al.* (2010) has used sophisticated geomatics devices that allow hunters to collect detailed spatially referenced information on weather, ice hazards, animal sightings, and other relevant observations. Wilkinson *et al.* (2011) are collaborating with Inuit residents near Qaanaaq, Greenland to incorporate scientific instrumentation to measure ice thickness and local weather variables (similar to that used in this study) into sleds that are pulled by local dogsled teams.

With these efforts recognized, there are four noteworthy distinguishing characteristics of the project discussed here. First, the approach includes detailed surveys of continuous ice thickness and topography measurements, providing a multi-year dataset for quantitative analysis of trail characteristics. Second, these measurements are combined with various data collected by the Barrow Sea Ice Observatory (Druckenmiller *et al.* 2009) to better understand the contributions of both ice growth and dynamics to the ice thickness distribution and to produce information resources for the community. For example, an automated mass balance site, which is installed annually in undeformed first-year shorefast ice, uses acoustic sounders to track ice growth and provides near-real-time information on sea level throughout the season (Druckenmiller *et al.* 2009). Third, relative to the spatial extent and roughness of the trails in the previously mentioned projects, the trails off Barrow traverse a very narrow stretch of highly deformed and heterogeneous shorefast ice. Barrow's trails are not typically placed with precise predetermined destinations in mind, but rather develop in response to encountered ice conditions and are often moved during the hunting season as conditions change (Druckenmiller *et al.* 2010). In general, the dynamic nature of Barrow's coastal ice makes for comparatively dangerous conditions. Also, unlike ice conditions in the coastal Canadian Arctic (Aporta 2009), there is significant interannual variability. Lastly, in recent decades, the waters north of Alaska have experienced a greater retreat in the extent of summer- and fall-time perennial sea ice in comparison to the seas of the Canadian Arctic. This has implications for the local availability of different ice types (e.g. less multi-year ice) during the fall freeze-up of shorefast ice.

Methods

Surveying ice conditions

Each spring, prior to the start of whaling, we obtained formal permission from the Barrow Whaling Captains Association (BWCA) to map and survey the ice trails. We agreed to stay clear of whaling activity and to perform measurements before active hunting (i.e. crews camped on the ice ready to pursue whales) or when hunters were temporarily pulled off the ice during periods of unfavorable weather or ice conditions. Most surveys were completed in the days prior to the first arrival of passing whales (typically in mid-April; George *et al.* 2004b) or when no open water was present along the shorefast ice edge. Because new trails are built and old trails re-routed during the season as ice conditions change, it was occasionally necessary to re-survey trails during active hunting. At these times, we were careful to not interfere with hunting and ended surveys well before reaching camps at the ice edge. To the best of our knowledge, all primary trails were surveyed, however, secondary trails (i.e. poorly maintained and/or infrequently traveled trails used to either scout ice conditions or to connect main trails) were occasionally not surveyed due to time constraints, rough driving conditions, or our unawareness of the existence of certain segments of trail.

An electromagnetic induction conductivity meter (9.8 kHz Geonics EM-31), which measures apparent electrical conductivity of the underlying half-space, was used to survey ice thickness along trails. Because sea ice has a negligible conductivity (approx. 20 mS m $^{-1}$) in comparison to that of seawater (approx. 2500 mS m $^{-1}$), the electromagnetic induction technique indirectly measures ice thickness (Haas *et al.* 1997). By placing the EM-31 on the ice surface (or a known distance above since air and snow also have negligible conductivities), the distance to the ice-water interface below can be inverted from the measured apparent conductivity using an empirically derived relationship between the two. By accounting for the instrument's distance above the ice, ice thickness can be inferred. In this study, however, measurements actually reflect the total layer thickness of ice and snow since surveys are performed along trails that have experienced heavy snowmobile traffic that significantly disturbs and compresses the snow cover. Therefore, we neglect snow depth and present total layer thickness measurements as measurements of ice thickness. Apparent conductivity measurements were transformed to total layer thickness using the following transformation equations for years 2008 to 2010 and 2011, respectively:

$$Z_t = 8.72 - 1.22\ \ln(\sigma_a - 12.4) \text{ and}$$
$$Z_t = 8.49 - 1.21\ \ln(\sigma_a - 14.9),$$

where Z_t is total layer thickness in m and σ_a is apparent conductivity in mS m $^{-1}$. See Druckenmiller (2011) for a description of the calibration procedures.

The EM-31 recorded data at 1-second intervals such that driving at speeds between 10 and 15 km hr $^{-1}$ resulted in sampling at approximately every 3–4 m. Data were then sub-sampled to 5-m spacing. Data points were assigned a water depth (nearest 5-m contour) using a bathymetry based on GEODAS (GEOphysical DAta System) depth soundings for the Chukchi Sea acquired from the National Geophysical Data Center (NGDC). The EM-31's footprint is roughly 3.66 m, which is the distance between its transmitting and receiving coils (Figure 3). EM-31 measurements are accurate to within a few percent of total thickness when surveying level undeformed ice up to 3 m in thickness (Haas *et al.* 1997). Despite accuracy decreasing over thicker ice, surveys across the entire extent of shorefast ice provide useful information regarding the ice thickness distribution, especially for the purpose of year-to-year comparisons. A differential Global Positioning System

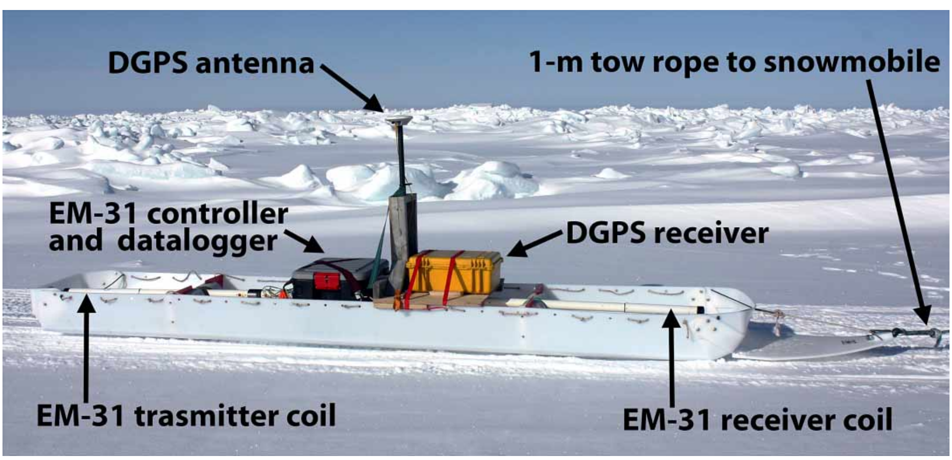

Figure 3. Ice survey sled with EM-31 and DGPS.

