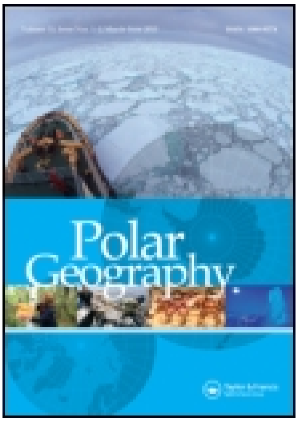

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A framework and database for community sea ice observations in a changing Arctic: an Alaskan prototype for multiple users

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Indigenous sea ice experts from three Alaskan communities, geophysicists, an anthropologist, and information technology specialists collaborated to develop an observational framework and a database to record, archive, disseminate, and analyze sea ice observations. Observations are based on ice uses and information about ice conditions, weather, ocean state, and animal behavior relevant to hunters and to community members. Daily logs kept during the ice season have been archived since 2006, with key variables extracted for subcategories pertaining to weather and ice observations, ice-related activities, and wildlife. The observation program and the development of the associated database are discussed in terms of community wishes and information needs and the potential uses for hunters, students, and others in coastal Alaska. Database records for Gambell, Wales, and Barrow, Alaska, are analyzed to arrive at a representative seasonal cycle of ice conditions for 2006/2007. This single year is placed into a longer-term context by examining interannual variability for freeze-up and breakup dates from 2006 through 2011 extracted from the database. We discuss the adaptive nature of the database framework and its relevance to coastal communities in gathering and transmitting knowledge about the ice environment that can help in adapting to rapid Arctic change.

For Inupiat and Yupik communities along the northern and western coasts of Alaska, sea ice is an important part of daily life and local culture. For much of the year it is an extension of the land, a platform for travel and a way to gain access to important subsistence resources (Eicken *et al*. 2009; Lowenstein 1981; Nelson 1969). Ice uses in the region include the building of trails that link neighboring communities and provide access to marine mammals at the edge of the shorefast ice (Druckenmiller *et al*. 2010; George *et al*. 2004) as well as hunting and butchering animals in the drifting ice pack (Kapsch *et al*. 2010; Krupnik and Jolly 2002). Sea

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ice is a dynamic environment, influenced by complicated interactions between currents, winds, water level, and ice morphology. The local Indigenous expertise required to safely negotiate potential hazards has been honed over centuries through observation and experiences, passed down through generations, and continually refined in response to new experiences. It transforms what an outsider might see as a desolate, even hostile environment into a productive and vital cultural landscape.

Through their close connection to and daily interaction with the natural world, Arctic Indigenous communities were among the first to recognize the impacts of recent Arctic environmental changes (Aporta and Higgs 2005; Huntington 2000; Gearheard *et al*. 2006; Krupnik and Jolly 2002). Hunters in Barrow, Alaska, report reduced hunting opportunities as a result of the extreme retreat of the summer ice and changes in the stability and characteristics of the shorefast ice (Gearheard *et al.* 2006; George *et al*. 2004; Druckenmiller *et al*. 2013). Inuit hunters in communities throughout Arctic Canada report shorter seasonal ice cover, travel concerns due to thinner ice, and more variable weather (Ford *et al*. 2009; Gearheard *et al*. 2006; Laidler *et al*. 2010). The decline in weather persistence and predictability is equally worrying because traditional cues for ice and weather prediction no longer apply. It leaves local people less confident in their ability to navigate the land or the ocean and to acquire essential resources (Gearheard *et al*. 2006; Hinzman *et al*. 2005; Weatherhead *et al*. 2010).

At a time of rapid environmental and socioeconomic transformation, residents in Arctic coastal villages are facing a dual challenge. On the one hand, they need to adapt their ways of using the sea ice environment for hunting and transportation while keeping track of both drastic and nuanced changes in weather, the ocean, and the ice cover (Druckenmiller *et al*. 2013; Huntington *et al*. 2010; Krupnik and Jolly 2002). On the other hand, the ways in which environmental knowledge is preserved and passed on from experienced hunters and ice experts to novices is changing. Oral traditions are partly giving way to other forms of communication. Moreover, with a growing demand on people's time, opportunities for personal instruction 'in the environment,' that is, on the ice or in a boat, are less abundant. Inuit hunters have proven to be adept at using technology, including satellite imagery and improved weather forecasts available online or through telecommunication (e.g. Aporta and Higgs 2005; Laidler *et al*. 2011). However, remote sensing and other modern information products, while useful, cannot replace the in-depth, intimate knowledge and understanding that come with the observation and personal use of the ice environment. Hence, the transmission of Indigenous sea ice knowledge, as well as its preservation and continuous rejuvenation, may be at risk. In his work with Inuit ice experts in Nunavik, Heyes (2011) describes these challenges as 'cracks in the knowledge.'

In the collaborative effort described in this paper, we aspire to fill some of these emerging cracks by first building a usable and accessible repository for local Indigenous sea ice knowledge. Second, we offer a framework and a user-friendly interface that helps to link Indigenous observations of sea ice conditions from the participating communities to geophysical research such as satellite remote sensing, and vice versa. The approach consists of four subsequent steps.

We started by building a team of Inupiat and Yupik sea ice experts from Alaskan communities, sea ice geophysicists, human geographers, and *database* experts. Much of the impetus for such partnership came from the International Polar Year

(IPY) 2007–2008, in particular, the Sea Ice Knowledge and Use (SIKU, Krupnik *et al.* 2010a) project, the Seasonal Ice Zone Observing Network (SIZONet; sizonet.org), and the Exchange of Local Knowledge of the Arctic (ELOKA; eloka-arctic.org). The latter two also contribute to the US Arctic Observing Network (AON; Lee *et al.* 2010).

Second, we jointly developed the approach that allowed these individual experts to grow into a true network. We designed a framework that records and preserves information about the sea ice cover and its seasonal and interannual evolutions viewed and interpreted by Indigenous experts. In contrast with a geophysical observing system, this approach focuses on sea ice features, weather events, and animal behavior important to Arctic subsistence users (Krupnik *et al.* 2010b). The conceptual framework of multiple ice uses and ice system services (Eicken *et al.* 2009) helps bridge between the Indigenous perspectives and geophysical studies of the Arctic environment.

Next, we produced a database using widely available software that not only captured the original observations but also helped extract key variables or events in a broader context. This database evolved considerably over the course of five years and was adapted to match the increasing breadth of the observations.

Based on the lessons learned over the first years of observations (2006–2009) and use of the prototype database, we developed an adaptive, web-based information system. It serves to archive, synthesize, and transmit observations of Indigenous experts during a time of rapid environmental change.

We envision this system to be a potential tool for other communities or research projects interested in similar questions. At the same time, the database of several thousand observation entries over eight years (2006–2013) taken in several communities in northern and western Alaska and the interface created to sort and analyze its content helps advance studies of the impacts of sea ice and climate change at the local and regional scale.

