ALASKA SHOREFAST ICE: INTERFACING GEOPHYSICS WITH LOCAL SEA ICE KNOWLEDGE AND USE

By

Matthew L. Druckenmiller

RECOMMENDED: ______________________________

____

____

____

Advisory Committee Chair

____

Chair, Department of Geology and Geophysics

APPROVED: ______________________________

Dean, College of Natural Science and Mathematics

____

Dean of the Graduate School

____

Date

ALASKA SHOREFAST ICE: INTERFACING GEOPHYSICS WITH LOCAL SEA ICE KNOWLEDGE AND USE

A

THESIS

Presented to the Faculty

of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

By

Matthew L. Druckenmiller

Fairbanks, Alaska

August 2011

Abstract

This thesis interfaces geophysical techniques with local and traditional knowledge (LTK) of indigenous ice experts to track and evaluate coastal sea ice conditions over annual and inter-annual timescales. A novel approach is presented for consulting LTK alongside a systematic study of where, when, and how the community of Barrow, Alaska uses the ice cover. The goal of this research is to improve our understanding of and abilities to monitor the processes that govern the state and dynamics of shorefast sea ice in the Chukchi Sea and use of ice by the community.

Shorefast ice stability and community strategies for safe hunting provide a framework for data collection and knowledge sharing that reveals how nuanced observations by Iñupiat ice experts relate to identifying hazards. In particular, shorefast ice break-out events represent a significant threat to the lives of hunters. Fault tree analysis (FTA) is used to combine local and time-specific observations of ice conditions by both geophysical instruments and local experts, and to evaluate how ice features, atmospheric and oceanic forces, and local to regional processes interact to cause break-out events.

Each year, the Barrow community builds trails across shorefast ice for use during the spring whaling season. In collaboration with hunters, a systematic multi-year survey (2007-2011) was performed to map these trails and measure ice thickness along them. Relationships between ice conditions and hunter strategies that guide trail placement and risk assessment are explored. In addition, trail surveys provide a meaningful and consistent approach to monitoring the thickness distribution of shorefast ice, while establishing a baseline for assessing future environmental change and potential impacts to the community.

Coastal communities in the region have proven highly adaptive in their ability to safely and successfully hunt from sea ice over the last 30 years as significant changes have been observed in the ice zone north of Alaska. This research further illustrates how Barrow's whaling community copes with year-to-year variability and significant intra-seasonal changes in ice conditions. Hence, arctic communities that have coped with such short-term variability may be more adaptive to future environmental change than communities located in less dynamic environments.

Table of Contents

Page

Page

List of Figures

Page

Page

Page

List of Tables

Page

List of Appendices

Acknowledgements

My doctoral research would not have been possible without the support of many. First, I thank my financial supporters: the Seasonal Ice Zone Observing Network (with support of the National Science Foundation; OPP-0632398), the University of Alaska's Resilience and Adaptation Program (a National Science Foundation Integrative Graduate Education and Research Traineeship Program), the Oil Spill Recovery Institute, and the Cooperative Institute for Alaska Research (Project CIPY-34 with funds from the National Oceanic and Atmospheric Administration under cooperative agreement NA17RJ1224 with the University of Alaska).

I largely owe the opportunity to have developed an interdisciplinary research project to the Resilience and Adaptation Program, and specifically to Terry Chapin and Gary Kofinas.

I greatly appreciate the support I have received from the Department of Geology and Geophysics. Thanks especially to Anupma Prakash for reviewing this thesis and for always offering helpful words of advice.

The many weeks I have spent in Wales, Alaska were made possible by the gracious community and those at the Kingikmiut School. Winton Weyapuk, Jr. and Herbert Anungazuk opened my eyes to what is required to hunt from sea ice in the Bering Strait.

My time in the field at Barrow would not have been possible or as enjoyable without the dedicated help of the Barrow Arctic Science Consortium (Glenn Sheehan, Lewis Brower, Bryan Thomas, Nok Acker, Quuniq Donovan, Scott Oyagak, and others).

Thanks to the Barrow Area Information Database (Allison Gaylord, Ryan Cody, and Adrian Aguirre) and the Alaska Ocean Observing System for satellite imagery and data support.

I am thankful for the wonderful opportunity to have worked alongside so many from (or affiliated with) the University of Alaska Fairbanks Geophysical Institute Sea Ice Group. I owe a special thanks to those who ventured onto the ice to lend a helping hand to my work: Anthony Doulgeris, Jeremy Harbeck, Josh Jones, Marie Kapsch, Jonas Karlsson, Chris Petrich, and Chris Polashenski. Mette Kaufman and Hyunjin Druckenmiller provided invaluable support with logistics and data management. I am very appreciative to Lew Shapiro and Andy Mahoney, whose past work provided a great foundation for this study.

I owe a great deal to the North Slope Borough Department of Wildlife Management (Taqulik Hepa, Craig George, Robert Suydam, Billy Adams, and others) for supporting my work in more ways than one. Thanks to Dave Ramey for always offering a cup of coffee.

I am indebted to the Barrow Whaling Captains Association (BWCA) for approving my research and welcoming me onto the ice. I especially thank BWCA President Eugene Brower for providing me opportunities to address the Captains each spring. Many hunters in Barrow have shared their knowledge, thoughts, and stories about sea ice: Billy Adams, Jacob Adams, Roy Ahmaogak, Herman Ahsoak, Arnold Brower, Sr., Eugene Brower, Gordan Brower, Harry Brower, Jr., Tom Brower, III, Jeff Leavitt, Warren Matumeak, Ben Nageak, Nate Olemaun, Crawford Patkotak, and Wasca Williams. In particular, Joe Leavitt was one whaling caption I could always count on to help me best understand the local perspectives on sea ice and hunting. Thanks also to Ronald Brower, Sr. for reviewing the spelling of Iñupiaq sea ice terminology used in sections of this thesis. These men have made my education and studies truly unique. Quyanaqpak!

I was lucky to find two mentors in Barrow to form my “local advisory committee”: Lewis Brower and Craig George. Thanks for sharing your ideas, stories, and contagious fascination with ice, and for playing a major role in this project.

On the academic side, I am extremely honored to have worked with those on my graduate advisory committee. Herbert Anungazuk taught me to listen to stories with an open mind, and to do my best to remember them. Igor Krupnik has helped me to see the importance of understanding who I am as a scientist, and of assessing my strengths and weaknesses. Thanks for your well-placed words of encouragement over the years. Mark Johnson has provided a great voice of reason, always somehow managing to reduce my stress levels. I thank Matthew Sturm for his constant reminders of the “big picture” and for pushing me to be a better writer.

Most importantly, I thank my advisor Hajo Eicken, who has challenged me more than anyone ever has, while also offering unwavering support. This project would not have been possible without Hajo’s commitment to bridging the divide between arctic research and local communities. His creativity, curiosity, and hard work have been a limitless source of inspiration and motivation.

I extend my deepest loving thanks to my family for sustaining me in unknowing ways. My son Elias (age 1) has always wished for an end to my studentship so that we may have more time for throwing rocks and chasing birds. My grandfather (age 92) has strongly insisted on seeing my diploma before he himself graduates to a higher position. Lastly, my wife Hyunjin has patiently listened to my struggles for years, and has never failed to simply tell me to “Just finish”. This was a journey we took together.

Dedication

I dedicate this thesis to Herbert Anungazuk (1944-2010). Herb was from the village of Wales, Alaska and intimately knew the sea ice environment of the Bering Strait region. He was a father, Vietnam veteran, hunter, story teller, and poetic writer on issues of concern to the Iñupiat and to the Kingikmiut people (the people of Wales). Herb served on my graduate advisory committee until his death in August 2010. My perspective on topics addressed throughout this work have greatly benefited from conversations with Herb. He always made it clear that the world is comprised of forces beyond man's control or knowledge.

Chapter 1. Introduction

The reductions in arctic summer sea ice extent and volume observed over the last few decades (Maslanik et al. 2007; Nghiem et al. 2007), along with other rapid social-ecological changes (AHDR 2004; ACIA 2005), reveal an arctic system undergoing significant transformation. Many societal challenges and opportunities associated with arctic change highlight the need for improved strategies that involve stakeholders in science, including community-based observations and monitoring (Chapin et al. 2004; NAS 2006; Eicken et al. 2009). While the observed dramatic thinning and retreat of perennial sea ice has the potential for far-reaching effects (e.g., in regulating global climate or driving geopolitical negotiations), other less conspicuous changes in the coastal zone can be more directly linked to local impacts. Shorefast sea ice, which comprises a small but disproportionately important fraction of the Arctic cryosphere, represents a unique area for interdisciplinary environmental and human-focused research. In arctic Alaska, it represents an accessible environment for understanding how local sea ice changes present challenges for Iñupiat coastal communities.

Shorefast sea ice provides a buffer between land and either drift ice or open water as it persists throughout much of winter and spring in the shallow waters along the coast because it is grounded and frozen to the sea floor. Shorefast ice controls rates of wave-induced and ice-induced coastal erosion, provides habitat for marine mammals and other aquatic life, and regulates near-shore interaction between the atmosphere and ocean. For industry, it provides a platform for coastal operations and infrastructure. For Native subsistence communities, it provides an "icescape" for travel and hunting, and plays a crucial role in shaping subsistence, local economy, culture, knowledge, and language.

The primary focus of this research is on coastal and shorefast ice in the Chukchi Sea near Barrow, which is Alaska's northernmost indigenous community (see Figure 1.1). The research explores local- to regional-scale shorefast ice morphologies and dynamic coastal processes that are important in the natural system and to the ongoing use of ice by the local hunting community. A central theme throughout is relating ice and environmental conditions to ice stability and human safety.

To the best of my knowledge, this work represents the first doctoral dissertation that combines sea ice geophysics with the local and traditional knowledge of an indigenous people in the Arctic. Having been exposed to the way the local Iñupiat whalers think about ice and use it to

Figure 1.1 Map of Alaskan whaling communities and sea ice extent. All eleven communities shown hunt bowhead whales and are member communities of the Alaska Eskimo Whaling Commission. Barrow and Wales have been the primary sites for my doctoral studies. The black dashed and solid lines represent the winter time (March) maximum sea ice extent in 1979 and 2010, respectively. The red dashed and solid lines represent the summer time (September) minimum sea ice extent in 1979 and 2010, respectively. Sea ice extent data, derived from passive microwave satellite imagery, was obtained from the National Snow and Ice Data Center.

their benefit, I aim to bring key aspects of their expertise into recognition by the broader sea ice research community. The sooner their knowledge, interests, and perspectives are appropriately accommodated by academic or scholarly research, the better and more broadly we may understand the changes taking place. A greater appreciation for the resulting challenges faced by communities will inevitably follow. Similarly, the practical operations by agencies, such as those performing search and rescue, ice forecasting, and marine navigation, may glean important useful information through the involvement of local ice experts.

Collaboration with the community of Barrow and with specific local individuals has greatly contributed to the interdisciplinary approaches I have used to monitor and understand the interactions between coastal sea ice and a marine-mammal hunting culture. I am not an anthropologist but have worked closely with local indigenous ice experts in ways an anthropologist might. Between 2006 and 2011, I have cumulatively spent a year in the community observing ice conditions, performing a range of geophysical-based measurements, traveling the community's network of spring ice trails, and talking with hunters. Barrow, a village with great experience in dealing with scientists, assisting with research, and sharing its knowledge and curiosities of the environment (Brewster 1997; Norton 2001), has provided a warm welcome.

To science and western culture, sea ice represents a remote and unforgiving setting reminiscent of the early explorers, an indicator of a global response to climate change, and a frontier for resource development. For hunters of marine mammals, the ice is an environment they must experience and become familiar with. More than once I have heard academics explain that for the Inuit sea ice is an extension of the land. This is inaccurate. To be on sea ice is to be in the realm of the ocean. Just as the ocean, sea ice is inherently dangerous and naturally foreign to man. When venturing onto ice, a new sense of awareness is required and the rules for assessing risk drastically change. I have learned that those well-acquainted with and dependent on sea ice take little for granted.

I propose that efforts to combine geophysics with local and traditional sea ice knowledge (and to combine our different reasons for fixating on sea ice) may ultimately contribute, however modestly, to the ability of Alaska's coastal communities to adapt to changes in the environment and the onset of potentially unfamiliar conditions. Adaptation requires not only an understanding of the changes taking place but also an awareness of how changes relate to the benefits people derive from their environment or the hazards they avoid. In other words, the intricate relationships between a community and their environment and the associated vulnerabilities must be understood. To assist in this aim, environmental monitoring must be transformed such that resulting information is relevant to the practical activities and decisions of local communities. Once the communication barriers between scientists and local experts are overcome, the necessary exchange of information and ideas will follow, providing a well-defined objective is established. In this thesis an objective is to better understand shorefast ice break-out events, which clearly pose an important threat to Barrow's hunters during the spring whaling season.

1.1 Combining geophysics with local and traditional sea ice knowledge

In 1969, when Richard Nelson published *Hunters of the northern ice*—an account of sea ice knowledge and hunting practices from Wainwright, Alaska—he and the people he wrote about were unaware that this region would soon become the "canary in a coal mine" for climate change. To Nelson, the hunters of Wainwright were competent and experienced travelers of ice-covered waters. After centuries of observing their environment, they were able to make calculated decisions regarding whether the ice was safe and where under-ice currents might carry a wounded whale. Nelson (1969), speaking of the hunters' knowledge, stated: "*It is fortunate that we realize ahead of time that there is a considerable practical value, to say nothing of limitless intrinsic worth, in collecting and preserving this information*." In these regards, the research efforts of recent decades have been considerably successful.

Local peoples in the Arctic have rightly been credited with observing some of the earliest signs of climate and environmental change at high latitudes (McDonald et al. 1997; Krupnik and Jolly 2002/2010; Fox 2003; Mustonen and Helander 2004). The first significant published accounts largely recorded the spoken stories and observations of elders, hunters, and community members. As similar stories from communities across the circumpolar North emerged, these projects were collectively successful in moving beyond the labeling of local and traditional knowledge (LTK) as mere anecdotal evidence of change.

LTK is acquired through long-term careful environmental observation and is largely bound by what is important to the core elements of human survival and culture. Accordingly, the details of the knowledge vary as a function of geography, latitude, and the environmental factors that influence the availability of food and water sources (Gearheard et al. 2006; Laidler 2006a). Spatially, LTK is mostly confined to the local scale. Temporally, it may be representative of many decades of observation or knowledge (Huntington et al. 2004). Native language typically plays a central role. It is often described as holistic (Sillitoe and Marzano 2009) as it directly acknowledges the interconnectedness of nature, people, and the spiritual dimension (Omura 2005). LTK recognizes relationships that are not captured by the focused, compartmentalized manner through which typical disciplinary science examines the world.

In comparison, science commonly seeks to make generalizations that represent a broad area over large spans of time, yet often relies on less than a few decades worth of direct observations (Huntington et al. 2004). Science typically employs a strategy of reductionism to penetrate systems and to arrive at a fundamental understanding for specific areas of interest. While models often serve to integrate different studies to acquire “system-level” understanding, the interconnections acknowledged by LTK are often greatly simplified or overlooked in traditional scientific approaches.

Today, interest in LTK is growing around the world as science increasingly addresses questions related to the interconnections between natural and social systems and as research trends toward more interdisciplinary and cross-epistemological research. In the North, research that combines scientific knowledge and LTK has proven useful in many ways (Berkes 2002; Krupnik and Jolly 2002/2010; Huntington et al. 2004; ACIA 2005; Eicken 2010). Such projects have identified locally-specific mechanisms for climate change impacts, provided validation for remote sensing investigations, identified priorities and localities for future research, offered insight into both interannual and interdecadal environmental variability, and recognized past-occurrences of rare or anomalous events.

Unsurprisingly, a renewed inquiry into indigenous sea ice knowledge has developed (Krupnik et al. 2010). Past anthropological studies, such as those listed in Table 1.1, focused on individual and community interaction with ice for survival and culture. Safe methods of ice travel, ice and weather forecasting, marine mammal hunting, methods of dress and improvisation are among the details addressed in these studies that remain testament to a broad and ever-evolving body of applied knowledge suited for life with sea ice.

1.2 From observations of change to adaptation

In addition to bringing LTK to the forefront of climate research as a valuable resource, human-focused research over the last two decades has well documented the unique challenges that local and indigenous communities face in responding to a changing climate (McDonald et al. 1997; Krupnik and Jolly 2002/2010; Fox 2003; AHDR 2004; Huntington et al. 2007). For the last three decades, use of the term ‘adaptation’ has increasingly pervaded scientific and political debates on how societies are to sustainably deal with climate and environmental change (Schipper and Burton, 2009). As adaptation is now an important consideration for arctic communities, several studies have examined community vulnerabilities and adaptation strategies (e.g., Chapin et al. 2004; Chapin et al. 2006; Furgal and Seguin 2006; Furgal and Prowse 2008; Ford and Furgal 2009). While some benefits from climate change are expected, the majority of impacts local communities face while adjusting to a new climate are believed to be negative and must be considered alongside the simultaneous non-climate stresses that many are experiencing

Table 1.1 Genealogy of relevant literature on local and traditional sea ice knowledge

Reference	Title	Location / Communities	Time Period
Boas 1888; Müller-Wille 1998	The Central Eskimo; Franz Boas among the Inuit of Baffin Island, 1883-1884, journals and letters	Baffin Island, Canada	1883-1884
Stefansson 1919	My life with the Eskimo	Alaska and Canada	1906-1918
Rasmussen 1927	Across arctic America: Narrative of the Fifth Thule Expedition	Greenland, Canada, and Alaska	1921-1924
Foote 1960	The Eskimo hunter at Point Hope, Alaska	Point Hope, Alaska	1959-1960
Nelson 1969	Hunters of the northern ice	Wainwright, Alaska	1964-1966
Freeman 1976	Inuit Land Use and Occupancy Project	NW Territories and Yukon, Canada	1973-1975
Lowenstein 1980	Some aspects of sea ice subsistence hunting in Point Hope, Alaska	Point Hope, Alaska	Late 1970's
McDonald et al. 1997	Voices from the bay: Traditional ecological knowledge of Inuit and Cree in the Hudson Bay bioregion	Hudson Bay Region, Canada	1992-1995
Krupnik and Jolly 2002/2010	The earth is faster now: Indigenous observations of arctic environmental change	Alaska, Canada, and Greenland	Late 1990's - 2001
Huntington et al. 2001	The Barrow Symposium on Sea Ice, 2000: Evaluation of one means of exchanging information between subsistence whalers and scientists	Barrow, Alaska	2000
Laidler 2006b	Ice, through Inuit eyes: Characterizing the importance of sea ice processes, use, and change around three Nunavut communities (doctoral thesis)	Nunavut, Canada	2003-2006
Gearheard et al. 2006	''It's not that simple'': A collaborative comparison of sea ice environments, observed changes, and adaptations in Barrow, Alaska, USA, and Clyde River, Nunavut, Canada	Barrow, Alaska and Clyde River, Nunavut, Canada	2004
Krupnik et al. 2010	SIKU: Knowing our ice: Documenting Inuit sea ice knowledge and use.	Alaska, Canada, Greenland	2007-2009
This dissertation	Alaska shorefast ice: Interfacing geophysics with local sea ice knowledge and use	Barrow, Alaska	2007-2011

throughout the Arctic, such as the lack of economic resources, increasing cost of living, barriers to locally-relevant education, loss of LTK, and human health issues (Ford et al. 2010).

Human-focused research has also revealed communities as diverse potential users of climate information (Pielke 2010). To date, documented adaptation strategies in the Arctic have largely been reactive to change (Ford et al. 2010). Unfortunately, it is often not until after disruption or loss of the benefits people derive from their environments that they begin to fully comprehend their functionality and value (Daily 1997). As research develops in this area to better incorporate stakeholder views and understand their decision making processes, more proactive strategies may emerge. Improved documentation of the traditional and emerging ways communities use sea ice is needed to enhance community-scale realizations of their dependence on intricate environmental processes and to make it clear where science can play a role in strengthening their adaptive capacity.

To produce information relevant to community activities and decisions, it is essential to not only consider general climate change information but also to understand the detailed challenges faced by more subtle forms of environmental change. In the context of sea ice change in the Chukchi Sea, shorefast ice forming later in fall and breaking up earlier in late spring and summer (Mahoney et al. 2007a) represents one of the more well-documented prominent changes taking place within the region. While these regional-scale changes in the transition seasons at the periphery of the ice-year (late fall and early summer) certainly have implications for how and when the community uses the ice, these are not necessarily the types of changes that are most difficult to adapt to in a given year. (Certainly, interannual variability and trends toward later ice formation present adaptation challenges in the longer-term context.) The more subtle changes taking place locally throughout the year when people are active on the ice often represent the unusual, unpredictable, and variable ice conditions that increase risk to ice-users, and thus may be a more appropriate target for adaptation strategies. For example, in recent years whalers have faced difficulty in finding safe and suitable places at the shorefast ice edge to butcher whales. The incorporation of large volumes of brash ice at the ice edge coupled with above freezing air temperatures in May presents a serious challenge to hunting crews trying to haul a 20 to 40 ton whale onto the ice. Such conditions in 2009 led to multiple whales being butchered in the water—a practice not yet refined by Barrow hunters as it has been by the whalers of the Bering Strait region. When discussing such impacts, regional observations become less informative, and the need for local observations and the involvement of local experts becomes apparent.

1.3 Research overview

As a whole, this dissertation focuses on monitoring local shorefast ice from complementary geophysical and LTK perspectives to better understand shorefast ice stability and related coastal processes. This effort builds on the previous work of many, both in the context of related work in the Alaska Arctic (e.g., Nelson 1969; George et al. 2004; Mahoney et al. 2007b; George et al., unpubl.) and focused studies elsewhere on the relationships between arctic communities and sea ice (e.g., Aporta 2004; Gearheard et al. 2006; Laidler 2006b; Tremblay et al. 2006; Krupnik et al. 2010).

During my time in Barrow, I have mapped the community's ice trails during spring whaling while at the same time characterizing ice thickness and morphology along the trails. This approach knowingly "biases" the types of information gathered since the "sampling plan" is guided by the choices of the hunting community. More information is acquired in some areas in comparison to others depending on how, when, and where hunters use the ice cover. Hunters do not return to the same place each year to make observations or measurements in the same way scientists often do. Scientists seek places that are representative of a larger whole, while hunters look for conditions that are conducive to a successful hunt.