(DGPS) capable of cm-scale accuracy was also frequently used to determine the vertical location of the surface; however, this data is not presented here. In 2008, the equipment was placed on a small plastic sled, attached to a waist harness, and laboriously hauled across the ice by foot. In 2009, we used a large wooden sled pulled by a snowmobile. This setup was replaced in 2010 by a 4-m long durable Ultra High Molecular Weight (UHMW) polyethylene sled (Figure 3), custom-designed for transporting the delicate EM-31 instrument across rough ice by snowmobile.

Providing ice information to the community

Since 2003, the Barrow Area Information Database (BAID) has provided an online interactive mapping service that in recent years has hosted satellite imagery of springtime sea ice for the Barrow region. Since 2005, the coastal radar of the Barrow Sea Ice Observatory has provided the community with an internet-based near-real-time animation of coastal ice dynamics (Druckenmiller *et al.* 2009). Both of these efforts have contributed in some degree to hunters being more accustomed to using science-based data products to supplement their knowledge of present ice conditions. However, such resources currently see less use by the hunting community in comparison to information sources they are more accustomed to, such as the National Weather Service's 5-day Marine Forecast of wind conditions.

Beginning in 2007, ice trail maps were produced and provided to the community before and throughout active hunting (mid-April through late-May). The maps (similar to that shown in Figure 4 but without ice thickness values) included GPS-tracked trail locations and a coastline with traditional and commonly used place names. The spatial coverage of the maps was chosen to include all trails in the given year, as well as the outer shorefast ice edge. Trail locations were overlain on synthetic aperture radar (SAR) satellite imagery (typically from 1–10 days before present), provided by BAID in cooperation with the Alaska Satellite Facility. With little required technical knowledge, SAR imagery, which is unaffected by cloud cover, allows hunters to discriminate between general ice types (e.g. rough ice versus smooth ice) and locate the shorefast ice edge during periods when the coastal lead is open. Hardcopy maps were distributed to hunters, usually through the central location of the community's Search and Rescue Base, which serves as a common meeting location for hunters and a jumping-off point for community search and rescue operations. Digital maps (JPEG image files) were distributed through email and an internet website.

Recognizing that ice thickness is not the sole determinant of ice type (age, floe size, roughness, and thermal state may be important), we explored a refined method for ice type classification. Using the cluster analysis tools provided by ArcGIS software, we calculated a z-score for each thickness data point in order to allow ice thickness values to exist in more than one class. The z-score is based on how many standard deviations an observation is from the mean within a moving window of specified length. For example, a z-score of -2.0 means that the data value is 2.0 standard deviations below the mean of the values within the moving window. Figure 5 presents an example of this approach applied to ice thickness from a single trail in 2010. Using geo-located photos taking during the trail survey, the classification of z-scores was manually adjusted such that the different identified ice types fell within mostly different classes. For example, light blue represents either rough ice or multi-

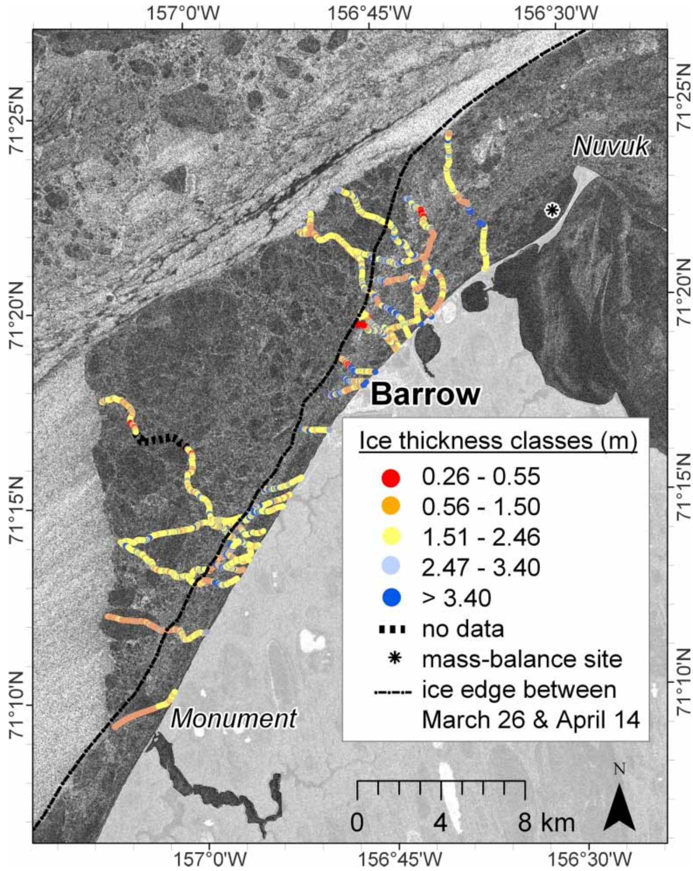

Figure 4. Ice trail map from spring 2010. Colors represent different ranges in ice thickness values according to a classification scheme based on 1 standard deviation from the mean of the entire dataset. Data points are presented at 5-m subsampled resolution. Note that the 2010 ice configuration was quite unusual after April 14 with most crews camped on a nearly north–south oriented ice edge far offshore.

year ice, dark blue represents prominent ridges, red represents thin ice that was wet on the surface, and orange represents either flat ice near the coast or very smooth ice in a refrozen lead. While the difference between the information presented by the two colored trails in Figure 5 is not dramatic, it presents an improved discrimination among ice types compared to classifying by ice thickness alone.