Building a network of coordinated community-based observations

The project began in 2006 as a collaborative effort of sea ice and cultural researchers and Yupik and Inupiat experts from several Alaskan villages (Eicken 2010; Krupnik 2009). The hunters agreed to keep daily or near-daily notes on local weather and ice conditions as relevant for their activities on landfast ice or among drifting ice. In contrast with standard sea ice logs such as those compiled by ship-based observers (Worby and Eicken 2009), the observation program we developed was not constrained by a standardized observation protocol. Rather, it was borne out of the recognition that the different forms of ice use in various coastal communities would guide recording the information relevant to local users.

The observers were asked to note key weather variables, including temperature and wind speed (and where relevant also wind direction), obtained from residential weather stations and general ice conditions. More specifically, they focused on the timing of key events in the annual ice cycle, such as the appearance of the first slush or drifting ice, when the ice becomes safe for travel, timing of ice breakup, etc. Beyond these requests, they were encouraged to report any local details they deemed important having to do with the ice environment, subsistence activities, sea ice travel, and community events. We encouraged them to use terms in their Indigenous languages, specific local place names, forecasting indicators, reference to their personal experience and memories of other community members whenever relevant.

Daily observations were started by late Leonard Apangalook, Sr. in Gambell, Alaska, in the spring of 2006 and have continued with observations by Paul Apangalook starting in September 2008 (Krupnik *et al.* 2010b). In fall 2006, ice experts Joe Leavitt and Winton Weyapuk, Jr. began keeping records in the villages of Barrow and Wales, respectively. The program expanded to include observers Clara-Mae Sagoonick in Shaktoolik, Norton Sound, and Simeon John in Toksook Bay, Nelson Island. In addition, under the Russian 'branch' of the SIKU project, four local observers, Roman Armaergen, Arthur Apalu, Alexander Borovik, and Oleg Raghtilkun, reported their observations during ice years of 2007–2008 and 2008–2009 in the Russian communities of Uelen, Yanrakynnot, Novo-Chaplino, and Sireniki, respectively (Krupnik *et al.* 2010b). Reports on unusual events and conditions were periodically received from the communities of Shishmaref, Savoonga, and Nome, Alaska (figure 1). Since 2010, some of the observers' entries during the spring ice breakup season have been systematically shared on the community web portal and archive developed for the collaborative Sea Ice for Walrus Outlook (SIWO; Eicken *et al.* 2011; http://www.arcus.org/search/siwo) project. The latter was largely built on the activities reported here.

The observers' logs provide a daily record of conditions throughout the ice cycle rather than a retrospective summary as might be obtained through interviews after the fact. While the focus is on weather, ice, and ice-associated activities, the observers describe how subsistence and community life are affected by changing sea ice. They note potential hazards, old and new, and identify specific weather or ice events or wildlife sightings. Observers often relate discussions with, or comments by elders or other hunters, or stories that were passed down through generations, lending deep historical context to an observation. Sea ice terms are often noted in local languages, usually accompanied by a description of meaning or English translation if one exists. The records reveal commonalities among the communities in the way climate change is impacting local interaction with the environment, including changes in sea ice formation and stability, wildlife migration patterns, and how local environmental changes affect subsistence harvest success.

Recognizing the importance of incorporating Indigenous terminology throughout the database, and its inherent cultural meaning and in-depth descriptive capacity for those who understand the language, community members and researchers are currently working to develop more detailed and nuanced documentation of local terminology that can be used in the SIZONet application. This will support not only providing definitions of terms but also modeling relationships between terms. For example, situating individual terms within a dynamic process description (e.g. sea ice formation) can contribute to a more holistic and nuanced understanding of a term by users. Users can include local youth, and we hope that this model will play a role in language learning and retention.

Developing a prototype database for observers' logs

Using Microsoft Access database management software, we created a prototype template in 2007 to house the daily records generated by the project observers. Over time, the database also accommodated several interviews with the observers, elders, and hunters, communications via email regarding important events, and

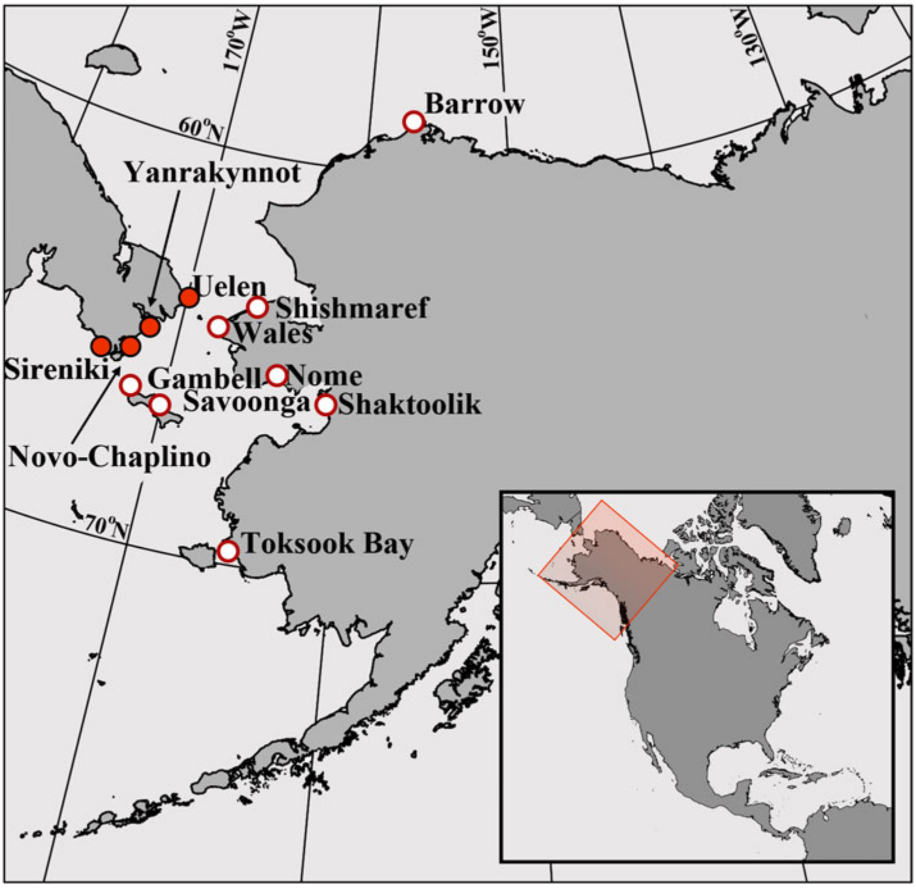

Figure 1. Locations of Alaskan (circles) and Russian (filled circles) villages participating in the local sea ice observations program.

photographs. Initially, the main data categories represented in the database included weather variables and general ice conditions, with subcategories for timing of the sea ice annual cycle and sea ice features and processes important to shorefast ice stability (see Table 1 for a summary of categories and examples of entries). Starting from this template, the structure of the database quickly expanded to include new, unique observations as they were received. In this way, the database design was guided by the observers themselves, as new variables were added from the growing collection of observational logs and from discussions with the observers, both in person and through phone and email communication. Periodically, observers reviewed the database and provided feedback about how well the categories captured the original contextual meaning that was intended. They also identified missing elements and suggested ways to improve the interface to make it more intuitive for community members.