This research organizes LTK according to how local ice experts travel, hunt, and assess risk, and accordingly strives to collect geophysical data that matches these categories of information. Through the use of maps of ice trails overlaid on radar-based satellite imagery I have developed a means for connecting with local ice experts to discuss their knowledge and observations. Looking back on the past five years, it is clear that these maps, along with the other material presented in this dissertation, have provided a highly effective tool for cross-cultural communication, a resource for hunters, and a lasting documentation of how the community uses the ice cover during spring whaling.

The timing for my research has proven greatly beneficial. The fourth International Polar Year, IPY 2007-2008, was the first IPY to incorporate social science, and as a result led to a number of interdisciplinary and international projects. I had the opportunity to place my research within two of such projects – the Seasonal Ice Zone Observing Network (SIZONet) led by my research advisor, Hajo Eicken, and the Sea Ice Knowledge and Use (SIKU) project led by Igor Krupnik. As a fellow in the University of Alaska Fairbanks Resilience and Adaptation IGERT (Integrative Graduate Education and Research Traineeship) Program, which focuses on the use of interdisciplinary research methods to address adaptation to arctic change, I had the opportunity to both develop a unique project but also to work with a highly diverse and interdisciplinary graduate advisory committee. My committee, chaired by Eicken (sea ice geophysicist), included Herbert Anungazuk (indigenous sea ice expert and culture specialist), Mark Johnson (physical oceanographer), Igor Krupnik (anthropologist), and Matthew Sturm (snow on sea ice geophysicist). While the core of my research is grounded in the physical sciences, the anthropological components helped to reveal the cultural contexts of my work, and supported my efforts to write a dissertation accessible to non-physical scientists. Learning how to combine western science with LTK has led me to understand that it is only worthwhile if you are open to epistemological and disciplinary compromise. This work is not representative of a typical doctoral thesis in the physical sciences, yet delivers findings and ideas that lay a foundation for potential new directions for geophysical sea ice research.

I delivered oral-session presentations of this dissertation work at multiple conferences and meetings. These include the Alaska Anthropology Conference (Fairbanks, AK, March 2007), the Arctic Energy Summit (Anchorage, AK, October 2007), the SIKU Session at the Sixth International Congress of Arctic Social Sciences (Nuuk, Greenland, August 2008), the Alaska Forum on the Environment (Anchorage, AK, February 2009), the Inland Northwest Research Alliance Symposium: "Lessons from Continuity and Change in the Fourth International Polar Year" (Fairbanks, AK, March 2009), the State of the Arctic Conference (Miami, FL, March 2010) and the American Geophysical Union Fall Meeting (San Francisco, CA, December 2010). I have also presented my research to the Barrow community through the Saturday School Yard Presentation Series (Barrow, AK, March 2007), students in the Alaska Native Science and Engineering Program (Fairbanks, AK, November 2010) and to K-12 teachers of the Bering Strait School District (Fairbanks, AK, November 2007 and August 2010).

As coastal ice conditions in the eastern Chukchi Sea provide the focus for this study, it is important to mention that the material presented here must not be freely extrapolated to other coastal areas in the Arctic. Bathymetry, the shape of the coastline, wind patterns, coastal ocean currents, and proximity to regional-scale ice transport regimes (e.g., the Beaufort Gyre) are amongst the many variables that drive local ice dynamics. Similarly, the LTK of the Iñupiat hunters from Barrow is not immediately representative of local ice experts from other Native whaling communities in Alaska, let alone of coastal communities elsewhere in the Arctic.

Performing such a comparison is not trivial (Gearheard et al. 2006), as I learned firsthand. During my doctoral studies, I had the opportunity to visit the community of Wales in Bering

Strait eight different times between the years 2006 and 2010. As part of the SIZONet project, I conducted measurements for geophysical ice monitoring and discussed ice conditions and safety with various local hunters and elders, such as Winton Weyapuk, Jr., who developed into the primary collaborator for the project. Although my research in Wales is not the subject of this dissertation, the experience provided both great contrast and similarity to my time in Barrow and illuminated the value of partnering with local indigenous ice experts. For example, the LTK of hunters from Wales, who rarely venture onto ice without a boat, focuses heavily on how to safely travel beyond the ice edge into open water and amongst drifting ice. In Wales, hunters like to tell stories of those that traversed the Bering Strait, and the dangers of drifting too far to the north into the Chukchi Sea. In contrast, during spring whaling in Barrow, hunters are in tune with monitoring the stability and consolidation of shorefast ice, and mostly analyze pack ice in terms of how it may interact with the shorefast ice. In Barrow, hunters retell stories of times when people broke away from shorefast ice and found themselves unwittingly adrift. Hunters' real-world, place-based knowledge hastens science to focus on the importance of local processes yet challenges science to slow-down in its approach toward reaching conclusions. Their interest in accurate "science" is not a profession, but rather fundamental to sustaining traditional ways of life.

This dissertation consists of four independent, but interrelated, primary chapters and a final conclusions and recommendations chapter.

Chapter 2—*Toward an integrated coastal sea ice observatory: System components and a case study at Barrow, Alaska*—summarizes efforts to work toward an integrated coastal sea ice monitoring program for shorefast and adjacent pack ice in the Chukchi Sea coastal zone. I describe the various components of the observatory and demonstrate their usefulness to the community through a case study of two significant shorefast ice breakout events that took place off Barrow in the spring of 2007. In the context of the overall dissertation, this chapter provides important background information by describing the state of the local sea ice research program at the time my doctoral field research began in 2007. The Barrow Sea Ice Observatory has served as a great resource and foundation for much of the work presented in the following chapters. Chapter 2, which benefited from coauthor contributions, is a published paper (Druckenmiller et al. 2009) by the journal Cold Regions Science and Technology.

Chapter 3—*Assessing the shorefast ice: Iñupiat whaling trails off Barrow, Alaska*—presents a detailed account of the Barrow community's use of shorefast ice during the bowhead whale hunt of five consecutive springs, 2007 to 2011. It discusses how observations of evolving ice characteristics are made in the context of establishing ice trails, selecting the location of whaling camps and potential butchering sites at the ice edge, and monitoring potential hazards. Ice use practices are discussed in terms of individual and community assessments of current local ice conditions, traditional knowledge, and personal preference. This multi-year documentation of whaling trails, alongside a geophysical record of shorefast ice conditions, shows how the hunting community deals with the intra- and inter-annual variability of shorefast ice extent and morphology. Chapter 3 represents an expanded version of a book chapter (Druckenmiller et al. 2010) published in *SIKU: Knowing our ice* (Krupnik et al. 2010).

Chapter 4—*Will the ice break-out? Interfacing geophysics with local and traditional knowledge using fault tree analysis*—develops a framework for understanding shorefast ice break-out events that incorporates both geophysics and LTK. I provide a thorough review of both the scientific literature and hunters' knowledge as it relates to key processes and environmental forces that play a role in shorefast ice stability. This chapter presents fault tree analysis as a method for conceptualizing failure and integrating expert knowledge. I offer insight into why the "rules" of LTK so often hold true in what may first appear as a highly variable and unpredictable system. I intend to submit a condensed version of Chapter 4 for publication in Cold Regions Science and Technology, or a similar journal.

Chapter 5—*Trails to the whale: Reflections of change and choice on an Iñupiat icescape*—summarizes findings of a project to research and monitor Barrow's ice trails during four consecutive spring whaling seasons, 2008 to 2011. I combine geophysical-based monitoring with local knowledge and ice-use to quantitatively document the community's interaction with the ice cover, which may serve as a baseline for assessing future change. A framework for analysis is presented with the intention for this monitoring project to continue in the long-term. I offer my thoughts on how this may be accomplished by providing useable information resources to the community and assisting in the traditional learning of young hunters. I intend to submit Chapter 5 as two separate journal articles for publication; one to the special issue of Polar Geography titled "The human geography of arctic sea ice" and another to Cold Regions Science and Technology.

Chapter 6—*Conclusions and recommendations*—presents overarching conclusions drawing from each of the four preceding chapters and other experiences during the research process. I end with recommendations for future research and continued efforts to sustain coastal ice monitoring in partnership with the community of Barrow.

The research presented within this thesis followed Institutional Review Board (IRB) procedures and was approved by the University of Alaska Fairbanks' IRB Office as Protocol # 06-54. I completed the required coursework in The Protection of Human Subjects (Collaborative IRB Training Initiative Course Completion Record # 361337).

References

ACIA, 2005. Arctic Climate Impact Assessment. Cambridge Univ. Press, 1042 pp.

AHDR, 2004. Arctic Human Development Report. Akureyri: Stefansson Arctic Institute, ISBN: 9979-834-45-5.

Aporta, C., 2004. Routes, trails and tracks: Trail-breaking among the Inuit of Igloolik. Etud. Inuit 28(2): 9-38.

Berkes, F., 2002. Epilogue: Making sense of arctic environmental change? In: Krupnik, I., Jolly, D. (Eds.), *The earth is faster now*. Arctic Research Consortium of the United States, Fairbanks, Alaska, pp. 335–349.

Boas, F., 1888. The Central Eskimo. Sixth annual report of the Bureau of Ethnology 1884–1885: 399–675.

Brewster, K., 1997. Native contributions to arctic sciences at Barrow, Alaska. Arctic 50(3): 277-288.

Chapin III, F.S., Peterson, G., Berkes, F., Callaghan, T.V., Angelstam, P., Apps, M., Beier, C., Bergeron, Y., Crépin, A.S., Danell, K., Elmqvist, T., Folke, C., Forbes, B., Fresco, N., Juday, G., Niemelä, J., Shvidenko, A., Whiteman, G., 2004. Resilience and vulnerability of northern regions to social and environmental change. Ambio, 33(6): 344-349.

Chapin III, F.S., Hoel, M., Carpenter, S.R., Lubchenco, J., Walker, B., Callaghan, T.V., Folke, C., Levin, S.A., Mäler, K.-G., Nilsson, C., Barrett, S., Berkes, F., Crépin, A.-S., Danell, K., Rosswall, T., Starrett, D., Xepapadeas, A., Zimov, S.A. , 2006. Building resilience and adaptation to manage arctic change. Ambio 35(4): 198-202.

Daily, G.C., 1997. *Nature's services: Societal dependence on natural ecosystems*. Washington, Island Press, 412 pp.

Druckenmiller, M.L., Eicken, H., Johnson, M., Pringle, D., Williams, C.C., 2009. Toward an integrated coastal sea ice observatory: System components and a case study at Barrow, Alaska. Cold Reg. Sci. Technol. 56: 61-72.

Druckenmiller, M.L., Eicken, H., George, J.C., Brower, L., 2010. Assessing the shorefast ice: Iñupiat whaling trails off Barrow, Alaska. In: Krupnik, I., Aporta, C., Gearheard, S., Kielsen Holm, L., Laidler, G. (Eds.), *SIKU: Knowing our ice*. Springer-Verlag, New York, pp. 202-228.

Eicken, H., Lovecraft, A.L., Druckenmiller, M.L., 2009. Sea ice system services: A framework to help identify and meet information needs relevant for arctic observing networks. Arctic 62(2): 119-136.

Eicken, H., 2010. Indigenous knowledge and sea ice science: What can we learn from indigenous ice users? In: Krupnik, I., Aporta, C., Gearheard, S., Kielsen Holm, L., Laidler, G. (Eds.), *SIKU: Knowing our ice*. Springer-Verlag, New York, pp. 357-376.

Foote, D.C., 1960. The Eskimo hunter at Point Hope, Alaska: September, 1959, to May, 1960, United States Atomic Energy Commission: 58.

Ford, J.D., Furgal, C., 2009. Climate change impacts, adaptation and vulnerability in the Arctic. Polar Research 28(1): 1-9.

Ford, J.D., Pearce, T., Duerden, F., Furgal, C., Smit, B., 2010. Climate change policy responses for Canada's Inuit population: The importance of and opportunities for adaptation. Global Environmental Change 20: 177-191.

Furgal, C., Seguin, J., 2006. Climate change, health, and vulnerability in Canadian northern aboriginal communities. Environ. Health Perspectives 114: 1964–1970.

Furgal, C., Prowse, T.D., 2008. Northern Canada. In: Lemmen, D., Warren, F., Bush, E., Lacroix, J. (Eds.), *From impacts to adaptation: Canada in a changing climate 2007.* Government of Canada, Ottawa, ON, pp. 57-118.

Fox, S., 2003. When the weather is Uggianaqtuq: Inuit observations of environmental change. University of Colorado Geography Department Cartography Lab, Boulder, CO. Distributed by National Snow and Ice Data Center. CD-ROM.

Freeman, M. (Ed.), 1976. *Inuit Land Use and Occupancy Project, Three volumes*. Thorne Press, 263 pp.

Gearheard, S., Matumeak, W., Angutikjuaq, I., Maslanik, J., Huntington, H.P., Leavitt, J., Matumeak Kagak, D., Tigullaraq, G., Barry, R.G., 2006. ''It's not that simple'': A collaborative comparison of sea ice environments, observed changes, and adaptations in Barrow, Alaska, USA, and Clyde River, Nunavut, Canada. Ambio 35: 203–211.

George, J.C., Huntington, H.P., Brewster, K., Eicken, H., Norton, D.W., Glenn, R., 2004. Observations on shorefast ice dynamics in arctic Alaska and the responses of the Iñupiat hunting community. Arctic 57(4): 363-374.

George, J.C., Norton, D.W., Brower Jr., H., unpubl. Observations on landfast ice break-off events "Uisauniq" near Point Barrow, Alaska. North Slope Borough Department of Wildlife Management, Barrow, Alaska.

Huntington, H.P., Brower Jr., H., Norton, D.W., 2001. The Barrow Symposium on Sea Ice, 2000: Evaluation of one means of exchanging information between subsistence whalers and scientists. Arctic 54(2): 201-206.

Huntington, H., Callaghan, T., Fox, S., Krupnik, I., 2004. Matching traditional and scientific observations to detect environmental change: A discussion on arctic terrestrial ecosystems. Ambio 33(S13): 18-23.

Huntington, H.P., Hamilton, L.C., Nicolson, C., Brunner, R., Lynch, A., Ogilvie, A.E.J., Voinov, A., 2007. Toward understanding the human dimensions of the rapidly changing arctic system: Insights and approaches from five HARC projects. Reg Environ Change 7: 173-186.

Krupnik, I., Jolly, D. (Eds.), 2002/2010. *The earth is faster now: Indigenous observations of arctic environmental change, Second edition*. Arctic Research Consortium of the United States, Fairbanks, Alaska. 384 pp.

Krupnik, I., Aporta, C., Gearheard, S., Kielsen Holm, L., Laidler, G. (Eds.), 2010. *SIKU: Knowing our ice: Documenting Inuit sea ice knowledge and use*. Springer-Verlag, New York. 300 pp.

Laidler, G.J., 2006a. Inuit and science perspectives on the relationship between sea ice and climate change: The ideal complement? Climate Change 78: 407-444.

Laidler, G.J., 2006b. Ice, through Inuit eyes: Characterizing the importance of sea ice processes, use, and change around three Nunavut communities. Doctoral thesis, University of Toronto, Ontario.

Lowenstein, T., 1980. Some aspects of sea ice subsistence hunting in Point Hope, Alaska: A report for the North Slope Borough's coastal zone management plan. North Slope Borough, Barrow, Alaska, 83 pp.

Mahoney, A., Eicken, H., Gaylord, A.G., Shapiro, L., 2007a. Alaska landfast sea ice: Links with bathymetry and atmospheric circulation. Journal of Geophysical Research, 112, C02001, doi:10.1029/2006JC003559.

Mahoney, A., Eicken, H., Shapiro, L., 2007b. How fast is landfast ice? A study of the attachment and detachment of nearshore ice at Barrow, Alaska. Cold Reg. Sc. Tech. 47: 233-255.

Maslanik, J.A., Fowler, C., Stroeve, J., Drobot, S., Zwally, J., Yi, D., Emery, W., 2007. A younger, thinner arctic ice cover: Increased potential for rapid, extensive sea ice loss. Geophys. Res. Lett., 34, L24501, doi:10.1029/2007GL032043.

McDonald, M., Arragutainaq, L., Novalinga, Z. (Eds.), 1997. Voices from the bay: Traditional ecological knowledge of Inuit and Cree in the Hudson Bay bioregion. Ottawa, Ontario: Canadian Arctic Resources Commission.

Müller-Wille, L. (Ed.), 1998. *Franz Boas among the Inuit of Baffin Island, 1883–1884: Journals and Letters*. University of Toronto Press, Toronto, ON, 312 pp.

Mustonen, T., Helander, E. (Eds.), 2004. *Snowscapes, dreamscapes – A Snowchange community book on community voices of change*. Tampereen ammattikorkeakoulu, Tampere. 565 pp.

NAS, 2006. Toward an integrated arctic observing network. Committee Report. National Academies Press, Washington, D.C., 115 pp.

Nelson, R., 1969. *Hunters of the northern ice.* University of Chicago Press, Chicago, 429 pp.

Nghiem, S.V., Rigor, I.G., Perovich, D.K., Clemente-Colón, P., Weatherly, J.W., Neumann, G., 2007. Rapid reduction of arctic perennial sea ice. Geophys. Res. Lett., 34, L19504, doi:10.1029/2007GL031138.

Norton, D.W. (Ed.), 2001. *Fifty more years below zero: Tributes and meditations for the Naval Arctic Research Laboratory's first half century at Barrow, Alaska.* The Arctic Institute of North America, Calgary, Alberta and Fairbanks, Alaska, 576 pp.

Omura, K., 2005. Science against modern science: The sociopolitical construction of otherness in Inuit TEK (traditional ecological knowledge). In: Kishigami, N., Savelle, J.M. (Eds.), *Indigenous use and management of marine resources*. Senri Ethnological Studies 67. Osaka, Japan: National Museum of Ethnology, pp. 323-344.

Pielke Jr., R.A., 2010. Creating useful knowledge: The role of climate science policy. In: Driessen, P.P.J, et al. (Eds.), *From climate change to social change: Perspectives on science-policy interactions*. International Books, pp. 51-67.

Rasmussen, K., 1927. *Across arctic America: Narrative of the Fifth Thule Expedition*. New York: G. P. Putnam's Sons, 415 pp.

Schipper, E.L.F., Burton, I., 2009. Understanding adaptation: Origins, concepts, practice, and policy, In: Schipper, E.L.F., Burton, I. (Eds.), *Adaptation to Climate Change*. Earthscan, London, pp. 1-8.

Sillitoe, P., Marzano, M., 2009. Future of indigenous knowledge research in development. Futures 41: 13-23.

Stefansson, V., 1919. *My life with the Eskimo*. Macmillan, New York, 538 pp.

Tremblay, M., Furgal, C., Lafortune, V., Larrivée, C., Savard, J., Barrett, M., Annanack, T., Enish, N., Tookalook, P., Etidloie, B., 2006. Communities and Ice: Bringing Together Traditional and Scientific Knowledge. In: Riewe, R., Oakes, J. (Eds.), *Climate Change: Linking Traditional and Scientific Knowledge*. Aboriginal Issues Press, University of Manitoba, pp. 123-138.

Chapter 2. Toward an integrated coastal sea ice observatory: System components and a case study at Barrow, Alaska*

Abstract

The morphology, stability and duration of seasonal shorefast sea ice in Alaska's coastal zone is changing alongside large-scale ice thinning and retreat. The extent and complexity of change at the local level requires an integrated observing approach to assess implications of such change for coastal ecosystems and communities. At Barrow, Alaska the local population is increasingly forced to adapt to less stable sea ice, loss of multi-year ice, and a shorter ice season. We are working toward an integrated coastal ice observatory to monitor shorefast and adjacent pack ice and to maximize the usefulness of information to the community and an assortment of other stakeholders. The observatory includes: (1) satellite remote-sensing datasets, (2) a coastal sea ice radar and webcam that monitor ice movement, (3) a mass-balance site that provides temperature profiles and thickness information for ice and snow, (4) sea-level measurements, (5) periodic ice thickness surveys using direct drilling and electromagnetic induction sounding, and (6) a program of regular, undirected observations by Iñupiat sea ice experts. Two shorefast ice break-out events off Barrow in spring 2007, which took place while the subsistence whaling community partook in a successful hunting season, are examined. Parsing the geophysical datasets obtained from the observatory using local expert knowledge has provided insight into the assessment of ice stability and the integration of information on ice growth, origin, morphology, and dynamics, as well as winds, weather, and currents.

---

* Published in slightly modified form as: Druckenmiller, M.L., Eicken, H., Johnson, M.A., Pringle, D.J., Williams, C.C., 2009. Toward an integrated coastal sea ice observatory: System components and a case study at Barrow, Alaska. Cold Reg. Sc. Tech. 56(2-3): 61-72.

2.1 Introduction

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

Over the past three decades the arctic sea ice cover has experienced significant thinning and reductions in summer minimum ice extent, with the lowest coverage ever observed in September 2007 (Rothrock and Zhang 2005; Stroeve et al. 2008). North of Alaska in the Chukchi and Beaufort Seas, the summer ice edge has retreated northward and the duration of the open water season has increased (Shimada et al. 2006). Shorefast ice forms later in the season and is generally less stable than in the past (George et al. 2004; Mahoney et al. 2007b). To support active responses and adaptation to these changes, observations must be relevant to a broad assortment of user groups. (Hutchings and Bitz 2005; SEARCH 2005; NAS 2006). National ice services typically provide graphical information on the regional and large-scale distribution of ice types and sea-surface temperature determined from remote sensing imagery, as well as regional sea ice advisories (e.g., Partington and Bertoia 1999). However, local communities and specific stakeholder groups typically require observations at higher resolution as well as of additional variables (Hutchings and Bitz 2005; Eicken et al. 2009).

Despite the importance of ice observations to arctic coastal communities and industry, few sustained measurement programs or observatories are in place today. (In the context of this thesis, the term observatory does not strictly refer to a stand-alone station that makes long-term measurements, e.g., like an astronomical observatory, but rather more broadly to include any observation program that has a well-defined, long-term mission and maintains a fairly consistent approach for collecting data.) This gap has motivated science to look toward the most sustained and thorough observations of coastal sea ice that have been carried out over centuries - observations by coastal users of the ice cover, such as the Iñupiat and Yupik Eskimo of Alaska and the Inuit of northern Canada (Boas 1885; Nelson 1969; Lowenstein 1981). For this reason, Barrow, Alaska was chosen as the location for a pilot coastal sea ice observatory (see Fig. 2.1), which began in the late 1990's and continues in an effort to increasingly provide an integrated approach to observing. Barrow was chosen for several important reasons, including:

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

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

Section 2.4 of this paper will demonstrate this integrated approach by examining how seemingly disparate observations collected during spring 2007 are combined to examine causal relationships associated with two shorefast ice break-out events (i.e., the detachment of shorefast ice). These particular break-out events were observed by the community and played a role in determining how hunters used and interpreted the stability of the ice cover during whaling season.