Interviewing hunters

After each whaling season, formal interviews (16 in total) and numerous informal conversations took place with whaling captains and crew members to discuss the impact of ice conditions on the hunt. These interviews were semi-directed (Huntington *et al.* 2009) and addressed the hunters' choices of trail and hunting locations, safety concerns, assessments of how vulnerable the ice was to breaking-out, and observations related to weather and ocean currents. Having traveled the trails each spring over the course of several weeks, we were able to ask location- and

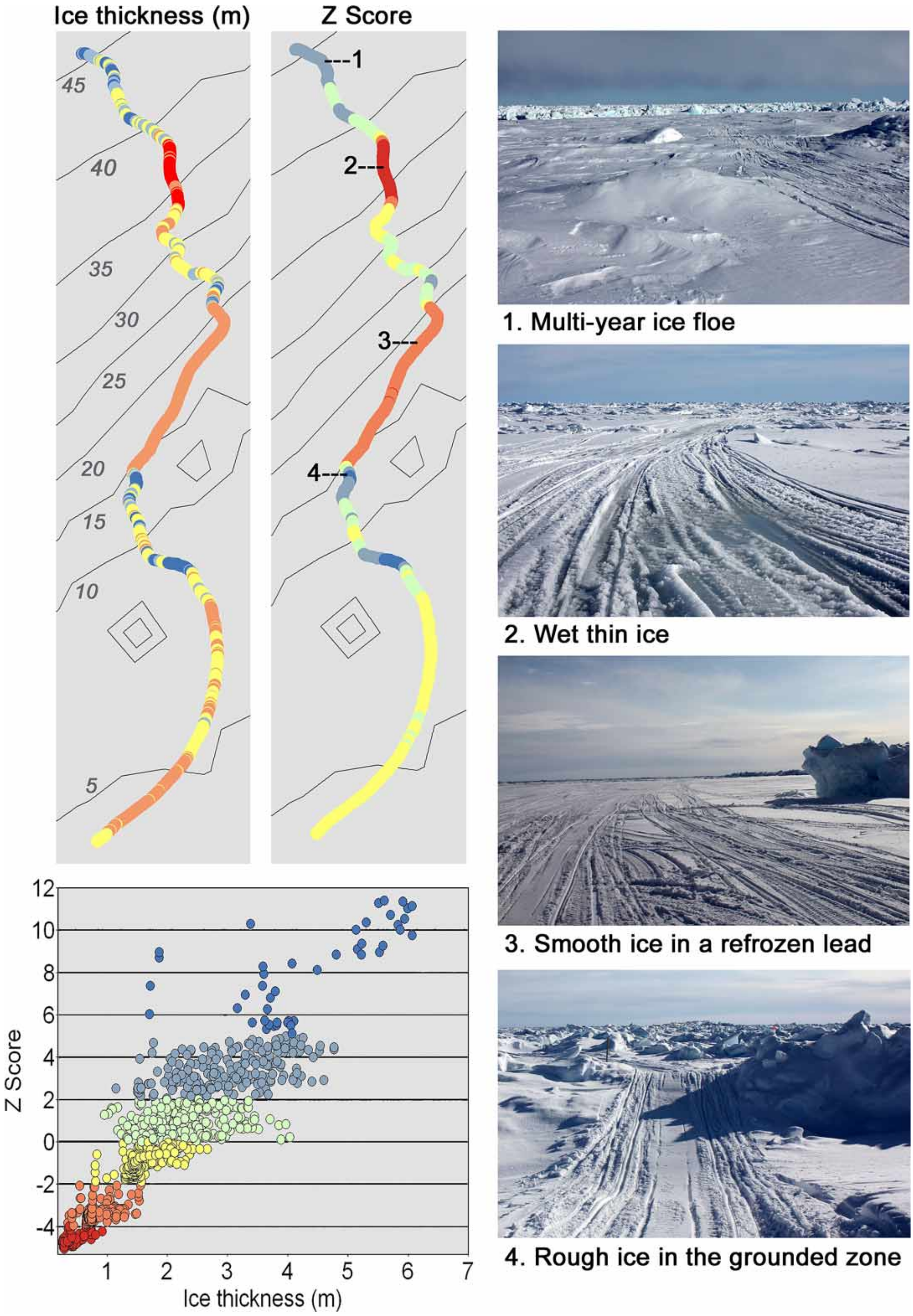

Figure 5. Ice trail morphology classification according to both thickness and type. *Top left*: Colors along the trail indicate ice thickness according to the classification scheme of Figure 4. Bathymetry is shown with 5-m contours. *Top middle*: Colors along the trail indicate z-score (using a moving window of a fixed Euclidian threshold distance of 50 m) according to the classification shown in the graph at *bottom left*. The numbers along the trail represent the different ice types shown in the column of numbered photos on the *right*. The trail used in this figure is from 2010 and is the second trail from the NE in Figure 4.

time-specific questions about ice conditions and why the crews chose certain areas. Hardcopy trail maps and satellite imagery were used to help focus the discussion on specific trails and ice features. Furthermore, the maps provided evidence that we had been well exposed to the range of local ice conditions in the given year, which gave credibility to our research efforts. All discussions were in English, but often used Iñupiaq terminology for ice features and weather conditions. We did not frame interview questions in the context of climate or environmental change, but specifically asked whether hunters had observed anything unusual or noteworthy about the present year in relation to past years.

Results

Ice conditions along trails

Shorefast ice interannual variability is assessed using thickness distributions derived from the ice thickness surveys along the trails. The results of four years of surveys are presented in Figure 6 as a map of trail locations and in Figure 7 as probability density functions (PDFs) of ice thickness. Although the location of the shorefast ice edge during the whaling season for each year is not explicitly indicated, it can be inferred from the outer trail termini (except for the early season trails shown in Figure 4 as those not reaching the ice edge).

Table 1 summarizes the ice thickness measurements from the trail surveys and compares these to measurements made at the mass balance site on 12 April of each year, which is the average date for the trail surveys. The modes for "level first-year ice" thickness (i.e. the thickness of level ice that froze in-place in fall) are roughly the same for all years at between 1.5 and 1.6 m, with a slightly higher value in 2010 at

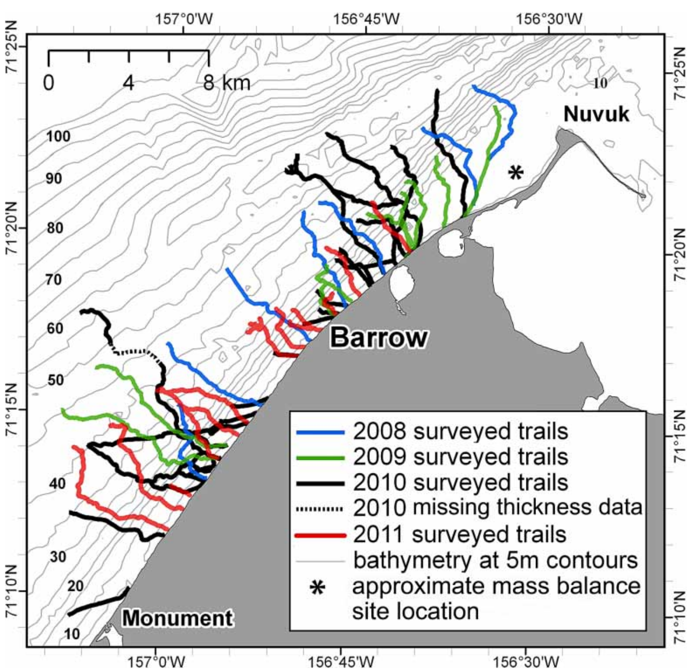

Figure 6. Trail and ice thickness survey locations (2008 to 2011).