Our approach of storing component parts of the original observation narrative in separate categories was based on several requirements. From a geophysical perspective, information about ice characteristics, processes, and events and ice use is important in the analysis of the local ice cover. The categories in the database focus

Table 1. Database categories and examples of specific events or variables recorded.

Category	Examples from drop down menus
Sea ice observations	
Annual ice cycle	Start ocean freeze-up, first stable shorefast, break up
Ice features	Ridges, melt ponds, cracks, slush berm along beach
Ice events	Breakout of shorefast ice, ice shove, ridging event
Ice type	First year only, multiyear, frazil, pancake, slush
Shorefast ice conditions	Not well grounded, pieces breaking off, deteriorating
Pack ice conditions	Visible from shore, some grounded, blown out
Lead conditions	Open, multiyear floes in lead, young ice covering lead
Weather observations	
Skies	Cloudy, partly cloudy, overcast, clear
Conditions	Blowing/drifting snow, storm/blizzard, fog, white-out
Precipitation	Snow, major snowfall, mixed rain & snow, rain
Visibility	Limited, unlimited, distance
Wind	Speed, direction, change in direction
Ice-related activities	
Sea ice travel	Breaking trail, observing/scouting, search & rescue
Boating	To hunting/gathering grounds, hunting, in lead
Whaling	Crews on lead edge, whale landed, quota reached
Hunting	From sea ice, on tundra, waiting for better conditions
Wildlife	Type of animal, sighted, not sighted, hunted, taken

on these attributes and allow for efficient data search and analysis capabilities. Also, by creating well-defined categories, this mainly qualitative data-set of narrative text can be treated in a more quantitative way; statistics can be performed on individual categories and fields. Lastly, the logs occasionally include information about the community that may be personal in nature (e.g. names of family/other community members and birthdates) or culturally sensitive and not intended to be viewed by public users. These details are not included in the categorized data fields but remain in the narrative, allowing us to share observation details pertaining to sea ice and the environment with a wider audience by displaying only the categorized data fields, while the full observation narrative is available to a more limited group (community members) via secure access.

Toward an adaptive, web-based sea ice information system

The second phase of the observations database development was focused on improving community access to the data while ensuring long-term secure data management and archiving. This led to a partnership in the spring of 2010 with the team of the ELOKA project (Pulsifer *et al*. 2012). Through a series of discussions and iterations the ELOKA team developed a novel approach to a community accessible web-based application for the display and dissemination of the data.

The Access database model was used to inform the design of the web-based application. Database fields and controlled data entry values used to populate dropdown menus (listed in Table 1) were migrated from the original Access database to the database used by the online application. The first iteration of the online application experimented with the use of a simple ‘schemaless’ database that stored data as key/value pairs and could be organized in a variety of ways without significant reengineering costs (Tiwari 2011). In the context of relational database systems like Access, a schema can be described simply as a model that defines a database in terms of tables and data elements that are stored, relationships between elements, data types (e.g. text, numbers, dates), and constraints or rules. Constraints can, for example, control allowable ranges for values (e.g. maximum hours in a day = 24) or ensure that a required data field does not remain empty. A schema provides structure and resulting benefits which include facilitating the maintenance of data integrity, performance optimization, and management of users and roles. However, highly structured data can also make modifications to the model difficult and expensive when changes to the database are required. A schemaless approach does not use a controlling schema which can offer a number of benefits: increased flexibility in creating links between data elements; the ability to readily add and change data fields without 'breaking' a database schema; increased efficiency when storing sparsely populated records – only data that exists is stored, i.e. no records with mostly empty fields; support for storage of a wide variety of content types including multimedia, html pages, and other documents; database access optimized for a Web environment; and the ability to manage data across multiple, geographically distributed servers (Pulsifer *et al*. 2010).

Despite the potential benefits of a schemaless database, the second and current iteration of the application uses the more common relational database management system. In this version, the open source PostgreSQL relational database software underlies an application written using the Ruby on Rails Web development framework. The benefits of the schemaless approach (i.e. ability to easily change data model) were not being fully realized as the SIZONet data model is increasingly well-defined and stable. Additionally, the schemaless approach was adding short-term development costs. Many of the data integrity and application support functions built into relational database software (e.g. various types of error checking and support of multiple users and roles), and necessary for this project, did not exist in the schemaless database software and needed to be written at the application level. Moreover, the tools and methods used are relatively new in comparison to the mature, more common schema-based relational database model. As a result, there were fewer software development support tools and established design and programming patterns available for use by software developers, ultimately adding cost to the workflow. Our experience was that both the relational and schemaless database tools had benefits and limitations, neither provides a perfect solution. The next iteration will expand search capabilities, introduce a more robust ability to link data elements, and provide the ability to upload, tag, and view multimedia content such as photos, video, and audio clips. These features will introduce the need for a more dynamic data model that would benefit greatly from the use of a schemaless database. Hence, a hybrid architecture that combines the schemaless and relational models is planned to support these enhancements.

In the currently released version, a user logs in as either a guest, a community member, or an administrator. Guest users are presented with a User Agreement that outlines appropriate use and citation of the observation data that they must accept to gain access. Guest users are not able to view the details of observation transcripts, which may contain sensitive or personal information, nor can they edit records. Users from participating communities can log in using an assigned username and password and are able to view transcripts, but cannot add or edit observations. Once logged in, administrators can see all data as well as add and edit observations. At present, downloading the data in its entirety must be done through a request to SIZONet. This may change in the future, following consultation with communities on the possible benefits (e.g. broader dissemination) and risks (e.g. misappropriation) of full data distribution.

Once logged in, users are presented with a simple search interface that allows them to search for keywords within the observation record and filter by observer and location. Search results are displayed as a select set of data fields structured in a simple browse table. Icons created by the development team in consultation with local community members and SIZONet researchers (figure 2) indicate observation elements in a given record. The icons were seen as an intuitive method for quickly communicating the content of observation records. From the browse table, a registered user with the appropriate permission can choose to edit an existing record. The web-application is role-based. Although the system is publicly available on the Internet, users who would like to add new data or view data that have been classified as sensitive or have other access constraints must register and be assigned the appropriate role by the system administrator. This multilevel access approach supports broad distribution of valuable observations while providing communities and the SIZONet team with the control required to appropriately manage their data.

The large number of possible data fields dictated that the data entry interface be divided into several tabbed pages. The data are organized by themes (weather, ice, wildlife, etc.), and the same multipage form is used to enter new observations.