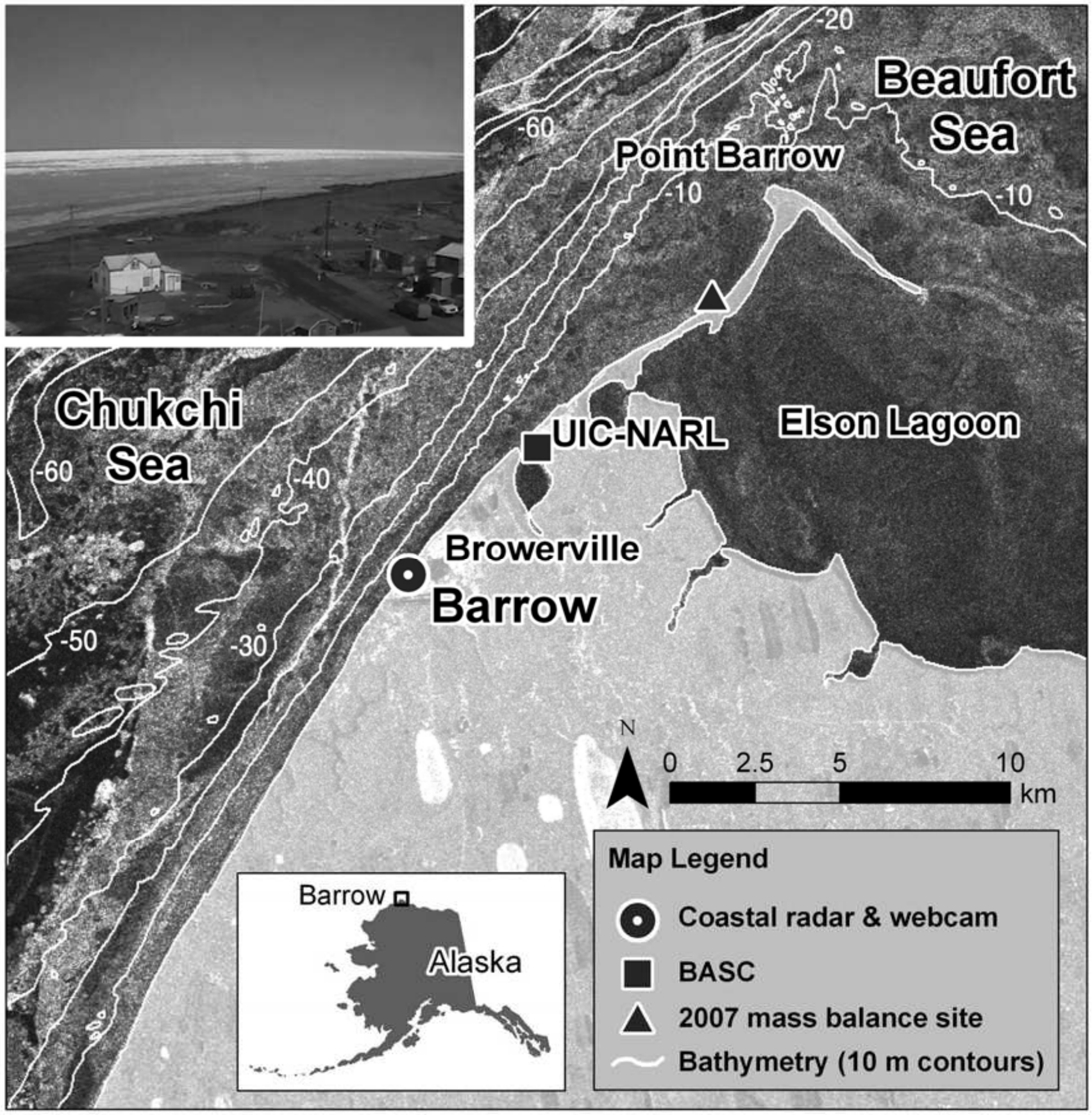


Figure 2.1 Map of the Barrow sea ice observatory overlaid on an ERS-2 SAR satellite image from 21 April 2007. Shown here are the coastline, bathymetry, and the fixed observatory components (coastal sea ice radar, webcam, and the 2007 mass-balance site, which includes a sea-level gauge). The photo in the upper left corner is a sample webcam image from 6 June 2007, in which the shorefast sea ice is clearly visible. The ice immediately off the beach is darker colored due to melt pond formation and the absence of snow.

A basic understanding of which variables are potentially involved in these types of events, along with local observations and expert testimony, allow us to develop a framework for analysis, sub-sample various data streams, and work toward coherent cause and effect explanations for what may lead to unsafe or unstable ice conditions. Because these observed dynamic events happen at a particular place and time, issues of scale and context can be addressed in regards to the community relevance of observations. This is particularly helpful given that it is often a great challenge for scientists to fully understand how the information and knowledge shared by local ice-experts relates to location- and time-specific assessments of ice conditions. The nature of this exchange between targeted science and a body of knowledge that encompasses a much broader perspective often leads to unexpected discoveries that extend beyond the initial vision of the scientist.

The foundation of this observatory is built on several years of collaboration with the Barrow community and maintained though partnership with the Alaska Ocean Observing System (AOOS)—a component of the US Integrated Ocean Observing System (IOOS) that is establishing coastal ocean observing and forecast capabilities. With the implementation of the AOOS, a formal user needs meeting was held in Barrow in 2006 to gather input from the community. Over the years, the needs of the community of Barrow have also been assessed through collaboration with local Iñupiat ice experts and hunters (Huntington et al. 2001) and the North Slope Borough's Department of Wildlife Management. These exchanges guided the early stages of the observatory's design, for example, through emphasizing the need for real-time measurements of sea level and potential floating ice surges. This guidance, along with continued efforts to seek input from community members, has led to the development of a robust and evolving observatory that is capable of responding to the challenging coastal ice environment (see Section 2.3).

2.2 Sea ice conditions and subsistence activities at Barrow, Alaska

Shorefast ice near Barrow forms in fall (typically November, but in recent years as late as December) through a combination of in-situ freezing and attachment of drift ice brought inshore by wind or currents (Shapiro 1975; Mahoney et al. 2007b; Kenneth Toovak, public testimony, 2000; Joe Leavitt, unpubl. obs., 2006). Starting in the 1990s, the northward summer ice edge retreat has impacted the distribution of multi-year ice in nearshore waters (Drobot and Maslanik 2003). In recent years, very little multi-year ice has been present at the time of freeze-up (George et al., 2004; Andy Mahoney and Hajo Eicken, unpubl. obs., 2005-2008), hence it has not been incorporated in the shorefast ice. Over the course of winter and spring, the shorefast ice is subjected to accretion, break-out and deformation events (Shapiro 1975; K. Toovak public testimony, 2000; Mahoney et al. 2007a) that result in a complex agglomeration of ice types and ages (A. Brower, Sr., unpubl. obs., 2007; Joe Leavitt, unpubl. obs., 2007; Mahoney et al. 2007a).

In spring, offshore ice motion typically results in the formation of flaw leads (open water and new ice) along the edge of the shorefast ice, generally between 1 and 10 km distance from shore. By mid-June large stretches of shorefast ice break-out or decay in place, with the eastern Chukchi Sea coast being free of shorefast ice by June 18 ± 13 days (Mahoney et al. 2007b).

The observatory focuses on the stability and morphology of the local shorefast ice, which is intricately linked to the subsistence activities of the Iñupiat community of Barrow. Sea ice is used as a platform for harvesting marine mammals, including seals and whales. In spring, during the bowhead whale harvest, as many as 200 or 300 people may be engaged in various activities on a stretch of shorefast ice extending approximately 10 km to either side of town and up to 10 km offshore. Transport of personnel and supplies to camps at the flaw lead takes place on a network of trails that are built on the ice starting in March or early April. When a crew successfully strikes a whale, dozens of people use block and tackle to haul it onto the ice for butchering (Hess 1999, Eicken et al. 2009). The whaling season ends in late May or early June. In recent years, the end of the season has been determined as much by the lack of stable ice as by the passing of the whale migration (J. Craig George, pers. comm., 2006).

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

2.3 Components of the observing system

This section will describe the various components of the observatory used to target a broad understanding of ice stability and related processes. Table 2.1 summarizes the observed parameters and the associated spatial and temporal scales of observation.

Table 2.1 Components of the Barrow sea ice observatory and observed sea ice and related parameters

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

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

2.3.1 Satellite remote sensing

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

Prior to August 2010, AOOS received raw and partially processed satellite data through the Alaska SAR facility and through the Geographic Information Network of Alaska (GINA). AOOS then corrected any geo-referencing errors in the images, locally archived, and displayed these on the Internet for public access. AOOS also collected existing data products from multiple web sites providing a single data access point. For example, AOOS displayed sea ice concentration maps from AMSR-E (Advanced Microwave Scanning Radiometer), FNMOC (Fleet Numerical

Meteorology and Oceanography Center), and GFS (Global Forecast System), as well as sea ice extent from MODIS. AOOS provided links to the existing NWS sea ice charts, forecasts, and analyses, and made available a data inventory of all sea ice products. AOOS staff at the University of Alaska Fairbanks worked with NASA over an eighteen month period to gain clearance for AOOS to provide SAR data (Radarsat-1) for the Barrow and North Slope region. This pilot project successfully delivered high resolution sea ice imagery through 2008. Additional remotely sensed data included cloud cover from AVHRR visible and sea-surface temperature (SST) from AVHRR and MODIS. AOOS was working with sea ice experts to create custom data products for its 'Barrow Page', a dedicated site for commonly-requested data products. As part of its forecast improvement effort, AOOS compared modeled hindcast sea ice concentration data with observational data (Johnson et al. 2007), and reported any significant differences back to the modeling community.

2.3.2 Coastal sea ice radar and webcam

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

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

Shapiro (1975) and Mahoney et al. (2007b) demonstrated that variations in backscatter from shorefast ice targets (radar reflectors) up to an hour prior to an ice break-out event may serve as an early warning system for the community. These precursory observations are characterized by a rapid and localized change in backscatter response without motion of the reflector, causing features in the image to flicker (Shapiro et al. 1987, Mahoney et al. 2007b). Mahoney et al. (2007b) have suggested that the rising and lowering of shorefast ice, which produces the change in radar reflectors, dislodges the ice and allows it to detach from the remaining shorefast ice. However, our current understanding of this phenomenon is not sufficient to implement an automated early warning system. In its present state, the observatory is collecting and interpreting data that, ideally, will lead to improvements in the identification of such precursor events (see Section 2.4).

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

2.3.3 Sea ice mass balance site and sea-level gauge

An automated mass balance site is installed annually in growing, undeformed shorefast first-year ice in a small embayment SW of Pt. Barrow in the Chukchi Sea (see Fig. 2.1). Local ice experts and analysis of SAR imagery confirm that the bathymetry and coastline in this area result in stable ice that typically sticks around until the period of primarily thermal ice decay in June. At this location the ice is homogeneous. It forms primarily through in-situ freezing rather than advection and deformation and provides ice and snow data representative of level, undeformed ice. The distance from the coastal road is sufficient to prevent contamination by traffic-generated dust that can increase ice albedo and accelerate melt. Because this site is separated from bottom-fast ice inshore by tidal cracks and is several hundred meters from grounded ridges offshore, variations in local sea level due to tides and surges can be measured from the vertical motion of the ice.

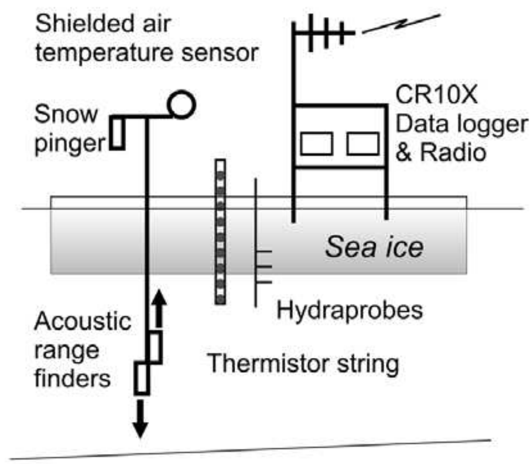


Figure 2.2 Schematic of sea ice mass balance site instrumentation and measurements.

Fig. 2.2 shows components of the mass balance site. Snow depth is measured with a Campbell SR50 sonic ranger fixed to a mast extending through the ice. Upward- and downward-looking underwater acoustic altimeters (Benthos, PSA-916) are fixed to the under-ice continuation of the mast. Ice thickness is calculated as the distance between the upper ice surface at the time of installation and the bottom of the ice. Instantaneous local sea level is calculated as the distance from the initial upper ice surface to the sea floor. Vertical temperature profiles through water-ice-snow-air are measured at 10-cm intervals with thermistor strings. Air temperature and relative humidity are measured 2 m above the ice with a shielded Campbell CS500 sensor. Dielectric permittivity measurements were made in 2006 and 2007 using Stevens Water Hydraprobes to assess their use for automated salinity measurements (Backstrom and Eicken 2006; Pringle et al. 2009). Data are recorded with a Campbell CR10X data logger, transmitted via FreeWave Radio to BASC and transferred via ftp to UAF where they are processed, posted on the web, and archived at UAF. This fully automated process results in data and plots of temperatures, snow and ice depths, and sea level updated typically an hour after measurement. Such sites operated from l2 February – 10 June 2006, 25 January – 9 June 2007 and 7 February – 17 June 2008. These dates were dictated by the time at which the ice became securely shorefast and by melt-out and final break-up.

2.3.4 Ice thickness surveys

Ice thickness surveys are conducted at key times during the ice growth season to obtain information on the morphology of the ice and potential anchor points, such as grounded ridges. In addition to the single-point mass balance data, thickness surveys map variations in ice thickness and type. A Geonics EM-31 electromagnetic induction (EM) device determines the apparent conductivity of the half-space below the instrument by generating a primary electromagnetic field at 9.8 kHz and comparing this to the secondary field generated by induced eddy currents in the seawater underneath (Haas 2003). Here, thickness values are obtained by applying a semi-empirical inversion equation derived for growing first-year arctic sea ice (Haas et al. 1997). Such measurements on sea ice have been validated by Kovacs and Morey (1992), Haas et al. (1997), and Eicken et al. (2001). The lateral resolution is on the order of the EM coil spacing of 3.66 m. Measurements in level ice have been found to be accurate within 10 cm of the true value averaged over the instrument footprint (Haas 2003). The EM-31 and a geodetic DGPS receiver, which measures surface elevation to within centimeters and geo-references the measurements, are either towed on a sled or carried depending on the length and trafficability of the transect. Measurements are made at two to 10-m intervals depending on the mode of travel (i.e., snowmobile versus walking). Snow depth is also measured manually along transects to correct the derived depths for true ice thickness, which are then validated against depths measured directly from drilling.

Repeat thickness profiles are measured perpendicular to shore in multiple locations, including in the vicinity of the mass-balance site (see Fig. 2.1). As measurements are made along the Barrow coastline where whale hunting crews establish trails from the shore to the shorefast ice edge, the thickness transects are often performed on these trails. Use of these pre-established trails not only allows for greater collection of data and spatial coverage but also makes thickness data more relevant to the whaling community, who are concerned with the state of the ice along their trail system. The majority of measurements are made toward the end of the ice growth season to obtain an estimate of maximum ice thickness for mass budget analysis. Additional transects, such as those detailed in Section 2.4.3, are performed at times of year or in locations where ice stability is in question or to support satellite and/or coastal remote sensing efforts.

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

2.3.5 Local observations by Iñupiat sea ice experts

Collaborations with local sea ice experts provide point source observations from an ice-user's perspective. Because Iñupiat ice experts follow the seasonal evolution of the ice cover, making note of specific deformation events and the distribution of key features such as grounded ridges or multi-year ice floes, their observations greatly assist in assessing ice stability. Two local sea ice experts, Arnold Brower Sr. and Joe Leavitt, have provided detailed observations of Barrow's near shore sea ice environment as well as general guidance for scientific field research campaigns. Brower and Leavitt have acquired their expertise through decades worth of subsistence activities (approximately 115 years between the two of them), including hunting bowhead whales and ice seals, which require ongoing evaluation and sharing of knowledge regarding the local sea ice, currents, and weather. Both have extensive experience working with researchers in Barrow and elsewhere in the Arctic and are familiar with attempts to interface local observations with physical western science (Gearheard et al. 2006). Brower (2006-2007) and Leavitt (2006-2011) kept near-daily written journals of sea ice and related observations. More frequent observations were made during periods of change in the ice cover or at times most relevant to activities on or near the ice, especially those related to whaling. Their sea ice observations were thus often made in the context of what they and others in the community were doing on the ice (e.g., scouting for potential ice trail locations, traveling on the ice to access local trapping areas, etc.).

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

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

2.4 Case study: Ice break-out events during the 2006/07 ice season

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

2.4.1 Coastal sea ice radar and SAR satellite imagery capture ice break-out events

On 31 March 2007 the sea ice radar captured a break-out of an apron of shorefast ice immediately off Barrow's coast. Animations of radar scenes show interaction with the nearby pack-ice, large-scale fracture, rotation about an apparent anchor point, detachment, and subsequent replacement of this ice in the shorefast zone. The entire event lasted thirteen hours. A second break-out event occurred on 28 May 2007, with the break-out line apparently along the ice edge left by the first event. Fig. 2.3 shows the sequence of key stages of these break-out events, which can be summarized as follows:

- Pack-ice drifting in a NE direction (see arrow A2 in Fig. 2.3a) collided with and destabilized the shorefast ice by breaking away a section of approximately 8 km^2 of the seaward landfast ice edge (SLIE) (see B2 in Fig. 2.3b). Strong radar returns along the new SLIE suggest the presence of high, presumably grounded, ridges along the break-out line.
- Next, a fracture developed with the clockwise rigid-body rotation of a portion of the shorefast ice of approximately 10 km^2 (see C2 in Fig. 2.3c). During this detachment the radar received increased backscatter from targets along the new temporary SLIE, which is indicated by the relatively dark reflectors to the right of the detaching ice in Fig. 2.3c. As this piece of ice rotated and created open water in its wake, drifting ice quickly

replaced the detached ice and came into position along the shorefast ice (see C3 in Fig. 2.3c).

- Between 1 April and 28 May, conditions (see Sections 2.4.2 and 2.4.4) allowed for both drifting ice and new ice growth to contribute to an extended SLIE in the area where the first break-out occurred (see Fig. 2.3d). On 28 May at 22:18 local time, the radar observed a rapid detachment of ice (see Fig. 2.3e) that resulted in the SLIE reverting back to the same position as immediately after the first event (compare the SLIE in Fig. 2.3F and 2.3c).

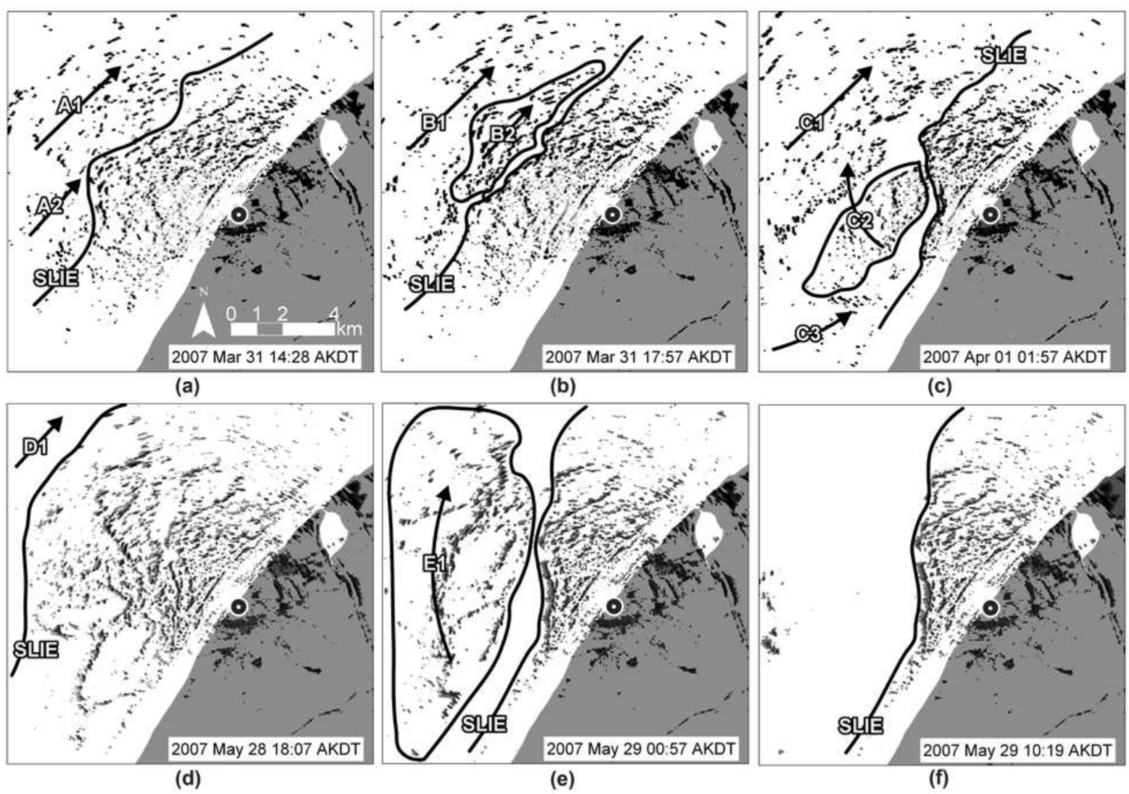


Figure 2.3 Radar backscatter images illustrating the late-March (images a to c) and late-May (images d to f) break-out events. The areas of solid gray are land, the circles near the image centers mark the radar location and solid heavy lines represent edges of ice areas of interest. SLIE denotes the seaward landfast ice edge determined from SAR. Arrows A1, B1, C1 and D1 indicate the direction of pack ice movement beyond the SLIE. See Section 2.4.1 for discussion of all other arrows.

Further investigation (see Section 2.4.3) revealed that the ice edge following the first break-out event was defined by an elevated ridge line. With sails of up to at least 3 m in height, the ridges were thick enough to be grounded on the seafloor, with water depths along the ridge line ranging from 10 to 30 m. While some pack ice temporarily attached itself to the shorefast ice along this ridge for 8 weeks before the second break-out event, the ridge itself remained in place and stationary throughout much of the remaining ice season. It was observable in SAR images from Radarsat and ERS-2 during this time. The bright line of backscatter indicated by “A” in the 21 April SAR scene in Fig. 2.4a shows newly-formed ice parallel to this ridge (see discussion in Section 2.4.3). Fig. 2.4b reveals the ridge as still present later in the season on 8 June 2007. This ridge finally deteriorated during the melt season.