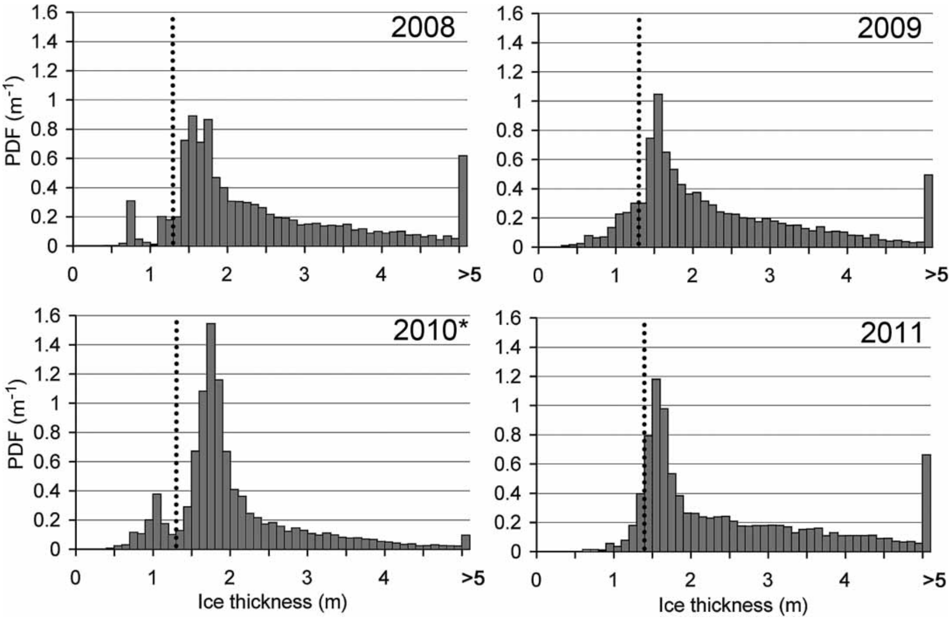

Figure 7. Probability density functions (PDF) of ice thickness from trail surveys for years 2008–2011. The last bin in each PDF represents all thickness values >5 m. The vertical dotted lines represent the ice thickness at the mass balance site on 12 April (see Figure 6) of each year. *Data does not include the early season trails, which can be seen in Figure 4 as those not extending to the shorefast ice edge.

between 1.7 and 1.8 m. The mass balance site measurements were at 1.3 m for years 2008 through 2010, and 1.4 m in 2011. The observed thicknesses from the trail surveys are greater, on average, by approximately 30 cm. This difference is explained in part by the inclusion of a compressed snow depth into the trail measurements (The average snow depth on 12 April at the mass balance site was approximately 25 cm). Moreover, the trails also traverse low-lying rubble fields with somewhat thicker ice contributing to the prevailing thickness mode. Most important, the modes for

Table 1. Ice trail and mass balance site thickness modes.

	Ice trail surveys					
	Thin ice mode[a]		Level first-year ice mode[b]		Mass balance site[c]	
Year	Ice thickness (m)	PDF value (m^{-1})	Ice thickness (m)	PDF value (m^{-1})	Ice thickness (m)	Approx. snow depth (m)
2008	0.7–0.8	0.31	1.5–1.6	0.89	1.3	0.2
2009	–	–	1.5–1.6	1.04	1.3	0.3
2010	1.0–1.1	0.38	1.7–1.8	1.54	1.3	0.4
2011	–	–	1.5–1.6	1.18	1.4	0.1

[a]Ice thickness mode less than level first-year ice thickness.
[b]Nearest mode to expected level first-year ice thickness.
[c]Measurements from 12 April, which is the average ice trail survey date. See the site location in Figure 6.

level first-year ice thickness show little interannual variability in both the ice trail survey and mass balance site data.

Significant interannual differences appear in other aspects of the data. Figure 7 reveals ice thickness modes for ice thinner and younger than that constituting level first-year ice in years 2008 and 2010, but not in 2009 and 2011. Satellite imagery and ground-based observations confirm that while thin ice was present at Barrow in 2009 and 2011, it was not traversed by the trails. Furthermore, the 2008 and 2010 thin-ice modes result from only one or two trail surveys across continuous stretches of thin ice. In other words, thin ice modes appear because hunters build a trail that either traverses a large flat pan of young ice or uses a smooth refrozen lead as a travel corridor, and not as a result of numerous disjointed thin ice sections distributed throughout the shorefast ice cover.

By assigning average ice thickness from the trail surveys to bins of underlying water depth, Figure 8 reveals interannual differences in the distribution of ridges (i.e. the thickest ice) observed along the trails. Data from 2008 and 2009 suggest that the majority of ridges existed at the 20 and 25-m isobaths, respectively. This agrees with the general observation of shorefast ice near Barrow and along the northern Alaska coast, which is that large, presumably grounded ridges are found near the 20-m isobaths (Mahoney *et al.* 2007a; Shapiro and Barry 1978). Years 2010 and 2011 offer contrasting ridge distributions. The 2010 data show a relatively even distribution of ice thickness across the range of water depths. In 2011, large ridges are observed near the coast and even thicker ridges at the ice edge. The former were due to a localized storm-driven ice shove event in February 2011 that resulted in large ridges (upwards of 11 m in height above sea-level) forming very close to shore. The latter was indicative of a prominent and expansive shear ridge along the lead that presented significant challenges to the hunters as they searched for suitable camp