Application development continues. As data entry and display functions are completed, a series of new features is included in the implementation plan. Features include advanced searching to find data in a larger number of fields and allow use of multi-criteria searching that can compare data across communities. Data download functionality will be supported and coupled with third-party software to enable advanced data analysis outside of the Web application. Exporting data into statistics applications (e.g. R, http://www.r-project.org/) allows for detailed quantitative analysis, such as the identification of potential trends in freeze-up or breakup dates. Mapping support is planned so that users can both enter and view geographic data and perform searches based on spatial criteria. The ability to add, view, and manage multimedia is currently being implemented. Lastly, we will work with ELOKA on using their long-term preservation system to regularly archive data from the operational system.

A key aspect of the database development is the need to accommodate new categories of ice types or related phenomena. These emerge as a result of shifting ice regimes or through the gradual increase in depth and breadth of the observations themselves. Hence, the database will continue to evolve and adapt in response to changing environmental conditions and the needs of the users. This approach reflects the dynamic nature of the local knowledge being documented. It also addresses some of the challenges inherent in developing databases to interface with Indigenous knowledge systems as outlined by Van Der Velden (2010), who rightly argues that content as well as community expectations are likely to change over time.

Exploring the database: seasonal ice cycles and year-to-year variability

The changing seasonal ice cycle along Alaskan shores

The observation records in the database (Table 1, figure 2) provide key information about the seasonal sea ice cycle and ice-associated activities in different communities. Here, we extend preliminary analysis of logs from Gambell (Krupnik *et al.* 2010b)

Figure 2. Database search results page.

and Wales (Eicken *et al.* 2012) and complete the first comprehensive, comparative analysis of such kind for the three core communities of our study. The data discussed are from 2006/2007, but the range of key events and different seasonal stages reflects ice conditions recorded from 2006 to 2012.

Gambell, Wales, and Barrow are situated along a climate gradient (at 63°47′N, 65° 47′N, and 71°18′N, respectively), with harsher atmospheric and oceanic conditions toward the North (Shulski and Wendler 2007). This is reflected in air temperature contrasts between the three communities, with Gambell, Wales, and Barrow averaging at –16.8, –19.2, and –26.6°C (1.8, –2.6, and –15.9F) in February and –1.5, –2.5, and –6.6°C (29.3, 27.5, and 20.1°F) in May, respectively (NOAA (National Oceanic and Atmospheric Administration) Climate Normals 1971–2000 for Wales and Barrow; data for Gambell based on the record from 1950 to 1997).

The seasonal ice cycles for these three communities are marked by four distinct periods (figure 3): open water season (complete or near-complete absence of ice), freeze-up (first ice formation in the fall until establishment of a solid or stable ice cover representative of winter conditions), winter conditions with thick solid ice present (at Gambell) or a stable landfast ice cover (at Wales and Barrow), and the melt season with surface meltwater ponding through the near-complete removal of sea ice in front of the village. Note, however, that the freeze-up or melt seasons may be defined by different types of activities or events in the communities due to contrasting ice conditions and subsistence activities.

The absence of ice during the summer has comparable impacts on all communities, with few or no ice-associated marine mammals present and greater fetch creating potential boating hazards in windy conditions.

The timing of freeze-up reflects the latitude and climate of the three communities, with the ice edge advancing from the northern Chukchi Sea toward the coast and down into Bering Strait before extending beyond St Lawrence Island. However, the observations also indicate that neither the duration of the open water season nor the timing of 'winter' ice conditions with a reasonably stable coastal ice cover follow this latitudinal pattern. Partly, this is due to local topography and ice dynamics. Shorefast ice at Gambell is a narrow (few tens to hundreds of meters wide), ephemeral feature, while at Wales, the coastline and ice deformation driven by strong currents result in a comparatively narrow (1–2 km wide off town) landfast ice cover that is well anchored throughout the season. At Barrow, despite earlier freeze-up, it is the combined action of winds and currents and the nature of the offshore pack ice that lead to the formation of grounded pressure ridges later in the season, with the landfast ice extending 10 km or more offshore in late spring.

From the perspective of the communities' ice use, winter ice conditions at Barrow and Wales are mostly determined by landfast ice stability and ice-dynamics events. As illustrated in the ice log excerpts below, onshore ice movement and associated ridge building help create a stable platform to hunt from. Rough ice or ridges may also present major obstacles during the building of trails for access to the lead edge later in the season.

> The pressure ridges along the edge of the shore ice are about 1/2 [mile] further out than usual. They are about 11/2 mile from shore. […] Hunters usually wait until they are certain that the ice is safe to travel on and will not break off and carry them away. It [the young ice] has changed from a gray/blue color to a near solid white color which indicates it has thickened considerably and may be safe enough