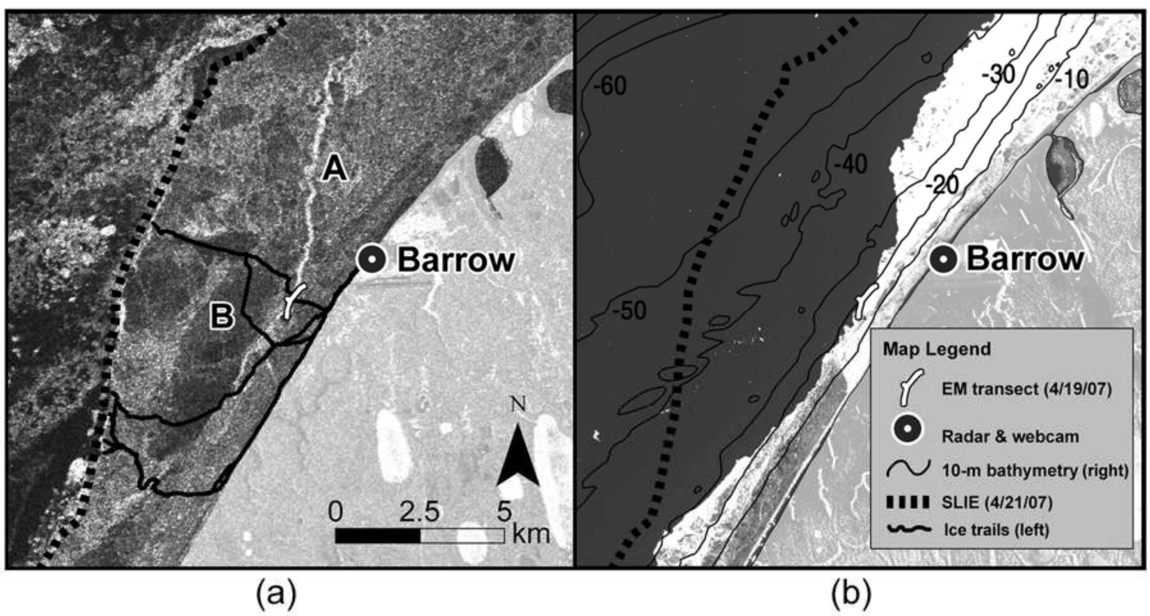


Figure 2.4 Satellite images of Barrow’s shorefast ice extent from before and after the 28 May 2007 break-out event. On the left (a), is an ERS-2 SAR image from 21 April 2007. The dotted line represents the seaward landfast ice edge (SLIE), “A” indicates a bright line of backscatter in a N-S orientation resulting from new ice at the attachment area, and “B” indicates a flat pan of ice brought in following the late-March break-out. The black lines represent ice trails used by hunters in May to access hunting camps at the ice edge. On the right (b), is an ALOS AVNIR-2 image from 8 June 2007. The dotted line represents the SLIE from 21 April 2007, shown in Fig. 2.4a. The area between the dotted line and the clearly visible shorefast ice edge represents ice that had broken away during the 28 May break-out and in the several days that followed. The EM thickness transects measured on 19 April 2007 (to be discussed in Section 2.4.3) are shown here in both figures.

2.4.2 Weather and ice conditions preceding and during the ice break-out events

A good description of the state of the atmosphere, ocean, and ice throughout the season comes from the mass balance site measurements and weather data obtained from the National

Oceanic and Atmospheric Administration (NOAA) data records for Will Rogers Memorial Airport in Barrow (approximately 2 km SE of the break-out location). These conditions correlate with the March and May break-out events. Fig. 2.5 shows sea-level air pressure (SLP) from NOAA records and the air temperature, sea level, and water temperature from our mass balance site. Fig. 2.6 shows wind speed and direction.

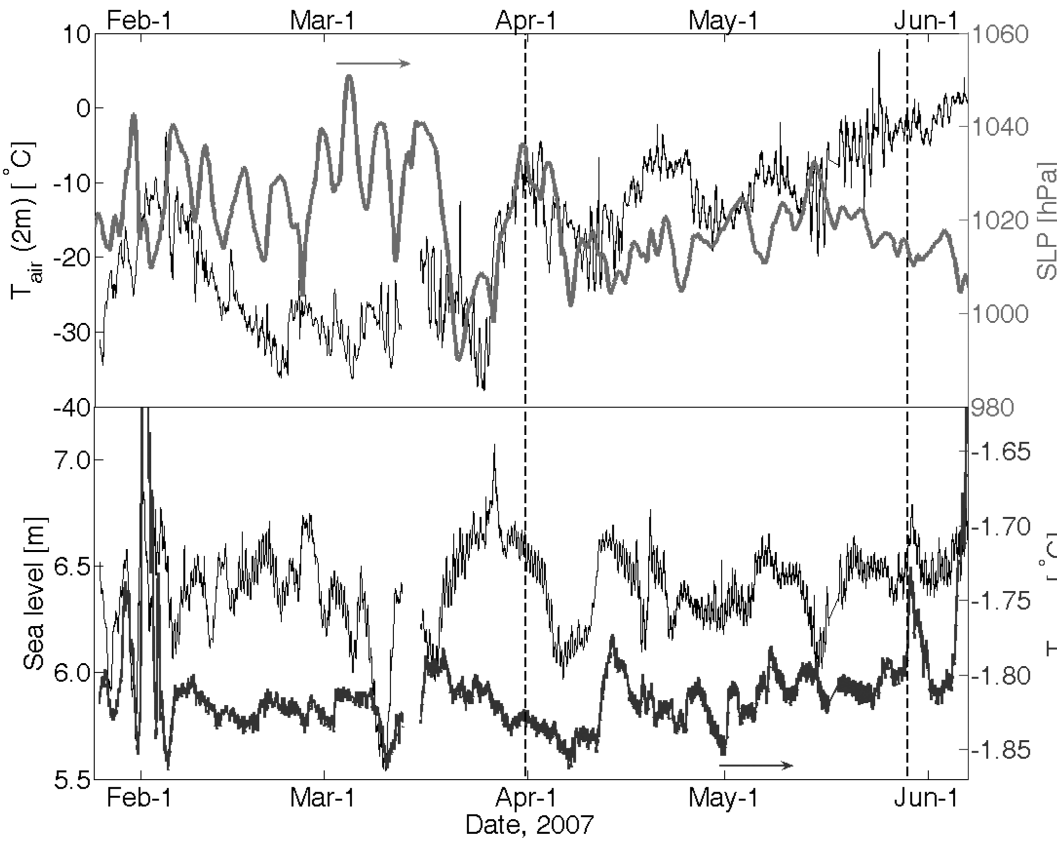


Figure 2.5 Timing of the 2007 break-out events with weather conditions. Dashed vertical lines indicate the break-out events. Top: air temperature 2 m above ice surface (light curve, left axis) and sea-level air pressure (heavy curve, right axis). Bottom: Sea level (light line, left axis) and water temperature (heavy line, right axis) at mass balance site. Water temperature is the mean of 5 thermistors, 1.45 to 1.85 m below the upper ice surface.

The March break-out event followed a week-long period of warming from approximately -30 to -10 ºC in air temperature associated with a rebound in SLP following extended low pressure during mid-to-late March. The under-ice water temperature showed no significant change at the time of the break-out (This contrasts with strong warming events in both late January and early

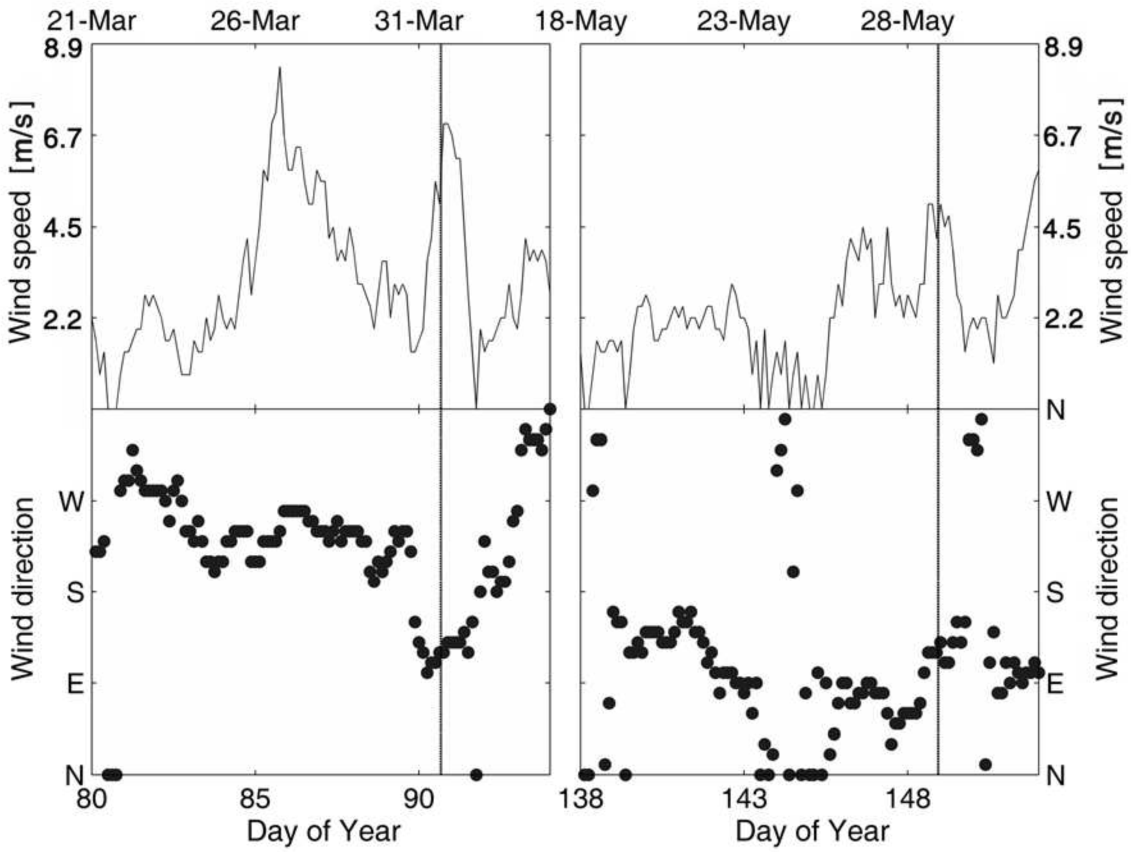


Figure 2.6 Wind speed (top) and direction (bottom) from Will Rogers Airport, Barrow before and after the 2007 break-out events. By convention, wind direction is the direction from which the wind blows. Dashed vertical lines indicate the break-out events. (Source: NOAA Local climatological data, Will Rogers Airport, Barrow.)

February due to the inshore advection of warm shelf water, and during the melt season in May and June). Sea level was relatively high for about three weeks during and after the period of low SLP in March. The most noteworthy feature here is the sea-level peak on 26 March (day 85), which was about 0.5 m above the sea-level from 10 days earlier. This coincided with a pronounced peak in wind strength during a sustained period of westerly- to south-westerly winds (see Fig. 2.6), and a small and gradual decrease in water temperature. Ekman dynamics dictate that the direction of induced surface currents in the ocean will be to the right of the wind forcing. For example, in an ideal case, a wind blowing from west to east forces the upper ocean to move southward, raising sea level along the SW-NE trending coastline at Barrow. Therefore, this period of elevated sea level may in part be due to wind-driven, inshore advection of cooler, off-shore water. This is particularly likely for the sea-level peak on 26 March. Such inshore forcing may have disturbed ice keels anchoring the shorefast ice to the seafloor, thereby preconditioning the ice for subsequent break-out while momentarily holding it in place. While not visible in this plot, break-out occurred just prior to low-tide, so off-shore tidal flow may have played a role. Here, it is important to note that Barrow has a very low tidal range of about 12.5 cm in spring (Hunkins 1965), therefore, the low-tide drop was much smaller than the preceding increase in sea-level attributed to the sustained westerly- to south-westerly winds.

Fig. 2.6 shows the 31 March break-out followed an abrupt, almost 180º shift in wind direction and a day-long increase in wind speed. For more than 10 days prior to the break-out, the prevailing winds were primarily west and southwest (between inshore and along-shore). By early morning 31 March (day 90), the winds shifted to the southeast — almost exactly offshore — and the break-out occurred near the peak in increasing wind speed. The initial direction of ice motion toward the northwest (Fig. 2.3a) supports the idea that the southeasterly wind had a large effect on ice detachment. The radar data also suggest that interaction and coincident displacement of weakly grounded or ungrounded shorefast ice with incoming offshore pack ice (arrow C3 in Fig. 2.3c) played an important role in the break-out.

A similar analysis of the 28 May event again shows break-out at the onset of strong SE winds. This break-out followed a week of weaker winds from the north and east and coincided with a pronounced increase in water temperature and sea level. The latter suggests inshore advection of warmer offshore water, also seen in late January in Fig. 2.5, but with solar heating likely contributing to the warming at this late stage of the season. Advection of warm water affects grounded ridges through ablation and de-stabilization (Mahoney et al. 2007b), potentially priming the ice for break-out under conducive winds from the SE. Furthermore, unlike the March break-out, interaction with the offshore pack played no role in this break-out event.

2.4.3 Ice thickness and distribution of potential anchor points

On 19 April 2007, EM thickness transects were performed in the area where the late-March break-out event occurred (see ‘B’ in Fig. 2.4a). The thickness transects crossed the break-out line sampling ice that was shorefast prior to the March break-out and ice incorporated immediately after it. The primary objectives were to characterize the features observed in both the sea ice radar and SAR imagery and to obtain thickness data that could be compared to the measurements at the mass-balance site, thus providing a basis to infer where the ice originated. The EM ice thickness profile, which consists of two segments—A to C and B to B’, is shown in Fig. 2.7. The average

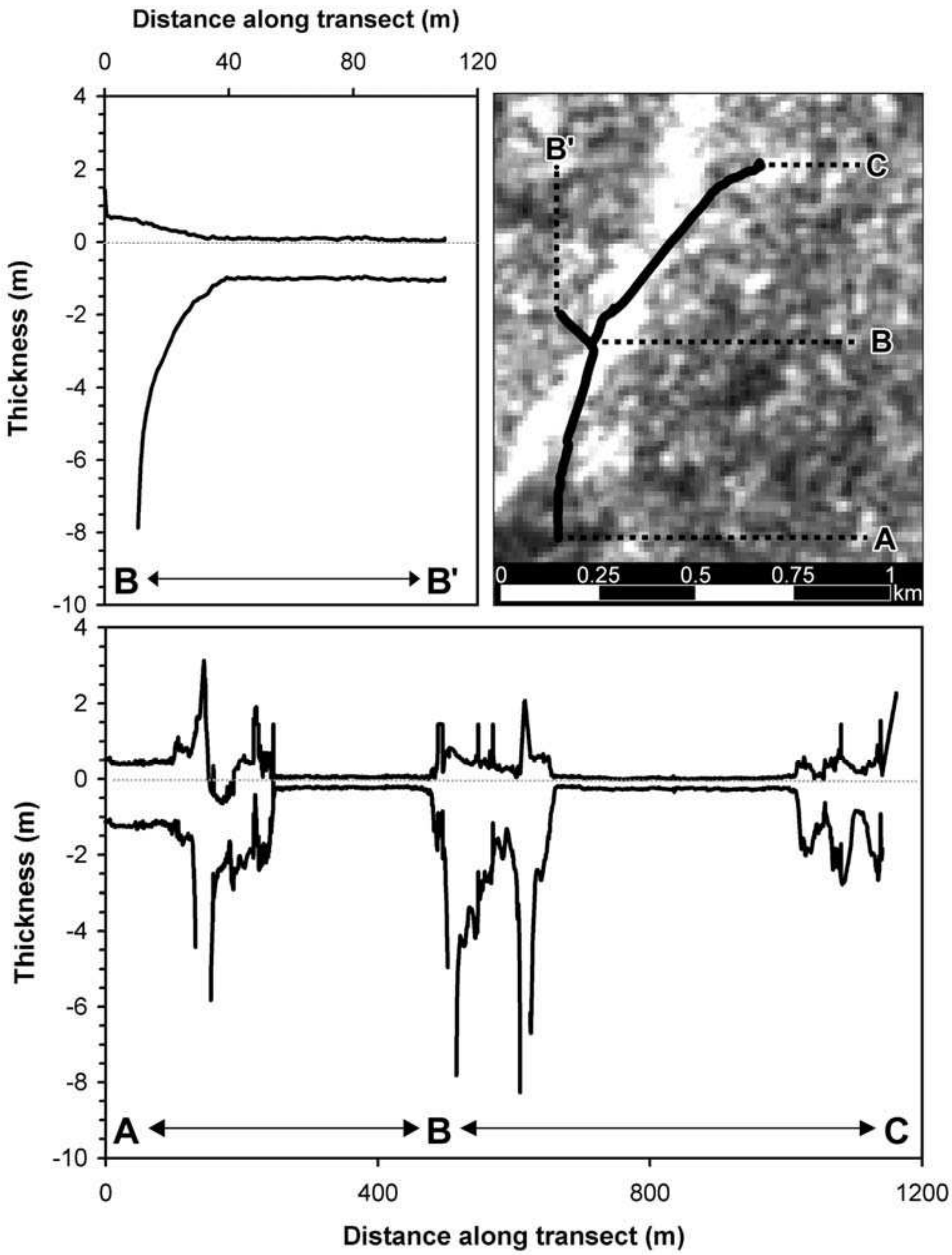


Figure 2.7 Ice thickness and surface elevation profiles from 19 April 2007 obtained using EM sounding and DGPS, respectively. The map of the transect in the upper right is overlaid on a SAR image from 21 April 2007. The bright pixels in this image represent the young saline ice that formed following the 31 March break-out event (see Section 2.4.1 and Fig. 2.4a). The location of transect shown here is also shown in Fig. 2.4a and 2.4b. Missing data at ridge keels are due to EM measurement values outside the bounds of the empirical equation used to calculate ice thickness from apparent conductivity.

thickness of the level undeformed ice along the profile A to C was 0.29 m, indicating that it froze in place following the break-out and deformational events of late March. Deviations between thickness drilling and EM-derived values ranged between 5 and 14 cm, which can be attributed to the difference in footprints (5 cm for drill versus several meters for EM-31) as much as the accuracy of the measurements. The EM and DGPS data revealed ridges along this profile with sail heights ranging from 1.5 to 3.1 m. Pressure ridges, and accordingly, keel depths are often underestimated using EM measurements by up to 30% (Haas 2003); therefore it is important to assess whether ridges are grounded using a ratio of keel depth to sail height (e.g., 4.4 for first-year ridges; Timco and Burden 1997). Given that the water depth in this region ranges from approximately 10 to 17 m, it is likely that at least one of the largest three keels was grounded on the seafloor, if only over a short distance.

Seaward of both ridges that formed during the first break-out event and the newly formed ice represented by the bright line in the SAR image of Fig. 2.4a, level ice thickness along the profile B to B' was about 1.65 m. This pan of ice was thicker than level ice at the mass-balance site (1.3 m around the same date). This difference can be attributed to the pan ice forming elsewhere, perhaps farther north, and being incorporated into the shorefast cover through advection following the break-out event.

The thickness of ice blocks in the ridges and rubble along the EM transects were also measured. Some blocks of seaward ice lifted onto the incoming ice sheet were between 0.85 and 1.05 m thick, slightly thinner than ice at the mass-balance site at the time of the break-out (1.25 m). Most of the ridges and rubble that formed during the deformation event, immediately following the break-out, consisted of blocks 0.20 to 0.58 m thick, as seen in the photograph of Fig. 2.8. Based on the ice movement apparent from the radar, the incoming parent ice sheet that deformed during this deformation event was most likely thin ice that had grown for less than one month due to the freezing of flaw leads to the southwest of this location, and driven into the area by the northeast coastal current. Remnants of this ice are apparent as uniform areas of low-backscatter in the SAR scene (see area "B" in Fig. 2.4a).

2.4.4 Local observations and community use of the ice

Uisauniq, the Iñupiaq term meaning "to be separated or cut off during an ice separation", is a central concern to those hunting or traveling on the shorefast sea ice (George et al., unpubl.). Throughout centuries lives have been lost as hunters broke-away, never to return. Many coastal

Figure 2.8 Rubble field and ridges created by deformation event immediately following the 31 March break-out event. The view is looking approximately south from the top of one of the highest ridges.

arctic communities possess extensive local and traditional knowledge on this subject and utilize this knowledge throughout the year as they evaluate local shorefast ice conditions (George et al. 2004). The Iñupiat identify a range of mechanisms that may act to detach a section of the shorefast ice. These include, but are not limited to, the nearby pack ice acting as an abrasive chisel against the shorefast ice, ice deterioration by offshore under-ice currents perpendicular to the ice edge, and rapid changes in sea level (George et al. 2004; George et al., unpubl.).

Table 2.2 summarizes the observations made by Leavitt that are relevant to understanding the ice and weather conditions and forcing under which the two ice break-out events in spring 2007 took place. The event on 31 March happened approximately one week before whaling crews began the annual task of clearing trails through the deformed shorefast ice to provide access to the open lead in order to establish camps for the bowhead whale hunt. The event on 28 May took place just days after the final whaling crews pulled off the ice at the conclusion of the hunt.

Table 2.2 Sequence of events pertaining to the break-out events as observed by Joe Leavitt (unpublished journal of sea ice observations, 2006/07)

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

[a] *"to the west" refers to the ice in the area of the break-out events.*
[b] *"Napa" refers to a commercial store located in Browerville (see Fig. 2.1).*
[c] *"gravel pit" refers to the coastal region immediately SW of Barrow.*
[d] *The "Hollywood trail" refers to a trail used for whaling located in the southern reach of the area that broke-out on 31March (see area "B" in Fig. 2.4a).*
[e] *Qaisagniq refers to a current traveling in a NE direction off Barrow.*

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

Following the formation of new ice after the 31 March break-out, many of Barrow's whaling crews established their camps in this region (see Fig. 2.4a) despite the fact that ice failure was a clear risk based on the thickness (A. Brower, Sr., pers. comm., 2007). The thickness of this new ice was approximately 0.29 and 0.65 m on 19 April and 9 May, respectively. This region, where many of the whaling trails and camps were located, was held in place by a few "key" ridges (J. Leavitt, pers. comm., 2007). Wesley Aiken (pers. comm., 2007), a Barrow elder and experienced whaling captain, noted that the "new thin ice piling up in April was 'lucky' because it made [the shorefast ice] stable at the lead for whaling." Favorable winds certainly added to this perception of stability. Neither Leavitt, A. Brower, Sr. nor the Airport's wind records (see Fig. 2.6) reported any significant west winds between 14 April and 27 May, the period in which most of the whales were harvested in this area. The lack of a west wind allowed the lead to remain open and help to prevent the northeast-drifting ice from colliding with the shorefast ice. A. Brower, Sr. noted that a strong west wind could have "folded" this ice. These experienced hunters staged their efforts in this area for two reasons: (1) whales were being seen and were accessible (Harry Brower, Jr., pers. comm., 2007), and (2) the ice and weather conditions did not present any clear warnings that a break-out was likely to occur (A. Brower, Sr., pers. comm., 2007).