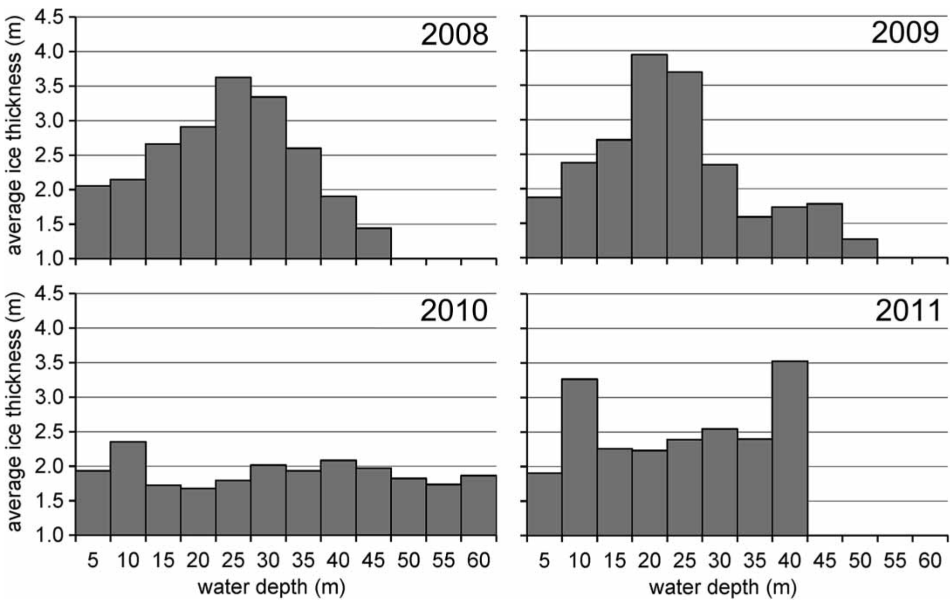

Figure 8. Average ice thickness along the trails in relation to water depth (binned into 5 m depth intervals).

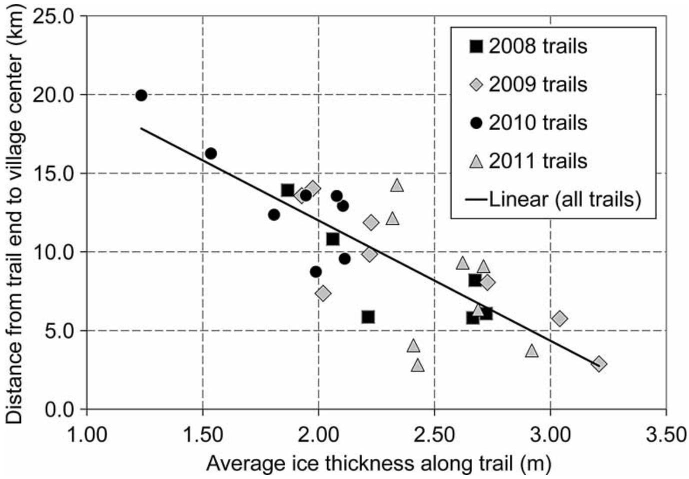

Figure 9. Average ice trail thickness as a function of the remoteness of the trail terminus. The average ice thickness for trails that terminate at or very near the shorefast ice edge is plotted against the distance from the trail's endpoint to the village center (71.2972°N, 156.7783°W). A linear regression of the entire dataset (solid line) yields a correlation coefficient of -0.80.

and butchering sites. In general, the absence of prominent ridges in shallower waters (i.e. up to approximately 20 or 25 m) suggests that the trails may have traversed poorly anchored and potentially unstable shorefast ice. Because ice stability must be assessed at higher spatial resolution than can be achieved through the trail surveys alone, such interpretations of the data are mostly useful insofar as they guide more detailed field-based measurements or interview questions regarding hunters' perceptions of stability.

Trail building strategies

If hunters placed their trails in the same locations each year, independent of ice conditions, trail surveys would provide a record of ice conditions in specific localities and could serve as a strictly physical-science approach to track interannual variability. Similarly, if the whaling crews sought a single ice type and placed their trails wherever that ice type could be found, trail surveys would yield spatial information on ice morphology without necessary consideration of the social system. Neither of these is true. Rather, trail locations vary and reflect the wide variety of choices hunters make as ice conditions differ from year to year. Interviews have shown that hunters decide on where to place their trails according to five primary considerations: safety, access to whales, availability of preferred ice types, convenience, and tradition. These considerations, which account for a large portion of interannual variability in ice trail locations, are summarized in Table 2. Trail building is not a simple optimization problem with only few variables to be weighed against each other, such as effort and navigability. Rather, hunters weigh many factors when deciding how to efficiently, effectively, and safely catch a whale in a dynamic and evolving environment. Many considerations are linked. For example, whaling crews' decisions to partner in trail building are often related to how much effort it takes to build a trail in a given year.

Table 2. Ice trail and hunting camp placement considerations and related ice characteristics. Linkages between considerations are indicated by like-shapes in the far left column.

Trail and camp placement considerations			Related ice characteristics			
Linkages	Major categories and examples	Changes	Roughness	Ice type	Extent	Edge condition
●	**Assessments of safety**					
	Access to well anchored and attached ice	↓[a, b]	X	X	X	X
■	Potential for a quickly navigated trail in case of an emergency		X		X	
■	Ability to make a trail wide enough for two snowmobiles to pass		X			
■	Potential for secondary access/ escape trails		X		X	
	Access to a good location for a naŋiaqtuġvik (safe camp)			X		
	Ability to avoid dangerous areas	↓[c]		X	X	X
○	**Access to whales**					
	Ability to observe surfacing whales (e.g. in an embayment at the ice edge)					X
	How the ice edge shape may funnel or deflect whales					X
	Ability to observe the water in the direction of the arriving whales					X
	Access to water deep enough for whales to dive				X	
	Potential for a camp remote enough to prevent village noise from disturbing the whales	↓[d]			X	
	Availability of preferred ice types					
	Multi-year ice for drinking water	↓		X		
	An ice edge level and stable enough to haul up a whale			X		X
	An ice edge suitable for launching a boat			X		X
	High ridges nearby for whale lookouts and landmarks when returning to camp in boats			X		X
	Convenience					
■ □	Required trail construction effort	↑[b]	X	X	X	
□	Travel time between camp and the village		X	X	X	
□	Cost of snowmobile fuel	↑				
□	Desire to build trail and establish camp together with other crews		X	X	X	
	Proximity of other crews in case of needed assistance [e]					X

Table 2. Continued.

Trail and camp placement considerations		Related ice characteristics				
Linkages	Major categories and examples	Changes	Roughness	Ice type	Extent	Edge condition
	Tradition					
○	Desire to use traditional hunting locations					
	Desire to build trail and establish camp together with other crews					
●	Avoidance of areas that traditional knowledge considers dangerous (e.g. north of Point Barrow)					

[a]See also George *et al.* (2004a) and Mahoney *et al.* (2007b).
[b]Several hunters have noted that thicker ice in the past resulted in smoother ice conditions overall but with larger grounded ridges.
[c]Mostly related to hunters' observations that warm air temperatures and warm water temperatures are increasing in occurrence during active hunting.
[d]Mostly related to hunters' observations that village noise is increasing and deflecting whales.
[e]Mostly related to the abundance and distribution of good hunting sites.