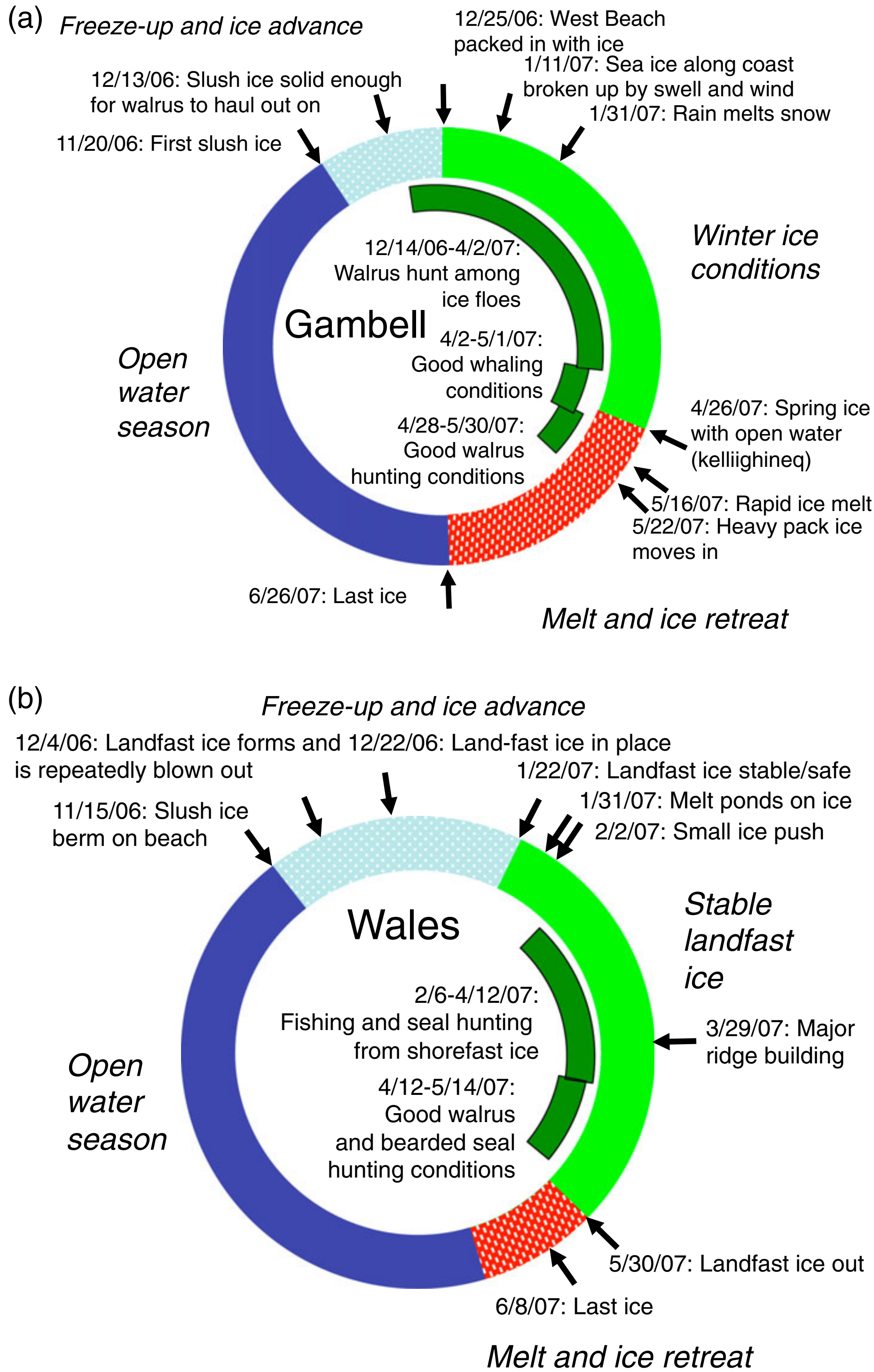

Figure 3. Seasonal cycle of sea ice and related activities as derived from sea-ice observations at Gambell (a), Wales (b), and Barrow (c) for the ice season 2006/2007.

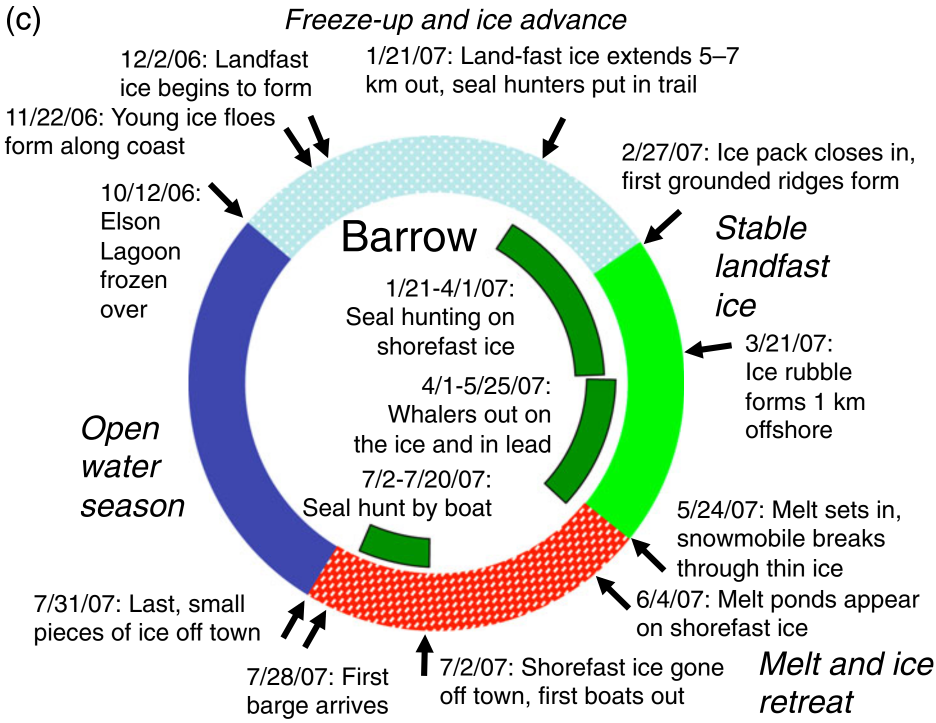

Figure 3. *Continued*

> to travel on. (W.W. Jr., Wales, AK, 22 January 2007)

> Yesterday when the visibility improved briefly I could see two new pressure ridges that had formed. They look quite high, perhaps close to 20 feet. There are fairly large snow drifts behind obstructions (houses) so there should be snowdrifts amongst the pressure ridges. (W.W. Jr., Wales, AK, 30 March 2007)

> The lead remains closed. The pressure ridges along the edge of the shore fast ice grew quite a bit higher in places. It looks like that low spot where a good boat launch may be was not affected too much. (W.W. Jr., Wales, AK, 31 March 2007).

At Barrow, in all years since the start of these observations, the comparative lack of grounded ridges has been a concern to hunters, in particular – as illustrated below – during the peak of the whaling season which may find a couple of hundred people out on the shorefast ice at any given time (Druckenmiller *et al.* 2010; George *et al.* 2004). At the same time, frequent winter shorefast ice breakout events provide access to seals for hunters close to shore.

> Water only 1/4 mi. out. All young ice breaks off from high tide, no grounded ice. Water is unusually close for this time of year. Brings out more seal hunters. (J.L., Barrow, AK, 2 February 2007)

> No sign of water. Young ice has crumbled up 1/2 mi out, flat pieces further out. […] Ice has bluish color, looks like that when the ice has just piled up. Ice is moving in, piling up all along the shorefast ice 1/2 mi. out. (J.L., Barrow, AK, 27 February 2007)

> No sign of water, ice as far as I can see. Ice finally looks normal with pressure ridges. Looks like 1st year ice low terrain to the west. (J.L., Barrow, AK, 28 February 2007)

> People out fixing trail, no sign of water. People talking ice is not anchored, all 1st year ice. (J.L., Barrow, AK, 16 April 2007)

At Gambell, shorefast ice stability is not nearly as much a concern because of its narrow width and availability of several locations to access open water under different ice conditions. The impact of ice dynamics on boat ramps in the ice and boating conditions among the ice floes are key processes tracked by hunters.

> Lost all our sea ice immediately around northwest tip of the island. Wind generated swells still 12 feet high. Pressure ridges along *west* shore washed away to where we now have gravel beach that side. North shore also with exposed gravel. Went to check Kiyellek [alternate launch site near village] this morning *east* of Gambell to find shore fast ice still there but weakening up somewhat. (L.A.Sr., Gambell, AK, 11 January 2007)

> Local ice broken up and packed tight by swells we had from a storm generated at *south* of the island. I call this 'flimsy' ice, because it breaks with waves that penetrate from the southern ice edge. Even marine mammals avoid this kind of ice condition, as it is hazardous to the animals too. We went out on a boat and got only one seal. It looks like game has taken refuge in more solid ice elsewhere. (L. A.Sr., Gambell, AK, 13 January 2007)

> Large ice floes pushed against *west* shore, with wind and current paralleling *west* shore and pulled up ice on all boat ramps. We will need to reopen launch ramps before conditions get favorable for boating. (L.A.Sr., Gambell, AK, 23 March 2007)

The observations compiled to date allow comparison with ice conditions extracted from remote sensing data extending back to 1979 (Kapsch *et al.* 2010). Moreover, the ice observers often discuss changes in ice conditions relative to those of the 1970s and 1980s during their time hunting as young men. Thus, at Gambell, ice conditions in recent years have allowed hunters to pursue walrus, seals, and even whales throughout the winter. In fact, rapid summer ice retreat (figure 3a,b) has driven hunters in Gambell toward such winter hunts as the number of favorable spring hunting days has been greatly diminished (Kapsch *et al.* 2010). At Barrow and Wales, winter ice conditions do not allow for boating early in the year and, as indicated in the ice observation logs (see also figure 3b,c), the much shorter window for the spring offshore hunt has presented significant challenges in recent years. In all communities, hunters have to travel further in pursuit of game associated with the retreating ice.