The whaling crews eventually pulled out of this southern area (see the trails in Fig. 2.4b) before the 28 May break-out event as they noticed the ice being worn dangerously thin by snow machine traffic and also detected wave motion lifting the thin ice (Harry Brower, Jr., pers. comm., 2007). Observations of previously refrozen cracks melting to yield open water provided an additional indicator that it was too risky to remain in this area (A. Brower, Sr., pers. comm., 2007). A. Brower, Sr. noted that warm weather and current erosion to the under-ice surface contributed substantially to this second break-out event.

2.4.5 Discussion

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

Table 2.3 summarizes comments made by four separate local ice experts regarding the 2006/07 ice season. These observations and SAR images provide a consistent picture that the season was characterized by a lack of both large ridges and thick multi-year ice. Both local and traditional knowledge (George et al. 2004; A. Brower Sr., pers. comm., 2006) and recent glaciological studies (Mahoney et al. 2007a, 2007b) point to the importance of anchor points such as ridges or thick multi-year ice floes in holding the shorefast ice cover in place.

The entrainment of multi-year ice in the shorefast ice cover is affected by the presence of near-shore multi-year pack ice during freeze-up. Fall freeze-up is occurring on average 16 days later now compared to the 1950's (Mahoney 2006). Coupled with concurrent changes in multi-year ice, this is considered a major cause of the observed changes in the coastal zone. As offshore multi-year ice usually moves southward in fall, a later freeze-up need not imply a reduced incorporation of multi-year ice in the shorefast ice zone. However, the northward recession of the multi-year ice edge in summer 2006 (NSIDC 2006) was likely the controlling factor in the reduced multi-year fractions in the shorefast ice cover in spring 2007.

Local observations and webcam, radar, and satellite imagery confirmed that the onset of stable ice occurred late in the season in 2006/07. This may be partially attributed to a storm on 13 November that brought strong NNW winds of up to 40 mph (or 18 m/s; NOAA 2006), disrupted freeze-up, and resulted in the season's first ice being broken-up and deposited on the shore. It was not until 2 January 2007 that Leavitt indicated that the shorefast ice immediately off Barrow appeared to be established for the winter.

Table 2.3 General observations of Barrow's 2006/07 ice season

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

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

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

Data from each branch of the integrated sea ice observatory were used to identify the important environmental influences on shorefast ice stability. Analysis of the data presented in this case study indicates that the late-March break-out event was most likely caused by a sequence of: (1) mechanical action of drifting pack ice causing detachment of relatively few grounded ridges along the shorefast ice edge, and (2) stabilizing onshore winds shifting to strong offshore winds. Significant factors associated with the late-May break-out were: (1) a weakened attachment zone, (2) the onset of spring surface warming and solar heating, (3) an insufficient number of grounded ridges, and (4) ablation at the ice bottom enhanced by under-ice currents. Despite conditions of thin, seemingly unstable ice, the community was able to safely and productively use this ice in the absence of destabilizing environmental forces (e.g., an onshore westerly wind that may have caused pack ice to collide with the shorefast ice).

The sea ice observatory data indicate that the March event was largely of a dynamic nature, without bottom ablation helping to un-ground or destabilize key ridges, as it appears to have contributed to the break-out in May. The absence of precursor events ("flickering", Mahoney et al. 2007b) during the March break-out also point to dynamic interaction with the pack ice as an important factor, with little or no settling and small-scale motion of ridges prior to the break-out. Both local experts and the observing system agree that during the May break-out event, bottom ablation, aided by advection of warm water from the lead areas adjacent to the shorefast ice edge, was pivotal in destabilizing the ice. Observations by Iñupiat ice experts, satellite imagery, and ground-based ice thickness surveys together point toward a substantial reduction in the number of anchoring points of the shorefast ice with implications for ice stability. Data compiled during future break-out events over multiple seasons will lead to better understanding of how a lack of grounding ridges affects the ability of local experts and geophysical monitoring to detect early warning signs of ice break-outs.

2.5 Conclusions

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

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

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

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

List of abbreviations

AOOS	Alaska Ocean Observing System
AKDT	Alaska Daylight Savings Time
ALOS	Advanced Land Observing Satellite
AMSR-E	Advanced Microwave Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVNIR-2	Advanced Visible and Near Infrared Radiometer type 2
BASC	Barrow Arctic Science Consortium
DGPS	Differential Global Positioning System
EM	electromagnetic
ERS-2	European Remote Sensing Satellite-2
GFS	Global Forecast System
GINA	Geographic Information Network of Alaska
FNMOC	Fleet Numerical Meteorology and Oceanography Center
IOOS	Integrated Ocean Observing System
MODIS	Moderate Resolution Imaging Spectroradiometer
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NSIDC	National Snow and Ice Data Center
NWS	National Weather Service
Radarsat	Radio detection and ranging satellite
SAR	Synthetic Aperture Radar
SEARCH	Study of Environmental Arctic Change
SLIE	seaward landfast ice edge
SLP	sea-level air pressure

sst sea-surface temperature

UNEP United Nations Environmental Program

References

Ainley, D.G., Tynan, C.T., Stirling, I., 2003. Sea ice: A critical habitat for polar marine mammals and birds. In: Thomas, D.N., Dieckmann, G.S. (Eds.), *Sea ice—An introduction to its physics, chemistry, biology and geology*. Blackwell Science, Oxford, pp. 240-266.

Aota, M., Ishikawa, M., Takatsuka, T., Ikeda, M., Shirasawa, K., 1988. Distribution of pack ice off Okhotsk Sea coast of Hokkaido observed with sea ice radar network. January-May, 1988. Low Temperature Science. Ser. A. Data Report, 47: 35-64.

Backstrom, L.G.E., Eicken, H., 2006. Capacitance probe measurements of brine volume and bulk salinity in first-year sea ice. Cold Reg. Sci. Technol., 46: 167-180.

Berkes, F., 2002. Epilogue: Making sense of arctic environmental change? In: Krupnik, I., Jolly, D. (Eds.), *The earth is faster now: Indigenous observations of arctic environmental change*. Arctic Research Consortium of the United States, Fairbanks, Alaska, pp. 335-349.

Bielawski, E., 1992. Inuit indigenous knowledge and science in the Arctic. Can. Arct. Res. Comm., North. Perspect. 20(1), 5–8.

Boas, F., 1885. The Eskimo of Baffin Land. Transactions of the Anthropological Society of Washington 3, 95-102. Washington.

C-Core, 2005. Ice island study (Final Report). Prepared for the Minerals Management Service, US Department of Interior. Prepared by C-Core. Report No. R-05-014-241 v1.0, August.

Chapin III, F.S., Peterson, G., Berkes, F., Callaghan, T.V., Angelstam, P., Apps, M., Beier, C., Bergeron, Y., Crépin, A.S., Danell, K., Elmqvist, T., Folke, C., Forbes, B., Fresco, N., Juday, G., Niemelä, J., Shvidenko, A., Whiteman, G., 2004. Resilience and vulnerability of northern regions to social and environmental change. Ambio, 33(6): 344-349.

Chave, A.D., Massion, G., Mikada, H., 2006. Science requirements and the design of cabled ocean observatories. Annals Geophys., 49(2/3): 569-579.

Drobot, S.D., Maslanik, J.A., 2003. Interannual variability in summer Beaufort Sea ice conditions: Relationship to winter and summer surface and atmospheric variability. J. Geophys. Res., 108(C7): 3233, doi:10.1029/2002JC001537.

Eicken, H., Tucker III, W.B., Perovich, D.K., 2001. Indirect measurements of the mass balance of summer arctic sea ice with an electromagnetic induction technique. Annals of Glaciol. Vol. 33: 194-200.

Eicken, H., Lovecraft, A.L., Druckenmiller, M.L., 2009. Sea ice system services: A framework to help identify and meet information needs relevant for arctic observing networks. Arctic, 62: 119-136.

Fox, S., 2003. When the weather is Uggianaqtuq: Inuit observations of environmental change. Boulder, CO: University of Colorado Geography Department Cartography Lab. Distributed by National Snow and Ice Data Center. CD-ROM.

Gearheard, S., Matumeak, W., Angutikjuaq, I., Maslanik, J., Huntington, H.P., Leavitt, J., Matumeak Kagak, D., Tigullaraq, G., Barry, R.G., 2006. ‘‘It’s not that simple’’: A collaborative comparison of sea ice environments, observed changes, and adaptations in Barrow, Alaska, USA, and Clyde River, Nunavut, Canada. Ambio 35: 203–211.

George, J.C., Huntington, H.P., Brewster, K., Eicken, H., Norton, D.W., Glenn, R., 2004. Observations on shorefast ice dynamics in arctic Alaska and the responses of the Iñupiat hunting community. Arctic 57(4): 363–374.

George, J.C., Norton, D.W., Brower Jr., H., unpubl. Observations on landfast ice break-off events "Uisauniq" near Point Barrow, Alaska. North Slope Borough Department of Wildlife Management, Barrow, Alaska.

Haas, C., 2003. Dynamics versus thermodynamics: The sea ice thickness distribution. In: Thomas, D.N., Dieckmann, G.S. (Eds.), *Sea ice—An introduction to its physics, chemistry, biology and geology*. Blackwell Science, Oxford, pp. 82-111.

Haas, C., Gerland, S., Eicken, H., Miller, H., 1997. Comparison of sea ice thickness measurements under summer and winter conditions in the Arctic using a small electromagnetic induction device. Geophysics, 62(3): 749-757.

Hess, B., 1999. *Gift of the whale: The Iñupiat bowhead hunt, a sacred tradition*. Sasquatch Books, Seattle, 256 pp.

Hunkins, K.L., 1965. Tide and storm surge observations in the Chukchi Sea. Limno. Oceanogr. 10(1):29-39.

Huntington, H.P., 2000. Native observations capture impacts of sea ice changes. Witness the Arctic, 8(1): 1-2.

Huntington, H.P., Brower Jr., H., Norton, D.W., 2001. The Barrow Symposium on Sea Ice, 2000: Evaluation of one means of exchanging information between subsistence whalers and scientists. Arctic, 54(2): 201-206.

Hutchings, J., Bitz, C., 2005. Sea ice mass budget of the Arctic (SIMBA) workshop: Bridging regional to global scales. Report from NSF sponsored workshop held at Applied Physics Laboratory, Univ. of Washington, Seattle, WA, Feb 28-Mar 2, 2005.

Johnson, M., Gaffigan, S., Hunke, E., Gerdes, R., 2007. A comparison of Arctic Ocean sea ice concentration among the coordinated AOMIP model experiments. J.Geophys. Res., 112, C04S11, doi:101029/2006JC003690.

Kovacs, A., Morey, R.M., 1992. Sounding sea ice thickness using a portable electromagnetic induction instrument. Journal of Geophysical Research, 56(12):1992-1998.

Krupnik, I., Jolly, D. (Eds.), 2002. *The earth is faster now: Indigenous observations of arctic environmental change*. Arctic Research Consortium of the United States, Fairbanks, Alaska, 384 pp.

Laidler, G., 2006. Inuit and scientific perspectives on the relationship between sea ice and climate change: The ideal complement? Climate Change, 78(2-4): 407-444.

Lowenstein, T., 1981. Some aspects of sea ice subsistence hunting in Point Hope, Alaska. Barrow, Alaska: North Slope Borough.

Mahoney, A., 2006. Alaska shorefast sea ice dynamics. Doctoral thesis, University of Alaska Fairbanks, Fairbanks, Alaska.

Mahoney, A., Eicken, H., Gaylord, A.G., Shapiro, L., 2007a. Alaska shorefast sea ice: Links with bathymetry and atmospheric circulation. Journal of Geophysical Research, 112, C02001, doi:10.1029/2006JC003559.

Mahoney, A., Eicken, H., Shapiro, L., 2007b. How fast is shorefast ice? A study of the attachment and detachment of nearshore ice at Barrow, Alaska. Cold Regions Science and Technology, 47: 233-255.

NAS, 2006. Toward an integrated arctic observing network. Committee Report. National Academies Press, Washington, D.C., 115 pp.

Nelson, R., 1969. *Hunters of the northern ice.* University of Chicago Press, Chicago, 429 pp.

Nichols, T., Berkes, F., Jolly, D., Snow, N.B., Harbour, T.C.o.S., 2004. Climate change and sea ice: Local observations from the Canadian Western Arctic. Arctic, 57(1): 68-79.

NOAA, 2006. National Climate Data Center. http://cdo.ncdc.noaa.gov, accessed 27 June 2008.

Norton, D.W. (Ed.), 2001. *Fifty more years below zero: Tributes and meditations for the Naval Arctic Research Laboratory's first half century at Barrow, Alaska.* The Arctic Institute of North America, Calgary, Alberta and Fairbanks, Alaska, 576 pp.

Norton, D.W., Gaylord, A.G., 2004. Drift velocities of ice floes in Alaska's northern Chukchi Sea flaw zone: Determinants of success by spring subsistence whalers in 2000 and 2001. Arctic 57(4): 347-362.

NSIDC, 2006. Arctic sea ice shrinks as temperatures rise. Press release, National Snow and Ice Data Center, University of Colorado at Boulder, October 3.

Partington, K., Bertoia, C., 1999. Evaluation of special sensor microwave imager sea ice products. Proceedings, International Geoscience and Remote Sensing Symposium, Hamburg, Germany, 28 June - 2 July (CD ROM).

Pfirman, S., Haxby, W., Eicken, H., Jeffries, M., Bauch, D., 2004. Drifting arctic sea ice archives changes in ocean surface conditions. Geophys. Res. Lett., 31, doi:10.1029/2004GL020666.

Pringle, D.J., Dubuis, G., Eicken, H., 2009. Impedance measurements of the complex dielectric permittivity of sea ice at 50 MHz: Pore microstructure and potential for salinity monitoring. J. Glaciol. 55(189): 81-94.

Reimnitz, E., Dethleff, D., Nürnberg, D., 1994. Contrasts in arctic shelf sea ice regimes and some implications: Beaufort Sea and Laptev Sea. Mar. Geol., 119: 215-225.

Rothrock, D.A., Zhang, J., 2005. Arctic Ocean sea ice volume: What explains its recent depletion? J. Geophys. Res., 110: C01002, doi:10.1029/2004JC002282.

Schofield, O., Bergmann, T., Bissett, P., Grassle, J.F., Haidvogel, D.B., Kohut, J., Moline, M., Glenn, S.M., 2002. The long-term ecosystem observatory: An integrated coastal observatory. IEEE J. Oceanic Eng., 27(2): 146-154.

SEARCH, 2005. Study of Environmental Arctic Change: Plans for implementation during the International Polar Year and beyond. Report of the SEARCH Implementation Workshop, May 23 - 25, 2005.

Shapiro, L.H., 1975. A preliminary study of ridging in shorefast ice at Barrow, Alaska using radar data. Third International Conference on Port and Ocean Engineering under Arctic Conditions (POAC), University of Alaska, Fairbanks, Alaska, 1976, 1, 417-425.

Shapiro, L.H., Barnes, P.W., Hanson, A., Hoskins, E.R., Johnon, J.B., Metzner, R.C., 1987. Mechanical properties of sea ice deformation in the near shore zone. In OCSEAP Final Reports, V.72, edited, pp. 357-584, U.S. Dept. of Commerce, NOAA.

Shimada, K., Kamoshida, T., Itoh, M., Nishino, S., Carmack, E., McLaughlin, F.A., Zimmermann, S., Proshutinsky, A., 2006. Pacific inflow: Influence on catastrophic reduction of sea ice cover in the Arctic Ocean. Geophys. Res. Lett., 33: L08605, doi:10.1029/2005GL025624.

Stroeve, J., Serreze, M., Drobot, S., Gearheard, S., Holland, M., Maslanik, J., Meier, W., Scambos, T., 2008. Arctic sea ice extent plummets in 2007. Eos, Trans. Am. Geophys. Un., 89(2): 13-20.

Timco, G.W., Burden, R.P., 1997. An analysis of the shapes of sea ice ridges. Cold Regions Science and Technology, 25: 65-77.

Chapter 3. Assessing the shorefast ice: Iñupiat whaling trails off Barrow, Alaska*

Abstract

At Barrow, Alaska, local Iñupiat whaling crews annually construct a network of seasonal trails through the shorefast ice during the traditional spring hunting season. These trails originate at locations along the coast and pass through diverse ice features, including tidal cracks, ridged and rubbled ice, and new and potentially flooded ice, before terminating at the shorefast ice edge where camps are established. The safety of this hunt relies on careful observation of evolving ice characteristics from freeze-up onward and the understanding of how the interplay between ice dynamics, ice thermal evolution, and ocean and atmospheric processes leads to both stable and dangerous conditions. Partnering with Barrow whalers, a multi-year mapping of whaling trails, alongside a geophysical record of shorefast ice conditions, provides insight into how Iñupiat hunters monitor the development of shorefast ice throughout winter and spring. Individual and community assessments of ice conditions and associated risks, local knowledge and traditions, and personal preference are summarized as they relate to trail placement. This chapter also discusses how documenting human use of the sea ice environment contributes to integrated observations of arctic change and adaptation.

* Published in a condensed version as: Druckenmiller, M.L., Eicken, H., George, J.C., Brower, L., 2010. Assessing the shorefast ice: Iñupiat whaling trails off Barrow, Alaska. In: Krupnik, I., Aporta, C., Gearheard, S., Kielsen Holm, L., Laidler, G. (Eds.), *SIKU: Knowing our ice*. Springer-Verlag, New York, pp. 202-228.

3.1 Introduction

Along a 35-kilometer stretch of coastline in northernmost Alaska, the Iñupiat Eskimos of Barrow have hunted the bowhead whale for centuries (Stoker and Krupnik 1993). As the whales migrate northward in spring toward summer feeding waters in the Beaufort Sea, the ocean is covered with sea ice that is continuously responding to the forces of winds and ocean currents (see Figure 3.1). A narrow shelf of coastal shorefast ice extends out from the land into potentially dangerous waters, shaping the environment that local hunters have come to understand. Whaling crews base their hunt from a network of trails that traverse the shorefast ice (tuvaq), often leading them as many as 16 kilometers offshore. The ice conditions they experience are always changing and each year brings new challenges. Hunting efficiently, safely, and respectfully according to Iñupiat customs requires careful observation, years of experience, and the accumulated knowledge passed down from earlier generations.

By March the shorefast ice off Barrow has been shaped by several months' history of ice growth and dynamics—events that have anchored the ice to the sea floor and the coast. A short traverse of only a few kilometers from the village reveals a vast assortment of ice types, thicknesses, and morphological features (cracks, rafted ice, etc.). Interpreting the make-up of the ice in terms of safety and ease of travel partially determines where the hunters will establish their camps. Understanding whale behavior and recalling past ice conditions additionally informs the hunters' strategies. In late March the first whaling crews begin to move out onto the ice. At this time, the shorefast ice is still evolving, and over the course of the whaling season (mid-April to late May) it deteriorates from its cold winter state. Hunters carefully assess the evolving conditions in relation to safety, on-ice travel, and successful hunting.

I traveled the trails, surveyed their locations, and spoke with hunters about how ice conditions informed and shaped their hunting and travel decisions during five consecutive springs, 2007 to 2011. During this same time various components of a geophysical-based ice monitoring system were recording information on shorefast ice thickness, growth, decay and deformation. Relating these observations to those of the hunters has stimulated conversations about the specific ice features and processes that the whalers consider important, led to interesting generalizations about shorefast ice variability, and provided important considerations for how to move forward in making scientific observations of sea ice useful to the community. It is my hope that this chapter sheds light on how hunters understand and interact with sea ice under current climate conditions.

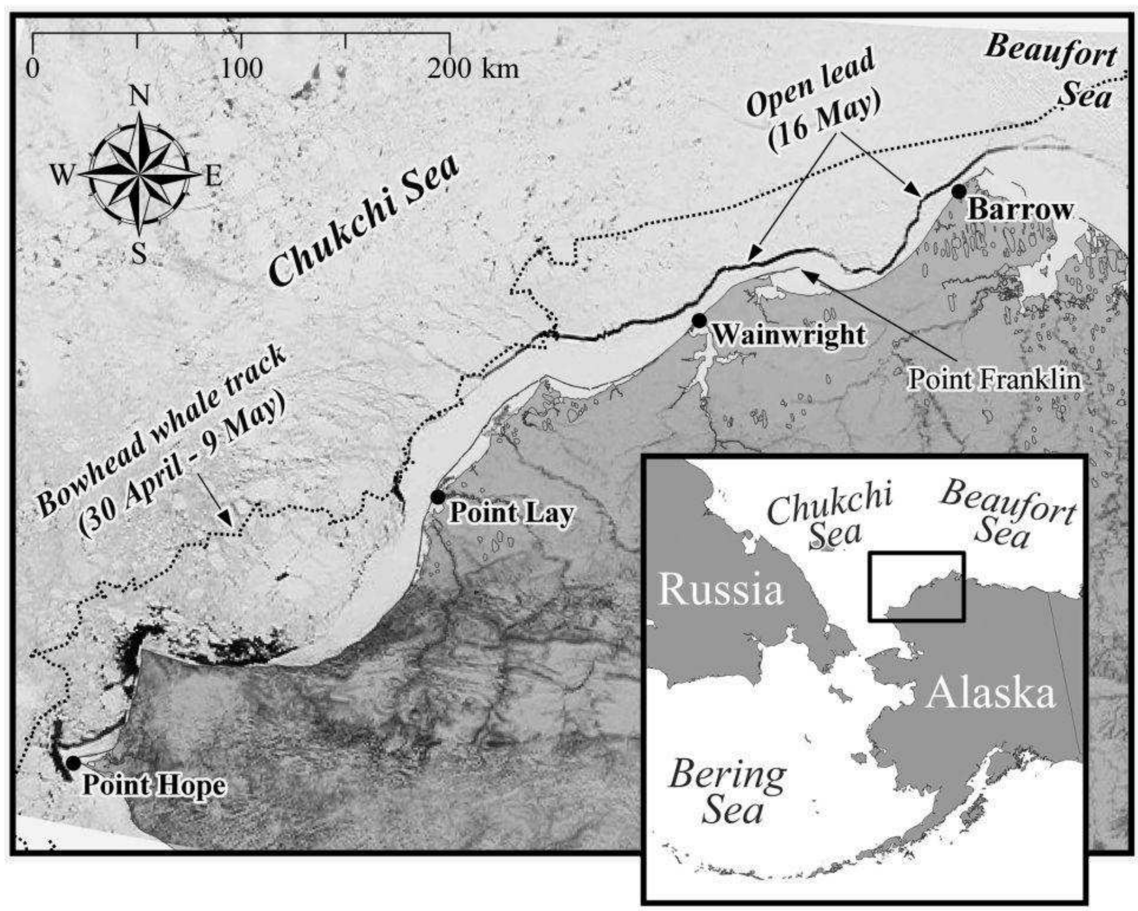


Figure 3.1 Map of the western arctic coastline of Alaska. Barrow, Wainwright, Point Lay and Point Hope are whaling communities officially recognized by the Alaska Eskimo Whaling Commission, and hunt in a similar fashion from the edge of the shorefast ice in spring. The dotted line shows the migration path of a satellite-tracked bowhead whale during the spring of 2009 (unpublished data, Alaska Department of Fish and Game). The whales typically migrate along this coastline between late March and early June, and regularly surface in open water of the persistent coastal lead system. The background of this map, a Terra MODIS (Moderate Resolution Imaging Spectroradiometer) satellite image from May 16, 2009, shows a lead opening in a pattern that mirrors the shape of the coastline.