Table 2 identifies the different shorefast ice cover characteristics that are directly related to trail building considerations and provides information on how some factors may be changing (increasing or decreasing). Roughness at scales ranging between 10 cm to several meters generally relates to the navigability of the ice cover, which for example, has implications for trail building effort and accordingly the crews' ability to build secondary access trails. Ice type relates to a whole range of considerations, from stability (e.g. thick first year ice with grounded pressure ridges) to ease of travel (e.g. flat young ice) to very specific uses of ice (e.g. hauling a whale onto thick multi-year ice). Extent not only defines the distance between the coast and the ice edge but it also determines the water depth at the ice edge, which relates to the whales' ability to dive and the likelihood that ridges near the ice edge may be anchored. Lastly, the condition of the ice edge, which here refers to its shape, orientation, and stability, is perhaps the characteristic that whaling crews pay the closest attention to since it relates directly to the specific location where active hunting takes place. Throughout interviews hunters regularly discussed the orientation of the ice edge as important to the likelihood of finding an open lead or how whales may be deflected when migrating past Barrow.

Ice thickness is not explicitly identified in Table 2 as a primary characteristic related to trail building because it is inherently considered as a factor in the four listed ice cover characteristics. Ice thickness is related to roughness (e.g. thinner ice pans are more susceptible to being broken and forming rubble fields) and to ice type (e.g. multi-year ice is thicker than first-year ice). Ice thickness relates to ice extent and anchoring strength since the thickness of a parent ice sheet (prior to deformation) is related to the size of pressure ridges (Tucker and Govoni 1981), and accordingly to their potential for anchoring to the sea floor. Lastly, ice thickness is a key consideration in deciding whether the ice edge is stable enough for hauling up a whale.

As hunters consider the factors presented in Table 2, diverse strategies emerge between the dozens of whaling crews as they seek, manage, or avoid different ice types. For example, as shown previously in Figure 7, trail surveys in years 2008 and 2010 revealed the use of relatively thin ice, which characterized the most productive hunting locations in each of these years. In 2008, several whales were caught from and butchered on a 1.5-km stretch of ice that was approximately 0.75 m thick. In 2010, the two southernmost trails (see Figure 4), which traversed large-pans of ice with thicknesses ranging between 0.90 and 1.30 m, served as harvest locations for most of the 14 whales caught that spring. Hunters considered these stretches of thin ice safe based on the absence of significant cracks and the persistence of favorable weather and drift ice conditions. Given the flatness of the ice, trail breaking was easy with abundant options for quick retreat if necessary. These were also good places for whaling, with ice thick enough to haul up a whale. During interviews following both seasons, whaling captains Jacob Adams in 2008 and Joe Leavitt in 2010 explained that whales were diving beneath these stretches of thin ice and coming back out to surface near the ice edge, and consequently near the hunters' carefully placed skin boats.

Figure 9, which presents average trail ice thickness as a function of distance between camps at the ice edge and the village center, demonstrates that whaling crews are willing to travel farther for thinner, and consequently smoother, ice. Travel time and snowmobile fuel represent significant costs to whaling captains; therefore minimizing distance to camp is weighed against access to an ice type that reduces overall trail building and navigation effort. During trail building, ice picks are used to break-up ice blocks from the high-lying areas into smaller pieces, which are then placed in the lower-lying areas. As a result, trail building does not remove ice but rather redistributes it to reduce large-scale ($>$10 cm) roughness.

If we focus only on the choices made toward preferred ice types, we neglect important information to be gained from those ice types that are only confronted when unavoidable. Hunter observations reveal ice types that are often less abundant and may be underrepresented in the ice thickness surveys. For example, in 2009 and 2011 whalers faced difficulty in finding safe and suitable places at the shorefast ice edge to butcher whales. The unusual incorporation of large volumes of muġaliq (an Iñupiaq term for a conglomerate of slush, brash ice, and snow that forms during periods of shear deformation) at the ice edge presented significant challenges. In 2009, a few whales had to be butchered in the water—a practice avoided by Barrow hunters in contrast to butchering practices by Bering Strait whalers.

Whaler Billy Adams explained that muġaliq is susceptible to ablation from the currents beneath, which makes it unstable once air and water temperatures warm in April or May. Referring to the incorporation of muġaliq at the ice edge in 2009, he stated:

> It is not very stable when it melts and breaks off. There is no safe place to jump on to. Once it breaks off it disperses in all directions . . . Once you get into that slushy ice, it's not a safe place to be in or to butcher a whale.

Hunters' observations also assist in identifying multi-year ice, which is important both to hunters and overall efforts to track the general mass budget of sea ice, especially as rapid reductions in the perennial ice pack are currently observed (Maslanik *et al.* 2007). When discussing the 2001 shorefast ice cover, Warren Matumeak noted:

> We had a whole lot more multi-year ice this year than in past years . . . Where did all that ice come from? These were some of the biggest pieces I have ever seen, there were so many of them [consolidated into one mass] . . . I haven't seen this many [piqaluyuk] sections before.

When many multi-year floes were found scattered throughout the shorefast ice off Barrow in 2010, the hunters were not surprised. While their long-term observations overwhelmingly acknowledge the decreasing abundance of old ice (or piqaluyuk in Iñupiaq), their time spent and miles traveled on the ice typically allow them to identify even trace amounts that get incorporated into the shorefast ice, and which are not easily detected using satellite imagery.

Information resources for the community

Both solicited and unsolicited feedback from hunters has shown that ice trail maps are largely considered as useful for on-ice navigation, general ice type discrimination (e.g. flat ice versus rough ice), a resource for search and rescue, and as a tool for communication between whaling crews, especially for directing people to butchering sites. In addition, specific trail locations in the maps allow hunters to geographically orient their interpretation of satellite imagery around familiar locations on the ice. This increases the usefulness of the satellite imagery, especially as whaling crews consider shifting the location of their camps during the season. Some hunters have noted that the maps provide a tool for those learning to use GPS devices. GPS technology provides an advantage to hunters, enabling them to navigate efficiently to previously visited sites, locate trails that have been covered in snow, and to find their way in poor visibility. Lastly, the maps have promoted project recognition amongst the whaling crews, which has been beneficial when coordinating ice surveys and hunter interviews.

On several occasions, trail maps with ice thickness values (similar to Figure 4 but with units of feet instead of meters) were distributed amongst the hunters. Surprisingly, the thickness information in such products stimulated little feedback or interest, which led to further consideration regarding the types of information shared and the appropriate level of detail. Hunters do not find overly precise or heavily-caveated data useful. As stated earlier, EM-derived ice thickness measurements cannot resolve the actual thickness of ridges thicker than 3–5 m, and therefore cannot be used to reliably infer grounding, at least not without detailed assumptions and knowledge of water depth.