Melt onset is of greater importance to Wales and to Barrow than to Gambell since the weakening of the landfast ice deprives hunters of a stable platform to launch from. During this time, weakening of thin ice through solar heating and excavation of surface snow and ice by snowmobile traffic presents a significant hazard (figure 3c; Druckenmiller *et al.* 2010). Shorefast ice decay concludes the whaling season in Barrow. Hunting of seals and walrus begins once the shorefast ice is broken out all the way to shore, allowing boaters to navigate a path among the remaining stretches of landfast ice. Both in Wales and in Barrow, offshore ice pack retreat was unusually swift in 2007 (and 2008) and greatly limited hunting opportunities.

Despite its southerly location and milder climate, Gambell experiences an ice melt and retreat season that is as long as that in Barrow. The local ice observations and traditional knowledge indicate that this is due to two factors. First, wind and current patterns promote the formation of larger expanses of open water off Gambell (kelliigheneq, figure 3a; see Krupnik *et al.* 2010b and Kapsch *et al.* 2010 for details) that delimit the start of 'spring ice' conditions and persistence of open water and ice decay. Second, the tail end of the melt season is punctuated by influxes of sea ice from the Russian Far East, in particular Kresta Bay in the Gulf of Anadyr that is swept past the western shore of St Lawrence Island and brings a last wave of walrus. As is clear from the observations at Wales (and supplementary satellite data; Kapsch *et al.* 2010), both in 2007 and more recent years, this ice either does not make it up as far as Bering Strait or is confined to the western part of the strait.

Variability in freeze-up and breakup cycles

While a detailed analysis of interannual variability of ice conditions requires a longer time series than considered here, a brief summary of the timing of three key events in the ice years 2006–2011 helps illustrate potential uses of the information collected in the database. These are the following: first signs of offshore ice formation, build-up of the first persistent shorefast ice, and the date of the shorefast ice breakup (figures 4–6). The systematic shift in the timing of these events reflects latitudinal and climate gradients, with roughly three to four weeks lag between breakup at Wales and at Barrow (figure 6). At Toksook Bay (figure 1), observations

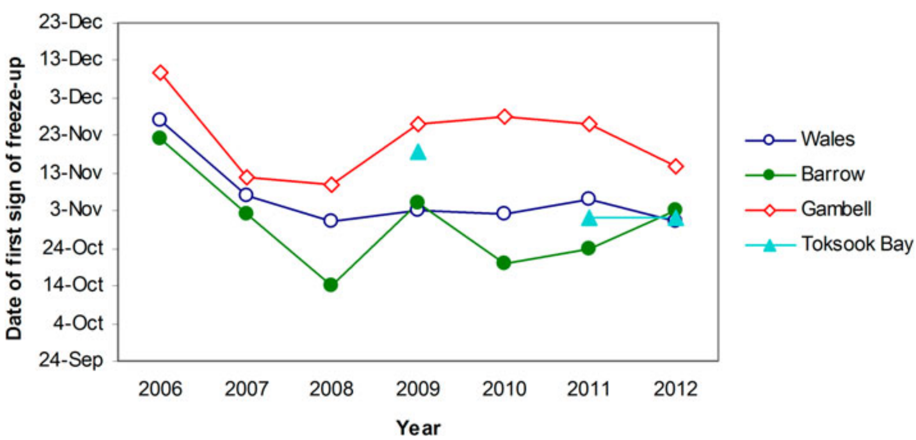

Figure 4. Dates of first signs of ocean freeze-up reported.

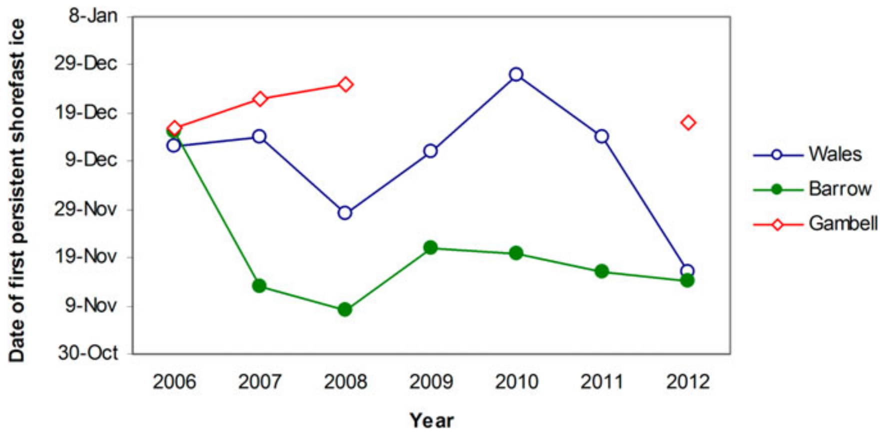

Figure 5. Dates of first persistent shorefast ice reported.

by Simeon John in 2009 (Fienup-Riordan and Rearden 2012) indicate breakup occurred two weeks prior to Wales.

Explanations for the narrow spread of freeze-up and shorefast ice formation dates in 2006, and the wider spread in 2008 and 2010 require a more detailed analysis. In this context, it is important to recognize that determining offshore ocean freeze-up dates is associated with significant uncertainty. Localized formation of slush ice at the beach occurs much earlier and differs from coastal ocean freeze-up with formation of locally aggregated ice floes. As with the formation of persistent shorefast ice, small-scale spatial variability and melt breakup or removal of early stages of ice can blur distinctions between different ice types. At the same time, the impacts of different ice types on boat or over-ice travel are much more distinct and reflected in the variables shown in figures 4–6. The contrasting observations with respect to timing of freeze-up at Toksook Bay happening earlier than at Gambell may also reflect the impact of freshwater runoff and more rapid cooling of the adjacent land surfaces.