This chapter is descriptive. However, for research aiming to bring western science together with local and traditional knowledge, it is important that a broad overview is initially achieved in order to more fully appreciate the scope of topics that may potentially serve as points of focus. Throughout this chapter, Iñupiaq terms for sea ice are used to illustrate the diversity of the Barrow whalers' ice terminology and the complexity of their knowledge. Whenever brief definitions are offered, they may not capture the full meaning and dimensionality of the term attributed by Iñupiat experts.

3.2 The shorefast ice environment

Shorefast sea ice is present off Barrow for much of the year, typically between November and July. Recent research has shown that the ice is forming later in fall and breaking up earlier in late spring (Mahoney et al. 2007a), and that multi-year ice is becoming less abundant (Drobot and Maslanik 2003). Scientific predictions for a warmer arctic and further reductions in summer minimum ice extent (and hence multi-year ice area) raise additional concerns for whether or not the "familiar" shorefast ice environment prior to the 1990s will persist. Community observations also indicate that sea ice is changing. However, these observations are made against different baseline conditions than the ones scientists may consider. Hunters understand and observe ice conditions largely in relation to how they and their ancestors have used the local ice cover for travel and hunting. Each hunter comes to understand the local environment based on his personal experiences and those of the elders who taught him. While accounts expectedly vary between individuals, a basic understanding of the primary factors that shape the local shorefast ice environment is widely shared by the community. Figure 3.2 presents a map that shows a few of the key factors that various hunters have mentioned as important.

Point Barrow (or Nuvuk), located about 10 kilometers north of the present village, extends into the waters where the Chukchi Sea meets the Beaufort. While Barrow resides on the Chukchi Coast and the community bases their spring whale hunt on that side of Point Barrow, it is not uncommon for hunters to also travel north of Point Barrow. A regional perspective is important as hunters attribute ice dynamics to winds and currents and understand that stresses in ice are often transmitted over great distances, such as from the Beaufort side of Point Barrow to the Chukchi side.

The dominant current is from the Northeast (piruġaġnaq) during most of the year. However, in mid-to-late May, there is a shift in the major current direction to that from the Southwest (qaisagnaq), and also an increase in current speed. Qaisagnaq, which derives its name from the observation that it "brings the animals", has been observed to also bring warm water that accelerates the bottom melt and break-up of shorefast ice. In 2007, while discussing ice conditions near Point Barrow, the late Arnold Brower, Sr., a Barrow elder and whaling crew captain, explained that there is more than one current that parallels Barrow's coastline. Often pieces of drifting ice of similar size can be seen side by side, yet traveling at different speeds. Somewhere near Point Barrow these currents converge with each other and also with the current

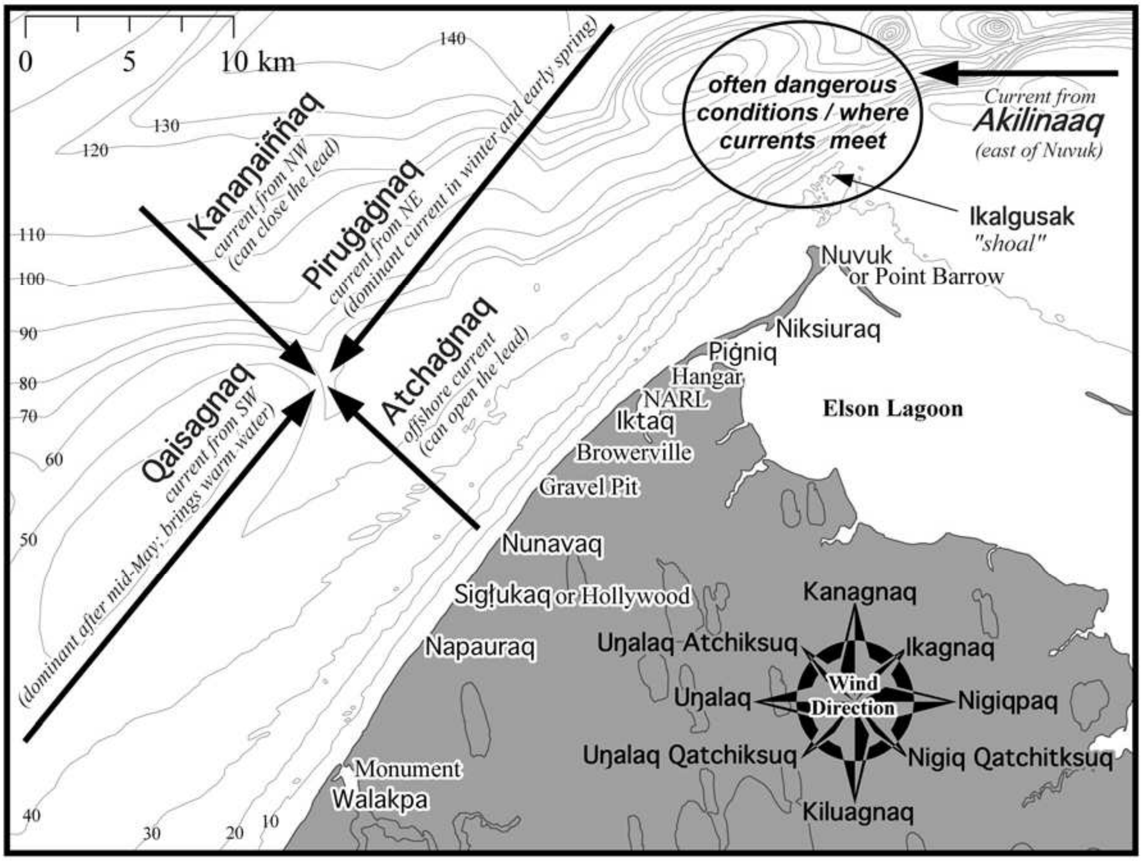


Figure 3.2 Traditional knowledge of Barrow’s currents, winds, and ice drift directions. A subset of the many traditional place names and other commonly used terms unique to Barrow are shown at locations along the coast. “NARL” refers to the site that was previously the Naval Arctic Research Laboratory. Bathymetry is shown as 10m contours.

that comes from east of Point Barrow. Joe Leavitt explained that the Iñupiaq word yuayuk describes “a place where currents meet”. During drift ice conditions, this meeting of currents can be observed by ice floes turning in circles. During open water conditions, “dunes” can be observed on the water as though it is boiling. As recalled throughout my interviews with hunters, old stories in the community tell of strong currents and ice conditions near Point Barrow that are very dangerous for spring whaling in comparison to ice conditions farther to the southwest, in the direction of the village. Traveling north of Point Barrow during an east wind is particularly dangerous. Today’s whalers often describe past experiences north of Point Barrow as defining moments for when they began to fully understand the risk of hunting on ice.

The dynamic conditions north of Point Barrow can lead to the formation of massive ridges, often through shear. These ridges are believed to ground in this area due to the presence of a shoal, known as Ikalgusak (shown in Figures 3.2 and 3.3). Joe Leavitt expressed the idea that perhaps this shoal represents a previous location of Point Barrow in the distant past. Here, these large ridges serve as a point of deflection for drifting pack ice coming from the east that could potentially impact and destabilize the shorefast ice off Barrow's Chukchi coast. When large grounded ridges near Point Barrow are absent, hunters pay special attention, watching for when leads on the eastern side of the Point close up with a strong east wind.

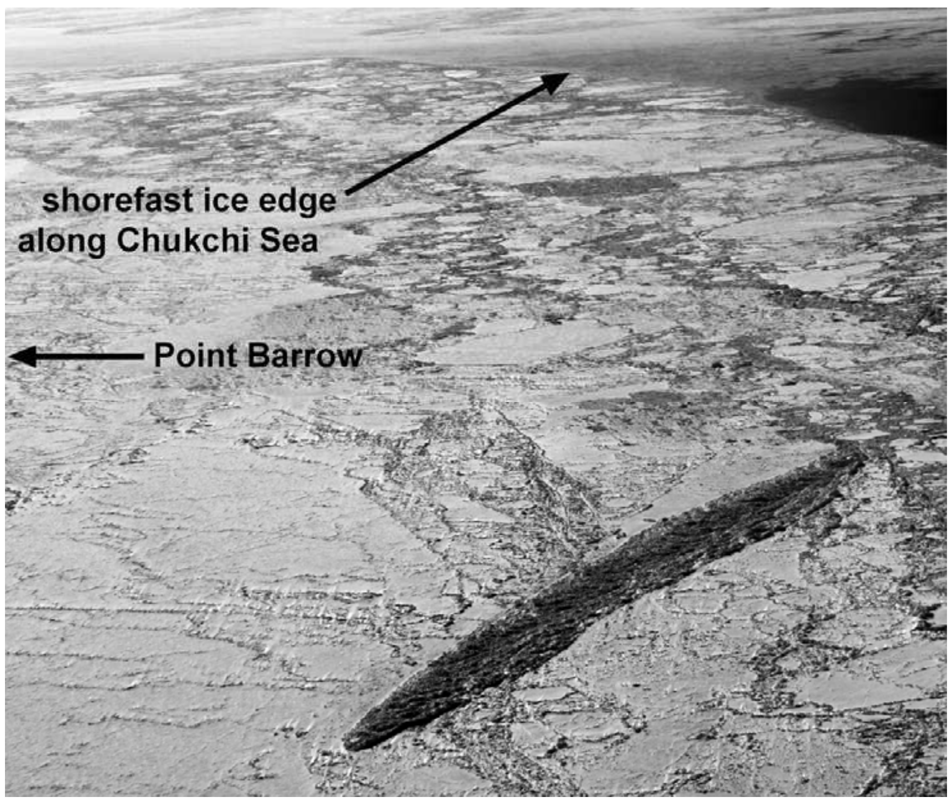


Figure 3.3 Large ridge formed at the shoal (Ikalgusak) north of Point Barrow. This photo (looking to the Southwest) was taken on April 11, 2010 during a helicopter flight.

Winds play a major role in the drift of pack ice and in determining whether or not the lead along the shorefast ice is open. Onshore and downwelling winds (NW to S) may bring in pack ice to close the lead, while offshore and upwelling winds (SE to N) may open the lead. When an offshore wind is strong enough, it can locally depress sea level by transporting water offshore, which can cause certain areas of the shorefast ice to detach when cracks form around grounded ridges (George et al., unpubl.).

There are general patterns in how the shorefast ice develops along Barrow's coastline. On the regional scale, Barrow Whaling Captain Eugene Brower explained in 2009 that the shape of the coastline between Wainwright and Barrow can influence local ice conditions. With Point Franklin providing a deflection point, Barrow's coastline north of Nunavaq bears the brunt of the pack ice moving in from the Southwest in comparison to that south of Nunavaq. (While this does not appear to be the case in 2009, as shown in Figure 3.1, an example of this is well-documented for 2011 as will be discussed in Section 3.5.5.) For this same reason, and perhaps also due to the intricacies of coastal currents, which are currently poorly understood by researchers, the pack ice typically approaches the lead edge slower and with less force south of Nunavaq than it does further north. This leads to the ice south of Nunavaq and Sigḷukaq being flatter and less rough than the ice further north. Also in this region the shorefast ice typically extends farther out than it does to the North. Once again, these are only general patterns and hunters clearly state that ice conditions are different each year.

3.3 Springtime whaling: A sequence of observations

Barrow has been the location of continuous settlements for at least 1,300 years, with periodic settlements traced back as far as 5,000 years. In the mid-1800s Yankee whalers began regular contact with the settlement at Point Barrow, and by 1890 multiple commercial whaling operations were in full swing employing hundreds of Iñupiat whalers (Braund and Moorehead 1995). When 1908 brought an end to commercial whaling, traditional subsistence whaling continued, but had been infused with technological advances, such as the bomb lance. Today, there are approximately 50 licensed whaling crew captains in Barrow that are responsible for supplying both the immediate community and their extended families across Alaska with food from the bowhead whale. Barrow whalers still use skin boats—umiat (wooden frames covered with bearded seal skins)—and operate as expert hunters by applying knowledge and skills that have been transmitted across generations for centuries. The success of the hunt relies on assessing the shorefast ice—one of the more complex, ephemeral terrains on earth.

3.3.1 Evaluating the ice in preparation for the hunt

Shorefast ice begins to usually appear off Barrow in November, and is generally quite variable in its extent through January as ice attaches and detaches. February and March are the major ice-building months. This is the time when hunters count on heavy pack ice coming in under the influence of a strong west wind to create grounded ridges. Careful attention is given to how the different regions of the shorefast ice develop (see Figure 3.4). First there is the flat ice zone (igniġnaq), which is typically either floating or bottom-fast, between the shore and ridges (ivuniq). Second, there is the zone were grounded ridges (kisitchat, which means "anchored") develop and provide the anchoring strength. These ridges may be either shear ridges (agiuppak) or pressure ridges. Multiple rows of ridges often exist between the igniġnaq and any extended floating shorefast ice (iiguaq), which is vulnerable to impact by drifting pack ice (George et al. 2004).

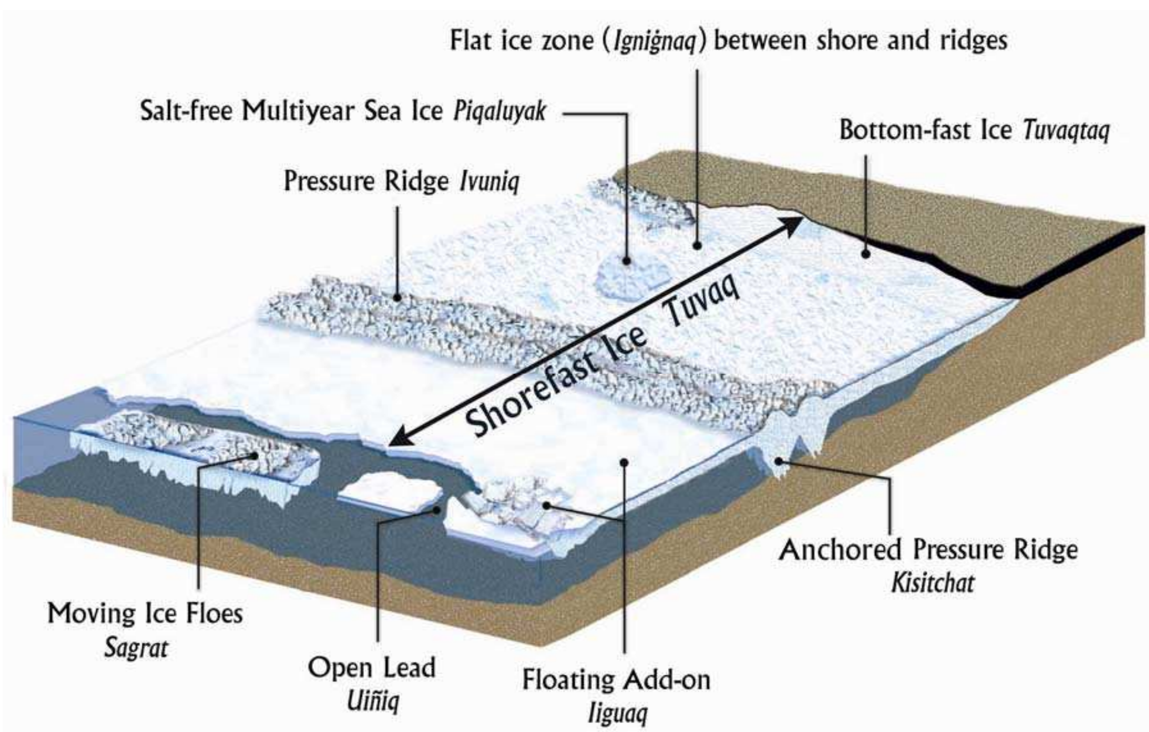


Figure 3.4 Schematic representation of coastal sea ice in the Chukchi Sea off Barrow. Both English and Iñupiaq terms for ice features are given (George et al. 2004). Modified with permission from an illustration by Deb Coccia.

Whaling Captain Crawford Patkotak explained that you have to observe the ice while thinking about what happened before. Hunters look for sediment entrained in ridges for clues that the ice scraped and grounded to the seabed as it formed. They examine the ice-makeup and question whether the ice near pressure ridges was there when the ridge formed or rather came in later. Every attachment represents a point of fusion where the ice may break out later in the season. Low winter temperatures are important for fusing the ice together. Winter is the time to watch the ice and decide where one needs to closely monitor throughout the whaling season. In addition to safety, hunters also examine the ice to determine the placement of snowmobile trails to be made from the beach to the open lead (uiñiq). Before a crew will bring their skin boat onto the ice a smooth and easily navigated trail must be built to the general area where they intend to hunt and wait for favorable conditions at the lead edge.

3.3.2 Building the ice trails

The physical process of building trails begins in late March. Both experienced and young members of the whaling crews use snowmobiles and ice picks to blaze and cut their trails across the shorefast ice according to a strategy that varies from crew to crew. A range of considerations exists for a whaling captain deciding where to place his crew's trail.

Safety and stability: The most important consideration for any whaling captain is the safety of his crew, which includes everyone from the hunters who will camp on the ice and pursue the whale to those who will come out to help with butchering and hauling meat. While every captain will agree that a successful hunt is not worth the loss of human life or of vital whaling equipment, different hunters have varying perceptions of risk. However, in general, a trail is chosen such that it traverses ice that is well grounded or securely attached to stable ice. Therefore, knowledge of the locations of cracks and points of attachment is important. It is quite common that winter seal hunters, who often travel on foot, provide detailed initial assessments of ice conditions.

Construction effort: Hunters must consider how much work it will take to build a trail. While a trail of several kilometers that connects one flat pan of ice (qaiġsuaq) to another may take only a few days work for several men, a trail of similar length that traverses extremely rough ice and multiple rows of large ridges may take several weeks. Those crews taught to go where the ice is rough, thick, and well-grounded, inevitably accept that they will work harder for their trail. It is common for several crews to work together on the same trail near the shore. Once the trail nears the edge, however, the crews will split their efforts to build individual trails to the ice edge that will branch off from the main one.

Navigability and potential for evacuation: It is important to be able to drive a snowmobile quickly along a trail, especially when in need of swift evacuation off the ice. In consequence, trails are made as straight and as smooth as possible, utilizing large interconnected pans of flat ice, and are built wide enough to allow two snowmobiles to pass each other. When describing these strategies for Wainwright in the 1960's, Richard Nelson (1969) discussed the use of refrozen cracks as a way to efficiently travel through areas of highly deformed sea ice. An initial trail is a product of scouting, which means it is usually not as direct as the crew would like. It is often necessary to straighten and improve certain sections once the final trail destination is determined near or at the ice edge. Trails usually approach the lead edge nearly perpendicularly to the coast since this represents the shortest distance to land. Alternative evacuation routes are often considered, resulting in more than one trail leading to the beach or to safer ice. It is in this region of safe ice that a crew will often place their naŋiaqtuġvik, which is a place where they store their whaling equipment and camp when waiting for the lead to open or for other favorable conditions. As Lewis Brower explained, the naŋiaqtuġvik is placed on "ice that can withstand any weather".

Ice edge conditions: Conditions at the edge are also critical for a successful hunt. Hunters prefer to find thick heavy ice (or rafted thinner ice) where they can place their camp, build a boat launch, and pull up a whale. Hunters indicate that ice thicker than 1.5 m is needed to haul up a large whale more than 16 m (53 ft) in length. Some prefer to find ridges near the lead that can be used as a perch to watch the water. Trail building when the lead is closed requires hunters to utilize observations made earlier in the season to make predictions for where the edge will be when the lead eventually opens. Even at times when the lead is open, ice conditions are not always ideal due to unstable or thin add-ons (iiguat; plural form for iiguaq), leaving the crews in wait for more suitable ice edge conditions to develop.

Proximity to other crews and distance from town: Some crews prefer to hunt in places far removed from others as they prefer solitude and because they believe it promotes self-sufficient hunting practices. When a crew is on their own, they must focus on killing the whale with the first strike, as they cannot rely on help from other crews. Conversely, some crews prefer to remain close to assist each other when needed or to share favorable ice and trail conditions. The price of fuel and the time it takes to get to a hunting location also play a role in trail placement.

Forecast of late spring conditions: Hunters must consider both the conditions at the time they build their trail and those that will be encountered toward the end of the season. A trail that crosses large flat pans of thinner ice is at greater risk of having the ice become dangerously thin once air temperatures warm, snow melts, and the warm current from the Southwest arrives. Some may build trails on top of ridges and keep on higher elevation ice for as long as possible. The advantage is not only that they can see greater distances to landmarks and open water but also because it reduces the likelihood of the trail being eaten away by warm water or snowmobile traffic. In contrast, other crews may decide to place their trail in the lower elevation ice between and throughout ridges since the ridge walls serve as side ramps to the trail and prevent heavily loaded sleds from tipping.