Discussion and conclusions

A four-year interannual comparison of shorefast ice thickness distributions sampled along ice trails has revealed a fairly consistent modal thickness that agrees well with the level first-year ice thickness, as confirmed by measurements at the mass balance site). This suggests that trail surveys provide a representative and meaningful approach to monitoring long-term changes in shorefast ice mass balance since the level first-year ice thickness mode is a signature of thermodynamic ice growth. Moreover, the geographic spread of trails and the diversity of strategies that guide trail placement ensure that a very broad spectrum of ice types is sampled.

Biases in the ice thickness surveys due to oversampling of certain ice types must be considered when quantitatively evaluating the ice thickness distribution. These biases, however, are meaningful as they relate to specific uses of ice. First, they reveal the ice types that hunters must select from each year. Hunting from sea ice requires compromising with the environment. Sometimes, conditions are not ideal for whaling and hunters must use ice types that are considered hazardous. During such times, they pay closer attention to environmental cues, such as changes in weather or ocean currents, that could lead to imminent danger by altering ice conditions. An investigation by Norton and Gaylord (2004) of ice conditions at Barrow during the 2000 and 2001 spring whaling seasons identifies a closed lead driven by persistent adverse winds as the main condition, as opposed to unsuitable shorefast ice conditions, that will keep hunters from whaling for extended periods of time in a given season. Secondly, biases directly relate to hunters' decisions and ice use strategies. For example, whaling crews will travel a greater distance from the village when the required effort to establish a trail is minimized by the presence of flat and relatively thinner ice. These observations present thin ice (relative to the thickness of level-first year ice) as an ice type that hunters often seek, rather than avoid. This is a noteworthy observation in light of popular media generalizations that thinning ice represents a threat to indigenous hunters. This contrast arises mainly because such generalizations use "thinning ice" as a proxy for a whole suite of changes taking place, including decreasing multi-year ice, shorter ice seasons, less stable ice, etc. Aporta (2002) explained that hunters in the Eastern Canadian Arctic have a similar preference toward thin ice, although it is mostly linked to the increased likelihood of finding seals that make breathing holes in cracks.

Trail surveys have also revealed significant interannual differences in several variables relating to ice thickness and morphology, such as the incorporation of favorable and unfavorable ice types (e.g. muġaliq) and the water depth at which the primary grounded zone(s) develops. Such features are monitored by hunters throughout the entire season since they have important implications for ice stability. In this context, interannual variability that is most important to hunters is not driven by season-scale thermodynamic ice growth as much as by the deformation and accretion history of the ice cover and the occurrence of short-lived thawing events.

Relating trail surveys to the experiences of the whaling community relies on the observations and assessments of individual hunters. Interviews allow hunter observations of noteworthy ice features to be spatially co-located with thickness data at specific locations along trails. Speaking of ice conditions in 2009, which was a year with a relatively early first thaw on 27 April, whaler Billy Adams stated:

> We had a bad season because of all that young ice coming in all the time and staying in [at the ice edge] . . . There was a lot of slush–ice . . . Even if there were whales we were kind of hesitant to go out there because of the unsafe ice conditions. We're not trying to take chances to kill a whale for loss of [human] life . . . It was May 12 when we went home . . . It had gotten hot and for many days straight. It melted everything and we just didn't want to stay out there with a lot of water all around . . . It just took a few days of warm weather from on top and, I think, [also] from the current on the bottom. The young ice had gotten soft. We wouldn't be able to pull up a whale on it. Once we know we can't pull up a whale then [whaling] is done for us.

Hunters very often preface their personal observations and understanding of traditional knowledge by acknowledging that it may be different from a response offered by another hunter. Because local and traditional knowledge is highly nuanced, it is expected that there will be slight differences between how individual hunters may describe a particular detail, especially since many hunters may not be as clear as others in translating their practical and experiential knowledge into words. Typically, hunters place great importance on accurate explanations and are often hesitant to speculate or to even generally discuss impacts from climate change. Nevertheless, indigenous experts' ability to recall the past allows for a critical perspective on how local ice conditions may be changing. The recognition of an exception or an outlier relies on a massive inventory of knowledge related to the "baseline" ice condition. Their culture's oral tradition of telling stories enables hunters to have knowledge of longer-term variability and periodic fluctuations in their physical environment (Minc 1986). Accordingly, their understanding and interaction with the environment transcends personal experience. For these reasons, it is extremely valuable when an elder whaling captain offers an observation of something they believe is new or unusual.

Providing ice trail maps to hunters offers a new approach for gauging interest in science-based resources and exploring how research can better provide useful information to the community. Data products must be developed such that they are compatible with the ways hunters already use information to evaluate ice conditions. Identifying the proper level of detail requires multiple iterations of a data product and continued community feedback. We have found that precise ice thickness information alone fails as a basis for hunters' decisions. Interviewing whaling captains on the minimum ice thickness sufficient to haul up a whale, would likely generate a wide range of answers. On the contrary, experts evaluating a potential whale haul-out site out on the ice would likely agree on whether the ice was suitable, and certainly their assessments would consider much more than ice thickness. The hunters would evaluate the ice for cracks and consider other factors that could compromise the integrity of the ice in addition to the weight of the whale. Berkes and Berkes (2009) also observe that Inuit indigenous knowledge rarely uses or values numerical precision. They argue that local and traditional knowledge maintains real-word relevance because precise categorizations are specifically avoided.

The raw ice thickness data from the trail surveys represent a conflation of information relating to the ice mass budget (ice growth/ablation and deformation) and the strategic use of the ice cover. Further data analysis may allow for a disaggregation of thickness measurements into categories that are unbiased and scientifically meaningful in new ways. For example, relating ice thickness surveys to a measure of overall local ice stability (i.e. the ability of shorefast ice to resist breaking-out) would represent a significant outcome of this project and potentially be of great interest to the community for safety reasons.