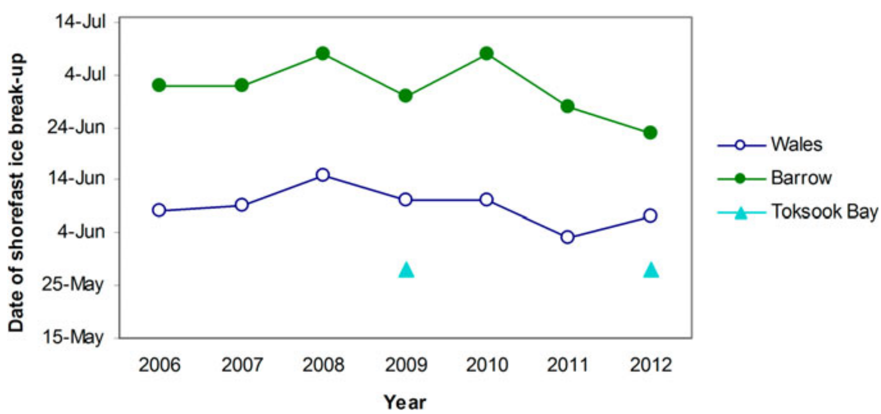

Figure 6. Dates of shorefast ice breakup.

Potential uses of community-based ice observations and databases

Based on the assessments of Inupiat and Yupik ice experts on our team and interaction with other collaborators from Alaskan coastal communities, the compilation, archiving, and dissemination of the type of community-based ice observations may be of value in several contexts.

First, it is an effective means of recording and disseminating expert knowledge about the ice cover during a time of rapid change. As discussed above and in earlier studies (George *et al.* 2004, 2006; Huntington 2000; Krupnik and Jolly 2002,), the record minimum of Arctic ice cover encountered in the fall 2007 and subsequent years was part of a longer-term pattern of greatly altered ice conditions relative to decades prior. Judged by a range of observations and reports from many Arctic communities, milder, less stable and less predictable ice conditions have been observed for well over a decade now. As a result, hunters have to adapt their assessments of ice conditions and strategies for safe use and travel over and among sea ice. Detailed observations from different communities can help take stock of the observed changes and provide a record of the evolving sea ice expertise of local hunters. More important, such observations serve as a body of reference that can supplement instruction and knowledge sharing among experts in different communities, as well as among more- and less-experienced hunters from various age cohorts.

Compilation of community-based sea ice observations into a database as a tool to support traditional knowledge speaks directly to the challenges identified by Heyes (2011), such as the combined impacts of rapid environmental change and shifts in how knowledge about the environment is now being passed and used by different generations. As expressed by Fred Tocktoo in Nome (personal communication, 2012), 'there is no set pattern anymore', and hence, hunters and other subsistence users out in the ice environment have to reacquaint themselves with sea ice conditions every season.

One of the potential outcomes of maintaining an accessible and user-friendly archive of local ice conditions is to reduce the vulnerability of individuals and communities to adverse ice and weather conditions. For example, observations of ice processes during freeze-up and their effects on the coastline may help mitigate the negative impacts of fall storms and, hence, aid preparedness at the community level. Moreover, by placing observations into a broader regional context, communities may better anticipate changes in the ice conditions and their prospective impact based on what hunters from areas further south have observed.

A second context of relevance is the potential use of the database as an educational tool for younger hunters and outside visitors, such as researchers, emergency responders, and others. With the evolving use of technology in rural Alaska, an online database may serve as a powerful source of local knowledge. It would allow the younger generation to complement instruction by elders and experienced hunters with information accessible via computer or mobile phone. With observers paying careful attention to hazardous ice conditions, extreme weather and other factors that determine a safe hunt, those unfamiliar or inexperienced have a stock of information readily available to aid their own understanding of the ice environment. In this context, comparison of ice conditions on a particular day of the year with past seasons or 'normal' conditions can also be instructive.

Additionally, the database can serve as a means to engage young students in rural communities in learning more about the sea ice environment, its uses by people and by animals, and the knowledge kept by Indigenous experts. Here, class visits by observers in their home communities to introduce the project and encourage exploration of the database can be of particular value. Students both contribute to the database by taking cell phone photos or videos while out on the ice with senior hunters and explore the knowledge base through specific assignments or class projects.

Finally, the database provides valuable context to Indigenous terms for various ice types and associated weather or ocean features. As pointed out by our team members, Inupiaq or Yupik terms for specific events or phenomena often convey substantial meaning in condensed form that is lost in translation. With a larger number of Indigenous sea ice dictionaries compiled during the IPY (see compilations in Krupnik *et al*. 2010a; Krupnik and Weyapuk 2010; Weyapuk and Krupnik 2012), the range of observations embedded in the database help illuminate the different facets of Indigenous and local sea ice terms and their specific meaning.

A key challenge is to ensure that archiving and access to the database meet the expectations that come with these and other prospective uses. An important element of the longer-term strategy is to ensure that potential users of the database recognize the context within which these observations were generated and the extent to which the entire context of each observation can be captured. Users also have to acknowledge and abide by potential restrictions by the communities with regard to data use. To address these challenges, we offer a hierarchy of access levels to the database information as outlined above. Moreover, potential database users receive instruction and have to abide by a code of conduct through a document tailored to a particular community. As stated, we are working to include support for the inclusion of interactive mapping and multimedia functions. This will allow for additional information about the context in which observations have been captured, including location and spatial relationships, images of people or landscapes, and audio/video narratives, to provide more details on the observations and the knowledge being imparted. While such features can provide a more holistic representation of observations and local knowledge, we recognize that through the encoding and translation processes necessary for capture within a digital information system, there will always be some information loss with respect to context. An information system can mediate connections between knowledge holders and others and complement knowledge exchange. However, such a system cannot replace the dialog and direct face-to-face interaction that is characteristic of Indigenous oral tradition.

Scientific value of a community-based observations database

The value of local Indigenous knowledge in understanding and tracking Arctic environmental change is now widely recognized. Recent work (e.g. Gearheard *et al.* 2006; Huntington 2000; Huntington *et al.* 2005; Krupnik and Jolly 2002; Krupnik *et al*. 2010a; Laidler *et al*. 2009) has been expanding the detailed perspective of the pioneers in Indigenous sea ice knowledge documentation, who focused on ice use and nomenclature but did not consider changes on longer time scales (Freeman 1984; Lowenstein 1981; Nelson 1969; Riewe 1991). As outlined by Eicken (2010), from the perspective of sea ice geophysics and biology, local and Indigenous knowledge can play an important role in providing broader spatial and temporal context for sea ice surface-based or remote sensing data. It helps inform hypothesis development and sampling strategies and aids in the detection of subtle, intertwined patterns of physical and ecological changes in the sea ice environment.

All of these scientific pursuits can benefit substantially from an interface between the Indigenous and geophysical perspective. One of the aims of this project is to work toward the development of such an interface through the growth of a network of experts and the building of a common database as a framework for sharing and reviewing information pertaining to the sea ice environments and its uses by people and animals. This goal is in line with the use of the database to record and disseminate information on the state of the ice cover at a time of rapid change. In this context, increasing the number of observers contributing to the database will help capture the full extent of sea ice expertise in different communities. For our core communities, we are already including observations by other experts as submitted formally or informally, e.g. by using other collaborative frameworks, such as the SIWO (Eicken *et al.* 2011). The database framework facilitates inclusion of a broader base of observations and helps compare and synthesize different observations.