Bowhead whale behavior: Understanding how the whales behave as they migrate along the ice edge also informs the hunter where to place his camp. When predicting where a whale will surface, hunters employ different strategies. Barrow elder Warren Matumeak explained that whales will swim beneath young thin ice, avoiding large ridge keels, and will surface in embayments along the edge (kaŋikḷuk) (see Figure 3.5). "Camping on the north side of these embayments and facing south" (manilinaaq) provides a good place to watch whales coming toward you and a good place to launch a skin boat. In turn, iluliaq refers to a location where you have only a view of whales traveling away. There are also hunters that prefer to place their camps at promontories along the ice edge (nuvuġaq) since these tend to provide good visibility and access to whales that swim from promontory to promontory and bypass embayments. Some hunters have also been taught that the whales are attracted to thick multi-year ice because it is shiny and may also provide feeding advantages. It is believed that ice with deep keels (thick multi-year ice or ridges) causes the water to churn and stir up krill.

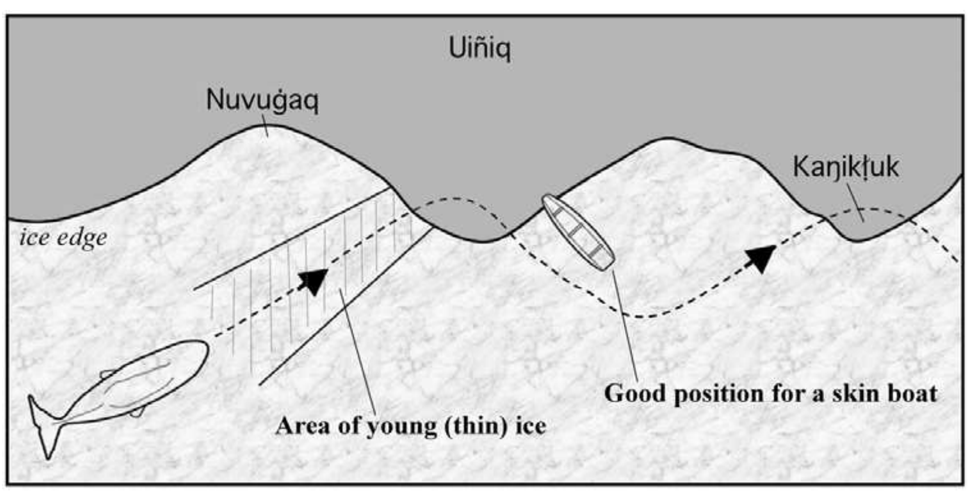


Figure 3.5 Likely path of a bowhead whale as it swims along the ice edge. Kaŋikḷuk is an embayment along the ice edge. Nuvuġaq is a promontory of ice extending out from the lead edge. Adapted with permission from a sketch by Warren Matumeak.

Elders' knowledge: In the end, the decision on where to place an ice trail for spring whaling may most strongly be influenced by tradition and what was taught by elders. Arnold Brower, Sr. noted that he learned from his elders to hunt in the North early in the season before the current from the Southwest strengthened, thus minimizing the risk of losing a struck whale that is carried under the ice by the current. When the current intensified in mid-to-late May, he would move his crew to the South. Whaling Captain Nate Olemaun discussed how he was taught that the waters off Sigḷukaq are rich feeding waters and are a good place to see whales. As noted earlier, many captains prefer to hunt south of the dangerous and unpredictable conditions north of Point Barrow, despite acknowledging that this is a good place to see whales since open water can always be found nearby, either on the Chukchi or Beaufort side.

The trail network built by the Barrow whaling community evolves throughout the season as ice conditions continuously change and crews move locations. To assist in navigation most crews use distinct markers for their trails, such as a painted wooden stakes or flags. Markers often note the crews' names. Trails are typically referred to by the name of the captain or crew or by the trail's point of origin, using the place-names and landmarks shown in Figure 3.2. Local etiquette dictates that if a crew wishes to use a pre-existing trail the captain of the crew that built the trail should be asked.

3.3.3 Observations at the ice edge

When crews are "along the edge of the ice observing the environment and looking for whales" (nipaaq) they must continuously monitor the ice on which they are camped and the pack ice beyond, both of which are influenced by wind and current. To monitor the currents, hunters typically drop a sounding line into the water. Barrow whaler Joe Leavitt explained how an increase in a current's strength starts at the bottom and develops upward over the course of a few days, providing advanced notice of potentially precarious ice conditions. In particular, ice moving against the wind is an indication that the current is moving with considerable strength. Currents, especially when bringing in warmer water, can lead to the break-up of ungrounded ridge keels near the edge resulting in the "throwing-up" of ice into the lead (muġaala; see Figure 3.6), presenting a danger to boats. When the lead is closed, these broken pieces can remain under the ice, only to emerge when the lead reopens.

A "water-sky" (a dark cloud band along the horizon that indicates open water; see Figure 3.7) serves as a way to monitor for incoming pack ice that may present a threat to those at the ice edge.

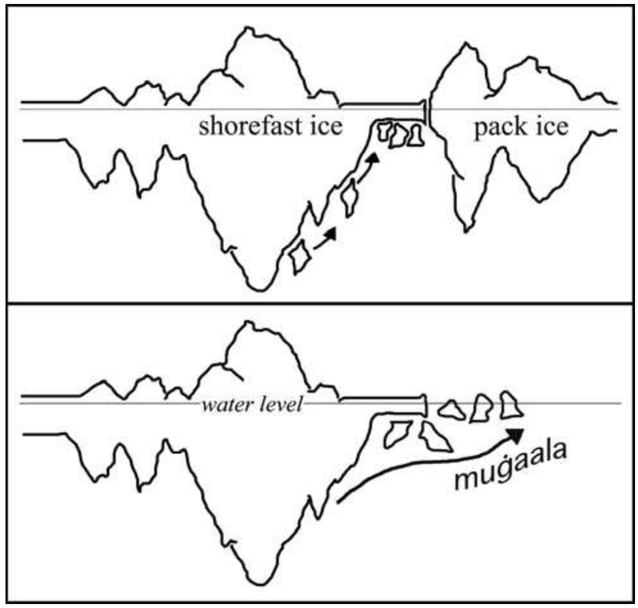


Figure 3.6 Muġaala ("throwing-up" of ice) at the ice edge. Following the opening of the lead as pack ice drifts away, loose pieces of ice detach from ridge keels (or from the bottom of rafted ice) and float up beneath the level ice or into the open water. When such pieces hit the level ice, they can produce a loud sound that is often misinterpreted by a hunter as a crack forming in the ice. Based on a description provided by Lewis Brower.

If the dark band begins to disappear, the pack ice is approaching. This is of particular concern when camped on iiguaq. In these conditions a whaling crew is forced to retreat to safer ice. When camped on multi-year ice at the lead, encroaching pack ice presents less of a hazard. The water-sky not only indicates open water off Barrow, but can also be used to track open water north and east of Point Barrow, which is important when ice near the Point is weakly grounded, as mentioned earlier.

It is also important to monitor the current's strength to avoid striking a whale when conditions may prevent the crew from being able to haul it to the ice edge for butchering. A strong current, especially near Point Barrow, has been known to defeat the efforts of several boats attempting to haul a single whale to stable shorefast ice. A decision "to launch a boat from the ice edge to go to the whale's path" (pamiuqtak) must be done only when conditions present an acceptable risk for the entirety of the hunt, which ends when the meat, muktuk, equipment, and people are on safe ice.

Figure 3.7 Dangerous open water on a whaling trail. Such “holes” may be attributed to heavy snowmobile traffic and warm water melting the ice from beneath. A “water sky” can be seen on the horizon, indicating an open lead. Photo by M.L. Druckenmiller.

3.3.4 Monitoring the shorefast ice

Hunters carefully watch the shorefast ice along their trail throughout the season. There are several features that they pay particular attention to, such as previously identified cracks, newly formed cracks in the flat thin ice near grounded ridges, and areas where slush ice has been incorporated into the shorefast ice. Barrow whaler Lewis Brower told of how his father Arnold Brower, Sr. had taught him to build small handmade rows of compacted snow to perpendicularly extend across cracks so that fracturing or disturbances to the snow piles would serve to monitor the cracks’ activity. Cracks or weak points where new ice has been added to the shorefast ice become particularly important in determining where the shorefast ice may break-out. Katak, which means “to fall,” is the Iñupiaq term used to describe a sudden drop in sea level where the floating ice near grounded ridges cracks and may lead to a break-out (George et al., unpubl.; Norton 2002).

Another feature that must be monitored is muġaliq, which is a conglomerate of slush, brash ice, and snow that forms during periods of ice shearing. This ice can be found anywhere throughout the shorefast ice zone since it can freeze in place as the shorefast ice evolves throughout the year. These areas are observed closely since they represent a particular danger as spring progresses. When frozen muġaliq warms it rapidly looses its integrity and acquires a quicksand-like consistency, breaking in a quiet manner. A quiet break-up process is particularly disconcerting to hunters since they often rely on sounds to warn of potentially threatening conditions, such as cracking and ridging. Muġaliq differs from qinu, which also refers to slush ice piling up and making ice (Nelson 1969). Qinu forms during the early stages of freeze-up in late fall or early winter, and, due to cold temperatures, develops into ice that is considered stable, especially in comparison to muġaliq.

By mid-to-late May, warmer air temperatures and the arrival of the warm current from the Southwest escalate the transition of shorefast ice toward increasingly unsafe conditions. The "glue" that is holding the weak areas together begins to release. Old cracks melt out, and newly formed "cracks open up, never to refreeze" (nutaqqutaq). After the snow melts, trails develop dark areas of water or extremely thin ice, where snowmobiles can easily fall through (see Figure 3.7). Also by this time, the majority of passing whales become increasingly large and difficult to pull up onto thin ice at the edge. Kasruq ("when one is done with whaling and pulls their gear off the ice") takes place when Barrow has either reached its quota of strikes or when ice conditions are no longer suitable for whaling.

3.3.5 Looking for old ice

The retreat and thinning of the Arctic's perennial ice, observed each September as the pan-arctic ice extent is at its annual minimum, is a clear indication that conditions in the Arctic have changed over the last 40 years. Since 1979 when satellites first began monitoring arctic ice, the extent has declined as much as 10.2% per decade (Comiso et al. 2008). After the mid-1970's, hunters along Alaska's Chukchi coast also began observing that ice conditions, in particular shorefast ice morphology and stability, began to deviate from what was considered normal for prior decades, as reflected in direct observations and elders' teachings (Norton 2002). In large part, these observations note that multi-year ice, which here refers to ice that has survived at least one summer's melt season, was becoming less abundant over the long term. Figure 3.8 shows multi-year ice near Point Barrow.

Both hunters and scientists view the presence or absence of multi-year ice as an indicator of change and as proxy for a range of processes related to stability and decay of coastal and offshore

Figure 3.8 Multi-year ice near Barrow. Whaler Roy Ahmaogak is shown standing in front of piqaluyuk that grounded near the shoal north of Point Barrow in 2009. Roy stated that "Ten years ago, the reduction in multi-year ice was not so noticeable. But in recent years we have seen a large disappearance of multi-year ice. I was surprised to see two-story piqaluyuk north of Nuvuk this year." The lower panel of images presents three QuikSCAT satellite scenes from December 1 of 2006, 2007, and 2008—prior to the whaling seasons discussed later in this chapter. The regions of ice appearing bright—corresponding to higher radar backscatter— north of Alaska can be interpreted as multi-year ice. In general, the amount of multi-year ice drifting near Barrow at this time of year is related to the amount of multi-year ice incorporated into the shorefast ice environment, which forms around this time. Photo by M.L. Druckenmiller.

ice. Scientists view multi-year ice as important for regulating the amount of solar energy that enters the ocean over the course of the summer and early fall, thus partially controlling the growth conditions for new ice in late fall. In the coastal environment, multi-year ice assists in the formation of shorefast ice by providing anchoring points. When winter approaches and the prevailing clockwise circulation pattern in the Beaufort Sea brings multi-year ice south- and westward, multi-year floes enter the coastal region during a time when ice dynamics and the growth of new ice build shorefast ice. The degree to which these processes coincide determines the amount of multi-year ice entrained into the shorefast ice zone.

With perennial ice retreating further to the North and less multi-year ice present during fall freeze up (Maslanik et al. 2007; Nghiem et al. 2007), the period of stable shorefast ice has grown shorter as well. A widespread concern of the Barrow community is that with the loss of multi-year ice, ice conditions will become increasingly unfamiliar and the hunting season will shorten. In the past, the whaling season often extended into the month of June, while in recent years the hunt has concluded around the third week of May. Crawford Patkotak, for instance, recalled that in 1987, a year with a lot of heavy multi-year ice off Barrow, his father Simeon Patkotak, Sr. landed a 16 m (52 ft) whale on June 15.

Whalers consider the advantages and disadvantages of multi-year ice. Hunters, similar to arctic engineers, appreciate the physical properties of multi-year ice and understand that it possesses greater strength than more saline first-year sea ice, but that it is also much more brittle and can shatter upon impact or as a result of a build-up of internal stresses due to surface cooling or heating. When hunters discuss multi-year ice, it is often noted that it is dangerous to camp on for this reason. However it is also often referred to as a stable platform to base a hunt from at the lead edge. This apparent discrepancy comes from the fact that whalers do not group all multi-year ice into one class. Ice is not simply first-year ice or multi-year ice. In fact, “multi-year” ice is not a term commonly used by Barrow hunters. Piqaluyuk is the term used to refer to multi-year ice that is salt-free and serves as a preferred source of drinking water. Large pans of this type of salt-free ice may shatter upon impact. Tuvaġruaq is a large region of old ice (perhaps often “old” first-year ice or second-year ice, and younger than piqaluyuk) that is stable and won’t shatter. Some hunters describe tuvaġruaq as not only a single type of ice but rather as a stable conglomerate of different types, potentially even of piqaluyuk and younger thin ice. This type of ice, when found along the edge, is resistant to break-out and is suitable for pulling up a heavy whale. However because of its thickness and associated freeboard, a ramp (amuaq) must be cut at the edge in order to pull the whale from the water.

3.4 Monitoring and mapping the ice trails

The research presented in this chapter is part of a broader effort to put in place a coastal sea ice observatory at Barrow that addresses both scientific research questions and the information needs of the community and other stakeholders that conduct activities on sea ice (Druckenmiller et al. 2009; Eicken et al. 2009). A key aspect of the observatory is to examine how geophysically derived ice thickness measurements and the monitoring of near-shore ice movement and deformation are relevant to the whaling community's springtime assessments of ice stability, safety, and hunting conditions. A coastal radar mounted on a building that overlooks the shorefast ice where many of these trails are located monitors the movement and stabilization of ice throughout the year. Collaboration with hunters and the community has enabled data collection during a time when they are most active on the ice.

Between 2001 and 2006, the North Slope Borough Department of Wildlife Management maintained periodic records of where and over what types of ice the community placed ice trails during spring whaling. After a suggestion that a more thorough and complete mapping of the trails take place each spring, I began this effort by mapping the ice trails during the spring of 2007, and continued through spring 2011. The trails were traveled by snowmobile with a handheld Garmin GPS (geographic information system). Using ArcGIS, a collection of GIS software products, the tracks were plotted and placed on recent SAR (synthetic aperture radar) satellite images to produce maps for the community. With input from the community and iterative improvements, these maps have evolved into a product that is useful for on-ice navigation, general ice-type discrimination (flat ice versus rough ice), and as a reference for Barrow's Search and Rescue operations.

With permission from the individual whaling crews, continuous ice thickness measurements were made along most trails using an electromagnetic-induction device (Geonics EM-31 conductivity meter), which estimates ice thickness by detecting the distance between the surface of the ice to the sea water below. This device was placed on either a wooden sled (2008 and 2009) or plastic sled (2010 and 2011) and hauled along the trails to provide quick indirect measurements (see Figure 3.9). Measurements are most accurate (to within a few percent of total thickness) over un-deformed ice less than 3 m thick in comparison to thicker, rough ice, such as ridges, but still provide detailed information about ice thickness variations across the entire extent of shorefast ice (Haas et al. 1997). While this chapter presents an overview of the data, a specific discussion of how these measurements relate to changing ice conditions and the responses of the hunting community will be discussed in Chapter 5.

This is not the first such project to map sea ice travel by high arctic communities. Other studies have done so (Aporta 2004; Tremblay et al. 2006) and likewise describe trail breaking and

Figure 3.9 Snowmobile hauling a sled with the ice survey instruments. Shown here is the EM-31 conductivity meter that measures ice thickness, a highly accurate differential GPS, and a radar-reflector mast, which allows the measurements to be located in the imagery collected by the coastal radar in downtown Barrow. The skyline of Barrow can be seen in the distant background. Photo by M.L. Druckenmiller.

navigation of these temporary landscapes as requiring an experienced ability to discern reoccurring environmental patterns.

3.5 A brief survey of weather and ice conditions during five years of whaling

Each year brings new and unique ice conditions to Barrow, and with each year a story can be told about how the community interpreted these conditions and responded during the spring whale hunt. From 2007 to 2011, I visited Barrow each spring to investigate ice conditions, map the ice trails, and speak with hunters.

3.5.1 Spring 2007: Successful whaling on thin ice following a break-out

The 2007 whaling season was very successful with Barrow landing 13 whales, including a record number of small juvenile whales, known as ingutuks. The locations where many of the crews chose to hunt demonstrated two important points. First, hunters tolerate ice conditions that may first appear unsafe if other conditions—the wind, currents, and tides—are favorable. The risk associated with specific ice conditions clearly relates to the length of time a hunter may decide to stay on the ice in that area. Second, hunters choose their camp locations based on not only ice conditions but also on whale behavior.

On March 31, one week before crews began constructing their trails, a break-out event occurred in the shorefast ice off Barrow (see Figure 3.10). Immediately following this event, adjacent first-year ice from south of the location piled up, and replaced the ice that broke out. This ice, despite being quite thin relative to the shorefast ice to the North and possessing few grounded ridges, remained in place throughout the entire whaling season and provided the location where most of Barrow's whales were landed (Druckenmiller et al. 2009). This circumstance may be in part due to the observation of one hunter that the whales were following the edge of the southern lead and overshooting the crews camped at the lead edge further north. Barrow reached its quota on May 25 and the ice broke out again on May 28 at approximately the same location as on March 31. Figure 3.10 shows the area of shorefast ice present between these break-out events. Also shown in this figure are the trails that traversed this region and a radar image from the March 31 break-out as recorded by the Observatory's coastal radar.

Barrow whaler Joe Leavitt, along with elders Arnold Brower, Sr. and Wesley Aiken, observed that this first-year ice was held in place by only a few "key" ridges and that favorable conditions allowed the community to successfully whale in this area. Except for between May 7 and 13, the wind throughout the season (see Figure 3.11) allowed the lead to remain open and prevented pack ice from colliding with the shorefast ice. Prior to the May 28 break-out, however, the trails in the South were worn dangerously thin by large amounts of snowmobile traffic and previously refrozen cracks began to open, which may have significantly contributed to the second break-out (Druckenmiller et al. 2009). After the trails in the South deteriorated some crews moved to the trails in the North to take advantage of safe ice conditions persisting later into May.

3.5.2 Spring 2008: Whaling in the North long after southern trails deteriorate

During the 2007-2008 ice year, stormy conditions during the period when ice moved in and stabilized along the coast contributed to a rough shorefast ice cover composed of highly deformed thin first-year ice. In some areas, ridges were exceptionally close to the beach due to the high winds driving these ridges near shore. This was particularly evident off Nunavaq, where some

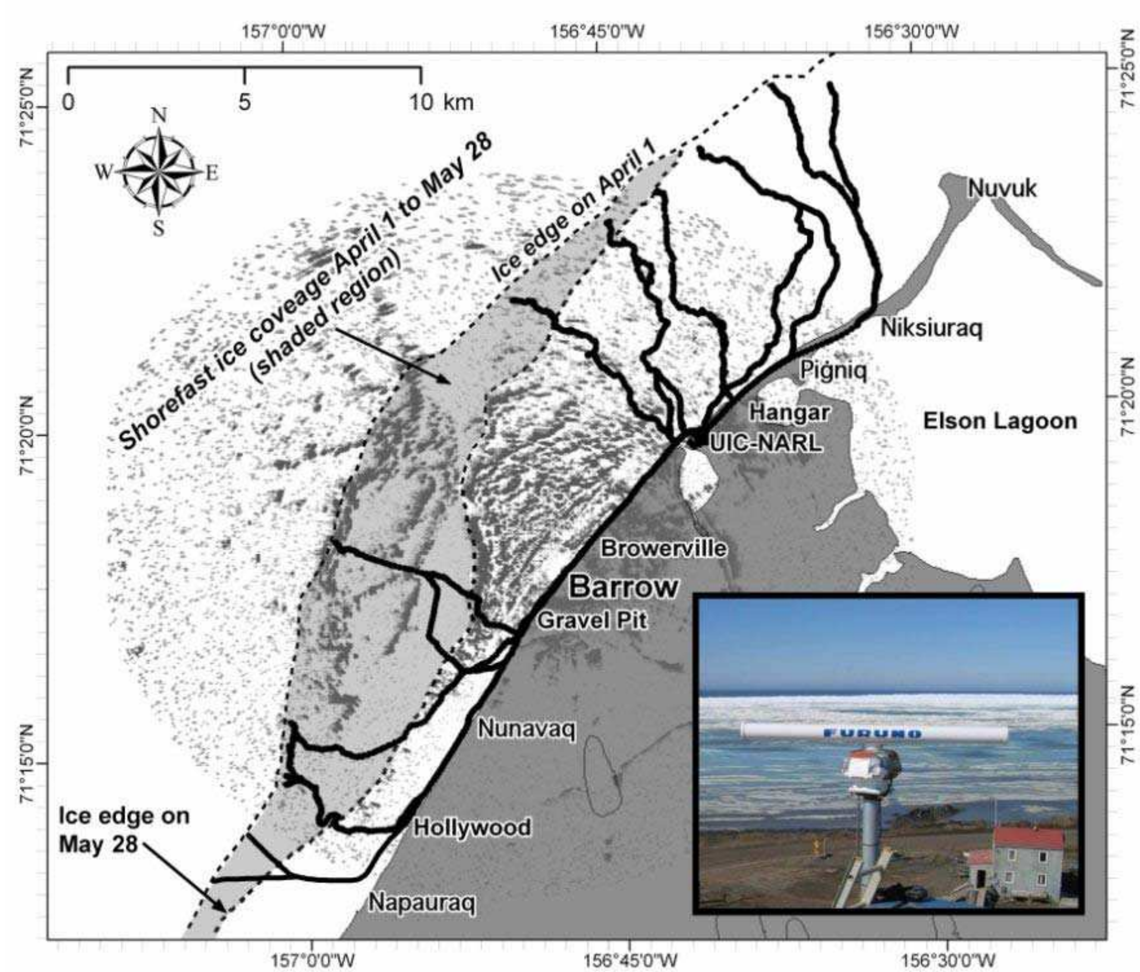


Figure 3.10 Map of the 2007 whaling trails. Many of the trails traversed the region that existed in the shorefast ice between break-out events on March 31 and May 28. The background in this image shows a sample radar backscatter image (dark speckles represent ice features with a vertical profile) as recorded during the breakout on May 28. The location of the main trail off Napauraq was hand drawn after the whaling season ended based on input from members of the community. The 10 kW X-band Furuno marine radar in downtown Barrow is shown in the lower right photo.

ice had even blown up onto the beach. Whaling Captain Harry Brower, Jr. explained that there was a repeated sequence of ridge building followed by ice coming in to add-on that contributed to a rough but stable ice cover. Brower decided to place his trail off Nunavaq (see Figure 3.12) because the ice off NARL was too rough.