As we explore a refined method for ice type classification that incorporates expert knowledge and direct visual observations made while on the ice (as shown by the "clustering" in Figure 5), we see greater opportunity for this project to collaborate with the community. In 2002, the NSB School District published *Agviqsiugnikun Whaling Standards* (Harcharek 2002) as an educational resource for young hunters that summarizes local and traditional knowledge of winds and ocean currents, bowhead whale morphological types, hunting equipment, and butchering methods. It encourages young whalers to travel their crews' trails in springtime and to sketch the different ice types they encounter. Accordingly, a future goal for this project is to provide young hunters with cameras and handheld GPS devices so that they may travel the trails to document encountered ice types in the manner that Warren Matumeak did and that the school district's *Whaling Standards* proposes. Ideally, this would contribute to the process of classifying the ice trail thickness surveys while also improving their ability to make ice observations that might later guide conversations with elders regarding ice conditions. We recognize, however, that such community involvement is often difficult to maintain. Furthermore, it remains unclear whether the whaling captains would support such an initiative. Elders have expressed concerns over hunters' increasing use of handheld GPS devices since reliance on this technology may affect or replace traditional navigation skills (e.g. as reported by Aporta 2005). In this context, we acknowledge that trail maps and satellite imagery may not always be used to supplement local and traditional knowledge and in some cases may detract an inexperienced hunter from learning traditional skills.

Because this project represents significant and intentional interaction between researchers and community members, there are perhaps considerable investigator (Norton 2002) and technology effects (George *et al.* 2004a) on hunter activities and the types of information hunters share. For example, we are not yet able to identify how the introduction of ice trail maps may be influencing hunter decisions on where they establish trails. This is particularly a concern in regards to those whaling crews that usually go out later in the season after the earlier, typically more experienced crews have already established their trails. Even before this project, it was understood that less experienced whaling crews are influenced by the decisions of more experienced crews and often encroach on their selected hunting sites. In the context of introducing bias, by focusing hunter interviews primarily on strategies for efficient, effective, and safe hunting, we intend to minimize discussions on climate or environmental change that are not initiated by those interviewed. Due to general awareness by the local community of the recent thrust of science toward climate change research and because we do ask questions regarding unusual observations, we anticipate some investigator effect (i.e. biases) on the types of information hunters share.

Future outlook

In comparison to the shorefast sea ice environment elsewhere in the Arctic, such as near coastal communities in northern Canada and Greenland, conditions at Barrow are more variable, which is largely related to its location at a regional-scale promontory of land, its steep coastal bathymetry, and proximity to the Barrow Canyon—a prominent underwater canyon that influences the strength of coastal currents. Barrow also experiences greater local heterogeneity in ice conditions; within only a few kilometers from the coast, a large range in ice types and morphologies can be found throughout much of the year. This project is documenting the persistence, mobility, and ingenuity employed by the hunters to deal with such variability. The range in strategies employed by the community defines the "decision space" in which they can maneuver to deal with this challenging environment. As this work continues into the future, it may begin to answer the question of whether Arctic communities, like Barrow, that have and continue to cope with such change and variability may be more adaptive to future environmental change than communities located in less dynamic, less variable environments. This work may be considered an important step toward describing Barrow's springtime use of sea ice in a manner that establishes a means for comparison with other communities.

One potential counterargument relating to Barrow's demonstrated resilience to environmental change relates to the delicate timing of spring whaling. In recent years, the average arrival of thawing air temperatures has been the third week in May, which is approximately the time when spring whaling comes to an end. The timing of these two events is somewhat related as hunters routinely attribute the development of unstable ice and dangerous spots along trails to both warming air and water temperatures, however, is not significantly affecting the harvest since the majority of the migrating whales pass Barrow by this time. More importantly, the late season (after 20 May) whales that pass Barrow are mostly large older whales, which are much less preferred by hunters than the smaller juvenile whales for a number of reasons. Hunters' selectivity toward the latter, which pass by Barrow in mid- to late-April, therefore shifts the vulnerability of spring whaling away from the onset of the melt season.

Even slight warming experienced during the time of whaling if coupled with decreases in ice thickness and stability may present important challenges to hunters even if the timing of the harvest has not yet been affected. Short-lived warming periods (thawing temperatures lasting <1 day) contribute to rapid trail deterioration, especially in areas of high traffic were snowmobiles have worn the snow and ice thin. Trails traversing areas of refrozen cracks or solidified piles of brash ice (muġaliq) can quickly break up while the typical level undeformed ice shows little sign of change (Druckenmilller *et al.* 2010). Annual coastal temperatures on Alaska's North Slope show an increasing trend over recent decades (Wendler *et al.* 2010) and studies have shown shorefast ice to be breaking up earlier in summer (Mahoney *et al.* 2007a). Therefore, there is cause for concern that the delicate timing between the abundance of stable ice and the arrival of the majority of whales to the region may be disrupted in the future. This would likely challenge the traditional bowhead whale hunt to a degree not yet experienced by the present day whaling community.

Whether the strategies employed by hunters have significantly changed in recent decades due to climate change remains mostly an unanswered question. If unidirectional environmental change continues, it is reasonable to assume that coping strategies will become more intensive. For example, if spring ice becomes thinner and less stable, the following types of measures currently taken by hunters may become far more predominate:

- increasing mobility and spending less time on the ice,
- developing trails with more options for quick escape routes to safe ice,
- towing captured whales a greater distance by boat to find suitable locations for hauling whales onto the ice for butchering,
- increasing the interaction between elders and youth to retain traditional knowledge and as a way to discover new knowledge (e.g. internet and science-based resources), or
- shifting investments from equipment necessary for the ice-based spring hunt toward suitable boats for the open-water fall hunt.

Sea ice provides an important ecosystem service to Arctic coastal communities by connecting them to hunting opportunities (Eicken *et al.* 2009). In order to gain insight into how future changes in ice conditions may influence the hunt, it is necessary to continue focusing on how ice conditions along specific trails relate to hunting success, or alternatively to major hazards that divert hunting effort. Continuing this work into the future may not only reveal how the community adapts but also eventually identify thresholds in the system (i.e. where changing environmental conditions prompt whalers to make fundamental shifts in their strategies). For example, when does the presence of young thin flat ice shift from being considered an ice type that provides for easy and efficient trail building to an ice type that must be avoided at all costs due to earlier and more persistent thawing temperatures?

In the broader context, an effort to identify thresholds must consider other factors that in some way influence the human–environment system of traditional whaling. Figure 10 summarizes these five major inter-connected factors: environment, whales, governance, local community, and whaling crews. For example, changes in the sea ice environment impacts the relevance of local and traditional knowledge, but it also may influence whale populations, which will in turn be considered by the International Whaling Commission as it sets the subsistence quota for Alaska's whaling communities. While examining these interconnections in the context of social and environmental change is beyond the scope of this paper, general consideration is necessary to provide a broader perspective to this work.

Figure 10. Five factors influencing the success of the Iñupiat's traditional spring whale hunt.

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