The particular power of the database is that it allows sorting and extraction of information that documents potential linkages between specific ice events observed at different locations. It can also point to the co-occurrence of ice features or weather patterns and human activities or the presence of animals at a given site. figure 7 provides a glimpse of such in-depth analysis by listing the observations made at Wales during the 2006/2007 ice season that refer to different ice features (slush ice, landfast or shorefast ice, and leads of open water) and ice-associated animals (fish, walrus, and whales). The figure reflects the seasonal cycle illustrated in figure 3b, with slush ice prevalent during fall freeze-up and shorefast ice forming later in the winter. However, it also highlights the ties between the ice cycle and ice use by the community of Wales, with the importance of fish (different cod species and flounder) increasing as people venture out onto the stable landfast ice to fish. Similarly, the appearance of leads at the edge of the landfast ice and beyond corresponds closely to references of beluga and bowhead whales observed by hunters. In the spring, observations of walrus increase with the onset of the walrus migration and hunters venturing out in boats from the stable landfast ice. The analysis presented in figure 7 is comparatively simple and straightforward.

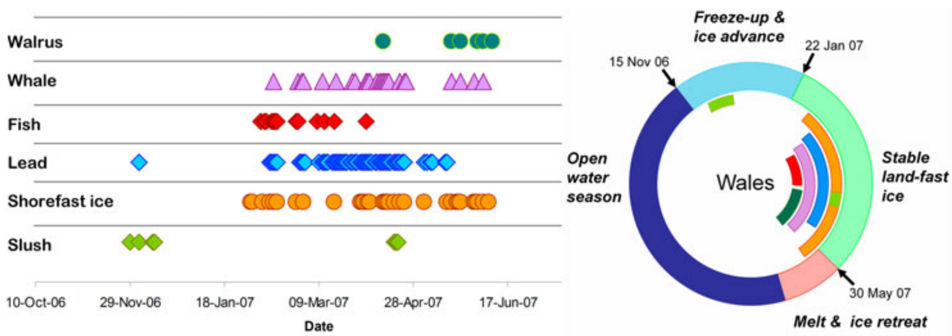

Figure 7. Timing of observations of different sea ice features (slush ice, shorefast or landfast ice, and leads) and ice-associated animals (fish, whales, and walrus) for all observations taken by Winton Weyapuk, Jr. at Wales in 2006/2007. Schematic at right places the timing of these features in the context of the seasonal cycle at Wales.

However, the existence of the database encourages future work that can explore quantitative, statistically significant patterns in ice conditions and use by people and by animals to better understand and respond to the changing Arctic icescape.

Such analysis can also help calibrate and 'downscale' model projections and assess how pan-Arctic or regional changes in weather, ocean and ice conditions play out at the local scale (Eicken *et al*. 2009). The observations highlight the importance of certain ice features such as shore ice berms or other forms of slush and young ice in amplifying or mitigating the impact of coastal storms on the shoreline (see also Eicken 2010). Here, observations across a broad study region for several years can help fill gaps in our understanding of coastal erosion and shoreline protection during fall freeze-up. The *database* may foster the development of protocols that could inform standardized 'coast watch' programs to assess and mitigate shoreline impacts of fall storms. Observations of landfast ice stability in conjunction with key ice, current, and weather patterns made at Barrow have already guided the deployment of offshore oceanographic moorings and coastal radar systems. These instruments may help gain better understanding of the interplay between atmosphere, ice, and ocean processes that often act in concert to destabilize the landfast ice cover, resulting in hazardous ice conditions (Druckenmiller *et al*. 2009; Petrich *et al*. 2012).

Currently, observations of weather variables such as wind speed or direction are not conducted in a standardized fashion by the local observers. However, estimates of wind direction and the identification of clear mismatches between weather reported or forecast by the National Weather Service (NWS) has led to plans for a more rigorous comparison between weather at the community level and information disseminated by the NWS. Thus, it is planned to provide collaborators in key communities with portable weather stations to record wind speed, wind direction, and air temperature while out on the sea ice. These observations would be flagged as such in the database and constitute part of a broader effort to improve NWS products in the region.

Shipping and other maritime activities are increasing rapidly in coastal Alaska and elsewhere in the Arctic. The database presented here can provide important information on prevailing ice conditions, environmental hazards, and vulnerable marine living resources in a particular location that may prove of value to first responders from the village to the state and federal level. Information such as compiled in figure 7 can be directly tied to online tools, specifically the National Oceanic and Atmospheric Administration's Environmental Response Management Application (ERMA) for the Arctic region. Future work will address the question how best to transfer information between our archival system and decision support tools such as ERMA.

Conclusions and next steps

Our collaboration seeks to assemble a record of community-based ice observations reflecting the local and traditional knowledge of ice processes that comes with extensive ice use throughout the annual ice cycle. We have developed a database that enables the archiving and dissemination of this information to potential users, including elders, hunters, and youth, in coastal Alaskan communities, as well as researchers studying ice geophysics, marine biology, or the functioning of ecological knowledge in local cultures. Rapidly changing ice conditions coupled with evolving local and Indigenous knowledge of sea ice and changing demands for ice-related information and instruction in coastal communities necessitated a stepwise, adaptive approach. The database has gone through three distinct phases, maturing along the way to the extent that it can now serve as a resource, which in turn will engender further modifications down the line. It is sufficiently flexible for evolving categories of ice tracked in the observation logs and new uses of the information contained in the records.

In the near-term, we will share the database framework with the participating communities and make it available to younger generations of hunters and students in the school system. This will meet one of the key objectives expressed by our community collaborators. In the midterm, the use of the database as a tool will help facilitate information exchange and scientific exploration at the interface between Indigenous and academic knowledge. Here, we plan to build on the experience of the SIWO effort that brought together ice experts from the Bering Sea and southern Chukchi Sea communities, the Eskimo Walrus Commission, National Weather Service, and academic researchers to share ice and weather observations from the perspective of subsistence hunting and travel over the sea ice (Eicken *et al*. 2011). We anticipate that access to the database's rich information content will allow the SIWO team to explore interannual ice variability in the northern Bering Sea and Bering Strait regions. Eventually, we hope to use it to improve methods for predicting sea ice and weather on timescales of a few days to more than a week.

Finally, we plan to offer the database design as a framework for others to utilize as a research, teaching, and communication tool. In this context, contributions by sea ice experts from the Nelson Island and Yukon-Kuskokwim Delta Region have been very encouraging. Developing the database into an online tool will also allow posting observations by a broader range of community-based observers, such as those gathered under the Alaska Native Tribal Health Consortium's Local Environmental Observer Network. This will help ensure continuity and proliferation of Indigenous sea ice expertise to the next generation of Indigenous hunters and users.

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Note

1. Deceased

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