Cold conditions in early April helped to provide stable shorefast ice at the start of whaling. Similar to 2007, but in stark contrast to 2009, 2008 experienced a dominating east wind that kept the lead open (see Figure 3.11). Most crews encountered good conditions in late April and early

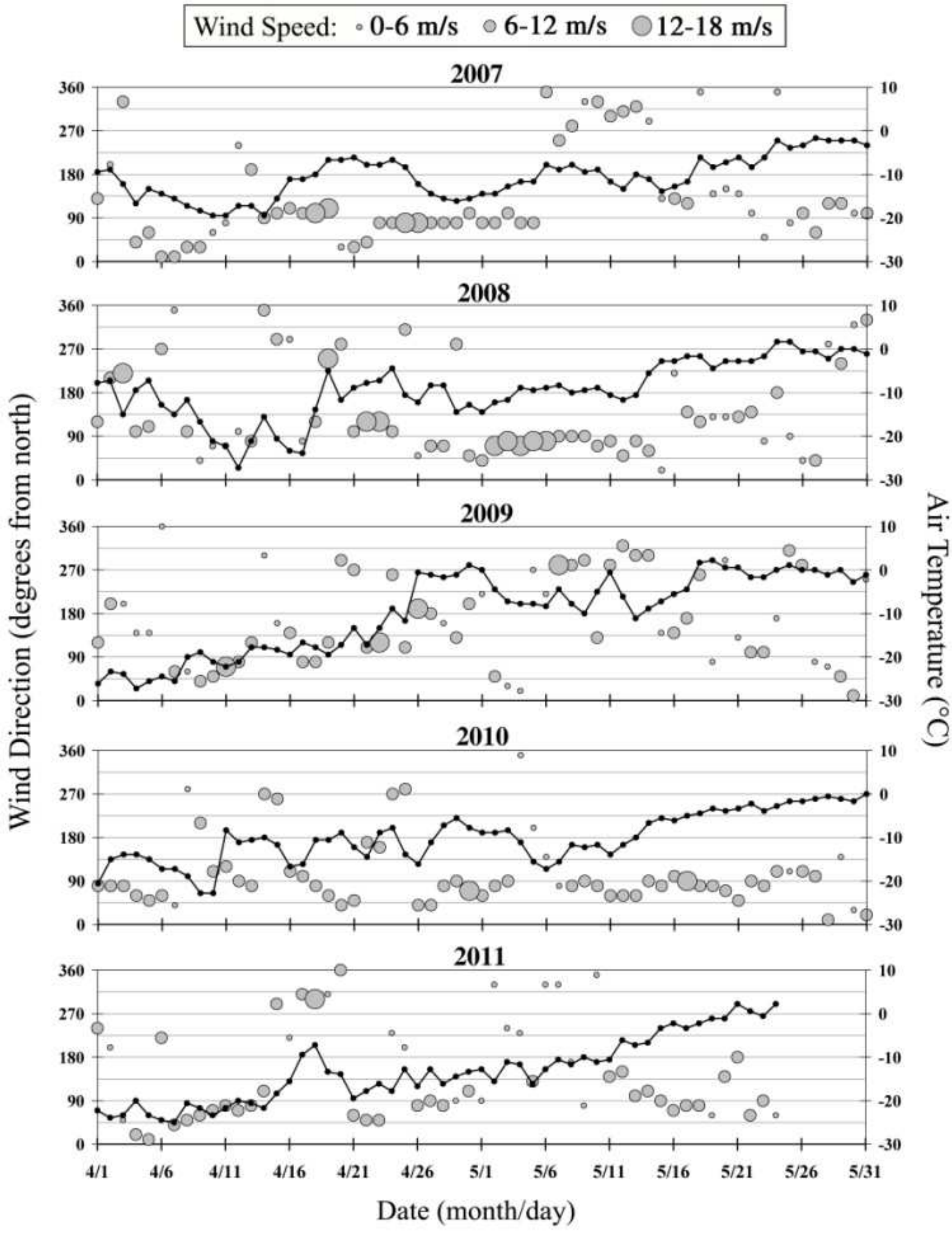


Figure 3.11 Winds and air temperature during the 2007-2011 whaling seasons. Wind direction and speed (maximum 2-minute readings) and air temperature (daily averages) are denoted by the grey circles and solid lines, respectively. Data was recorded at the Post-Rogers Memorial Airport and accessed from the National Climate Data Center.

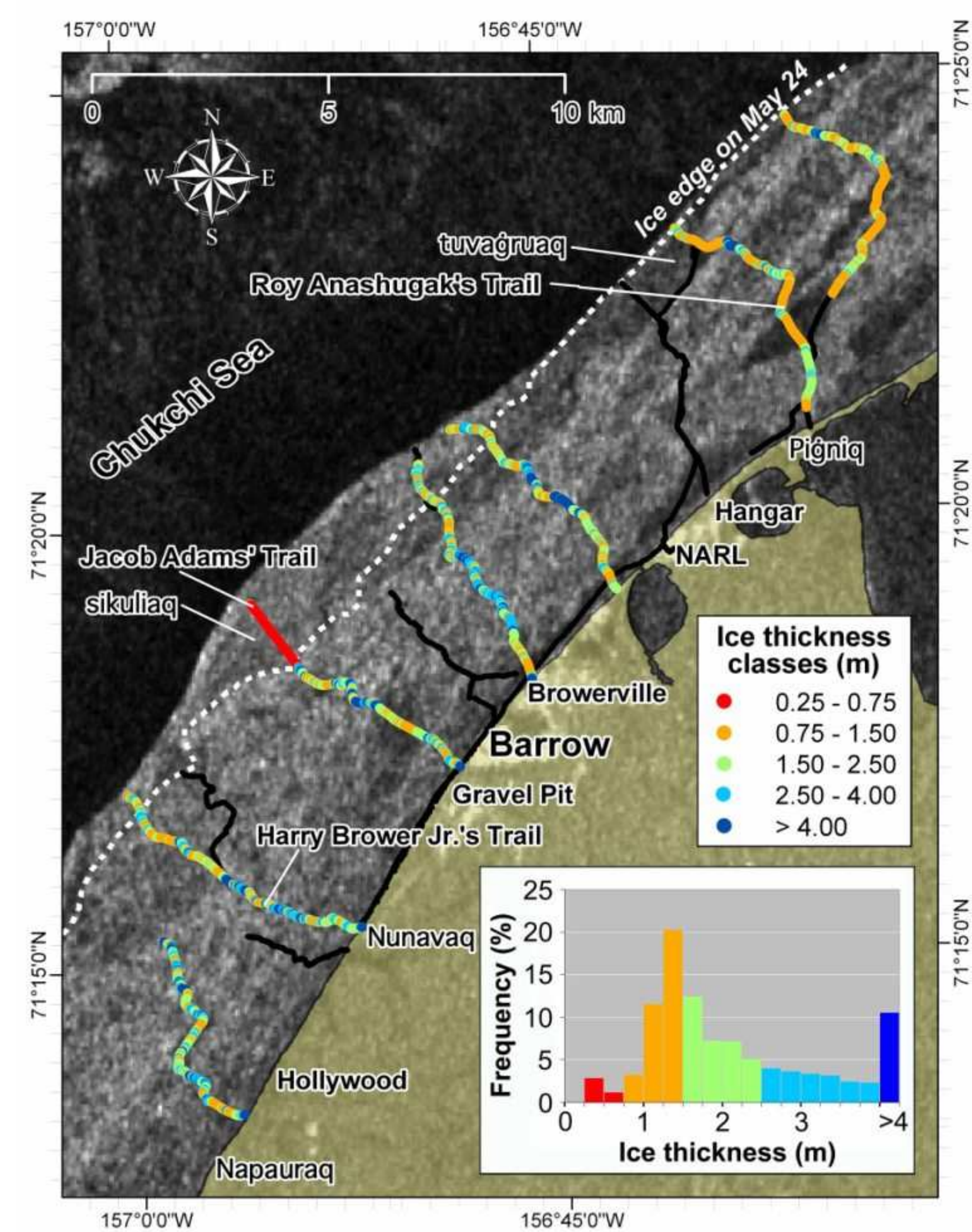


Figure 3.12 Map of the 2008 whaling trails. Trails are shown here with ice thickness data overlaid on select trails where measurements were made. The two trails south of Nunavaq were not fully mapped since they were incomplete at the time of mapping in early to mid-April. The trail off Barrow was abandoned before making it to the ice edge. The SAR image, acquired by the RADARSAT-1 satellite and provided by the Canadian Space Agency, is from April 5, 2008.

May, allowing Barrow to catch a lot of whales during this period. The first whale was landed by Eugene Brower's Aalaak Crew on April 26. However, while the east wind tended to keep the lead open, it also presented a hazard—crews pulled off the ice when offshore winds became strong (12 m/s or 25 mph) believing that such a wind can drop the water level and lead to a break-out as floating ice cracks away from grounded ridges.

Whaling Captain Tom Brower, III reported that in the first week of April a late-season snowfall, which contrasts from a more firmly packed winter snowfall, led to hazardous conditions. First, the fresh snow served as an insulating layer allowing the warm currents to more efficiently melt the thin ice from below. Later in May, when air temperatures increased, the snow quickly melted, which then in turn accelerated surface ablation through enhanced solar heating. Crews that were unable to land whales earlier in the season concentrated at the trails north of Browerville as those to the South became dangerous with areas experiencing bottom melt by warm water and eroded thin from snowmobile traffic. Brower reported having to abandon their trail off Napauraq in early May only after a few days of heavy use.

Figure 3.12 shows the 2008 trails and where ice thickness measurements were made during the season. While data are useful from the standpoint of tracking long-term trends in the thickness distribution of shorefast ice, the data also assist in understanding how different types of ice are used by the community. For example, Figure 3.13 shows the cross-sectional thickness profiles from two trails. The thin ice at the end of the Jacob Adams's trail was chosen for a camp since it was identified as flat ice where whales would be swimming beneath (see Figure 3.5 and related discussion) and surfacing at the edge. Their crew, amongst many others, decided this sikuliaq (young ice) was a good place for a camp. However, they reported having to retreat to their naŋiaqtuġvik (safe camp; labeled in Figure 3.13) multiple times when the west wind brought in the pack ice and when the strong east wind threatened to drop sea level and break the extended floating ice from the grounded ice. Significant portions of this sikuliaq broke off following impact with pack ice brought in with the west wind on April 25. However, the ice remained safe and allowed several crews to stay camped there. Adams landed a 9 m (30 ft) whale on May 7, just before the remainder of the sikuliaq broke out. Adams noted that such ice is suitable for pulling up a whale approaching 12 m (40 ft) in length, but would not be sufficient for a whale of 15 m (50 ft).

By mid-May, crews abandoned Adams' trail since newly deformed rough ice at the edge prevented easy access to open water. As previously mentioned, many crews moved to the trails north of Browerville. Older, thicker, and more stable flat ice (tuvaġrauq) near the edge allowed

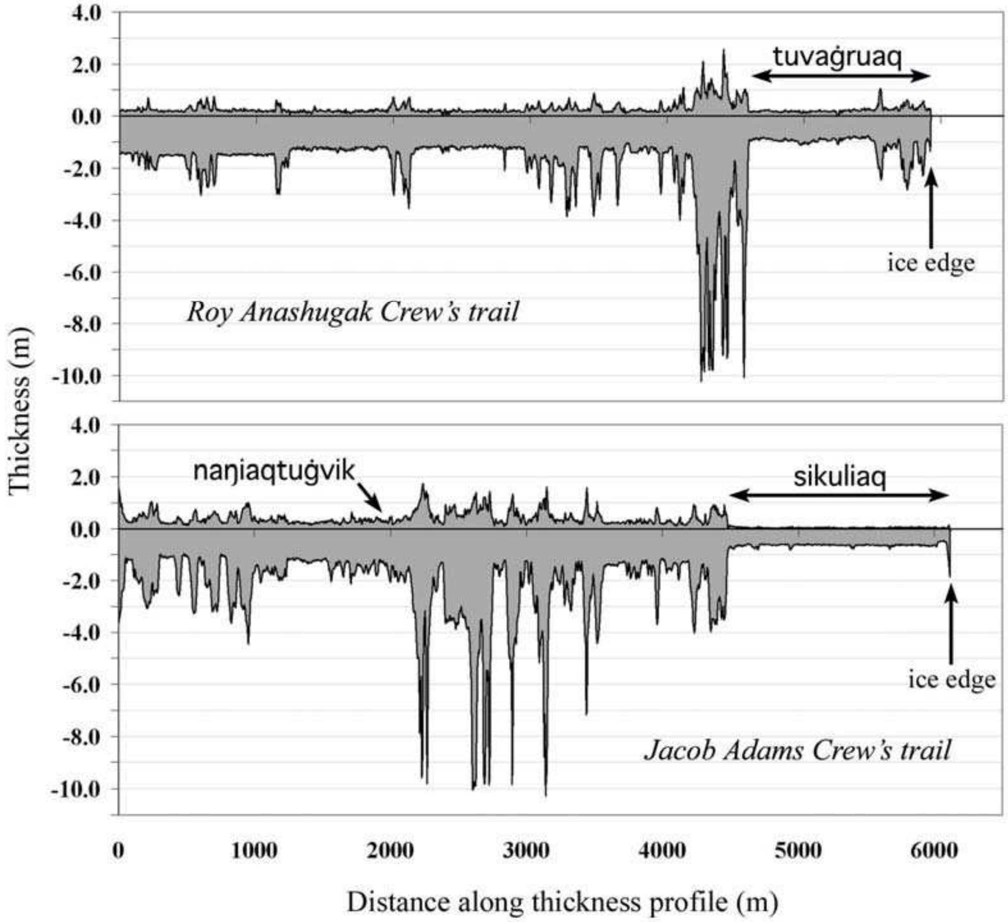


Figure 3.13 Cross-sectional ice thickness profiles along two different whaling trails. The 2008 trails of Roy Anashugak Crew and Jacob Adams Crew were measured on April 5 and 7, respectively (see Figure 3.12). Labeled features are based on interviews with Jacob Adams, Herman Ahsoak, and Gordon Brower. The level ice in the zones labeled "tuvaġruaq" and "sikuliaq" had average thicknesses of 1.0 and 0.5 m, respectively. The location of the ŋaŋiaqtugvik, or "safe camp", is shown for Adams' trail but was not documented for Anashugak's trail. Differential GPS was used to survey the surface elevation and an EM-31 conductivity meter was used to measure ice thickness. True thickness is the total thickness of ice above and below the water line, which is at zero. The proportionality between the x and y axes is such that the thickness is emphasized. Ridge thicknesses over 4 m are underestimated by up to 30 % due to instrument limitations (Haas 2003).

crews to easily connect these trails together near the lead (beyond the last row of ridges) with secondary trails (not shown in Figure 3.12). This enabled hunters to travel between camps without the need to come a long way back toward shore in order to get on another trail. Also, connected trails always provide more numerous escape options in the case of dangerous conditions. Unlike the sikuliaq further to the South this tuvaġrauq remained in place into late May, beyond the end of the whaling season.

3.5.3 Spring 2009: West wind leads to unsuitable ice edge conditions

The shorefast ice of 2009 was representative of typical ice conditions in recent years with a few noteworthy differences, which are discussed later in this section. Off NARL and Browerville the shorefast ice was heavily ridged and deformed with few areas of level ice. Despite the near-absence of larger pieces of old ice, it was very stable all the way to the last major row of ridges at about 3 km offshore. The few scattered pieces of piqaluyuk were landward of already well-grounded ice, providing little advantage to the crews, other than as a source of drinking water. The last row of grounded ridges was separated by a system of cracks from the outermost floating ice. The ice off Gravel Pit had formed in place and was very flat and thin, yet with no noticeable cracks. Due to the lack of anchored ice, except for a few ridges close to shore, the crews in this area were extremely cautious of any drift ice that approached. The conditions off Hollywood were similar to those off Gravel Pit—flat ice that had mostly formed in place—although many hunters indicated that it was more firmly grounded. In this area, notable cracks developed later in the season. The ice off Monument formed a large promontory of shorefast ice (nuvuġaqpuk) that extended approximately 11 km offshore (see Figure 3.14). The distance required to reach the edge was one reason crews may have decided against hunting in this area, but perhaps the more important reason is that most believed this promontory of ice would eventually collide with pack ice and break away. However, surprisingly, the nuvuġaqpuk remained throughout the entire whaling season.

Despite stable conditions along the general extent of the shorefast ice, the pack ice, winds, and currents never cooperated to make the ice edge suitable for whaling. Tuuq is when the pack ice collides with the shorefast ice edge and acts as a chisel (George et al. 2004). While such events surely present danger to crews camped at the edge, they are also relied on by hunters to “fix-up” the ice—to thicken thin ice through deformation and to rid the edge of dangerous attachments (iiguat). An ideal sequence of events would involve heavy pack ice coming in to “fix-up” the ice, driven by the wind and/or current in such a manner that hunters are able to foresee the event and pull off the ice. Next, the lead would open to reveal ice edge conditions suitable for safely hauling up a whale.

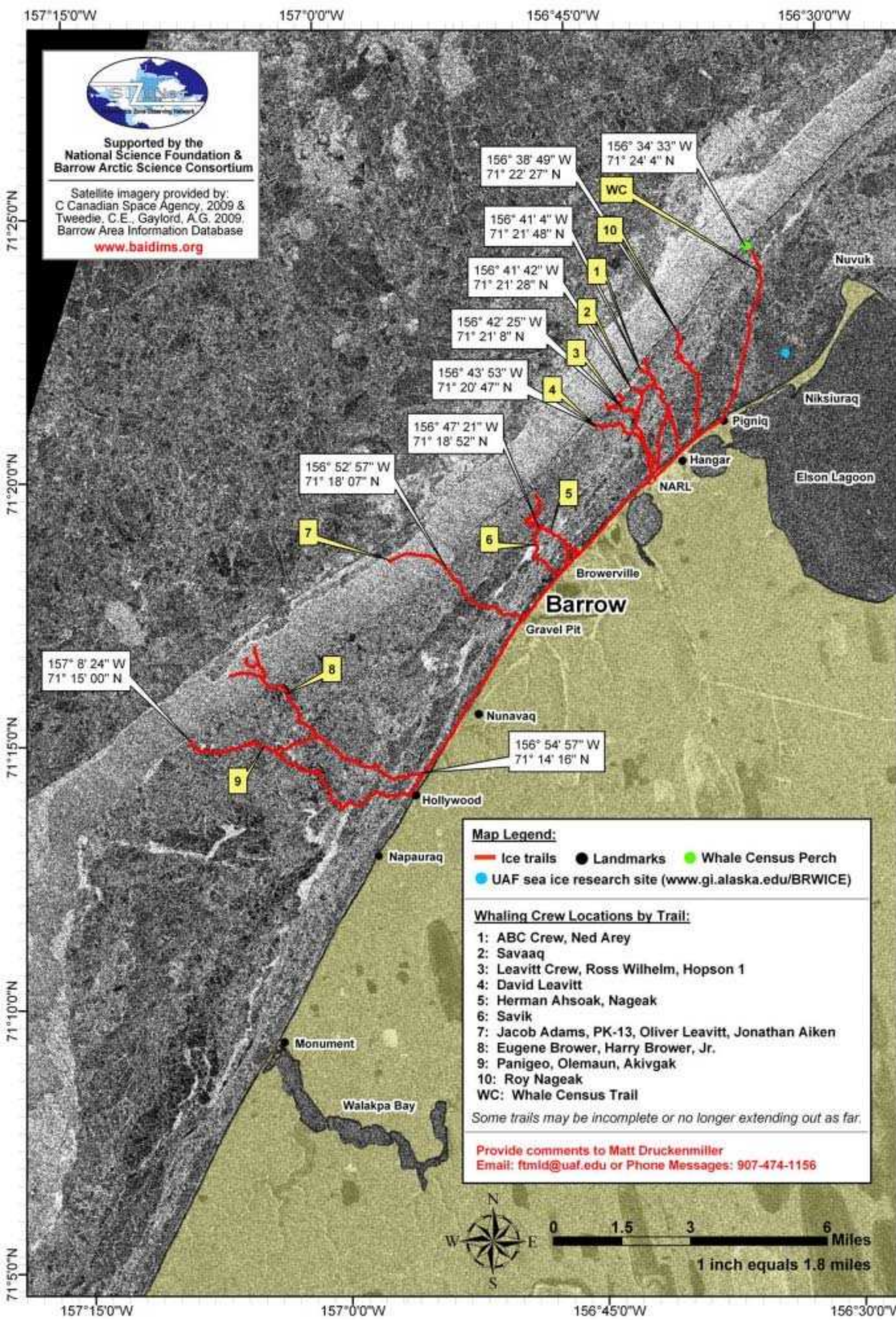


Figure 3.14 Map of the 2009 whaling trails. This exact map was provided to the community during the whaling season. The SAR image, acquired by the European Remote Sensing satellite ERS-2 and provided by the Canadian Space Agency and C.E. Tweedie and A.G. Gaylord, is from May 16, 2009 just prior to the opening of the lead shown in Figure 3.1. Various GPS locations are labeled to assist with navigation. Locations are also shown for the camp of the 2009 bowhead whale census orchestrated by the North Slope Borough's Department of Wildlife Management and of our sea ice mass balance site that measured level ice growth and other variables of interest.

Beginning on April 20, just as most crews were finishing their trails, the west wind arrived and dominated throughout the remainder of the whaling season (see Figure 3.11). The wind-driven pack ice either formed iiguat or on occasion built up a moving one-story high wall of slush ice (muġaliq) along the edge. Especially for the crews off NARL, iiguat persisted and when one broke off another formed. Gordon Brower recalled that in late April his crew was fortunate to be camped on tuvaġruaq for a few days but that the area was still considered unsafe since it was only connected to the grounded ice by thin young ice. Many hunters described 2009 as a "waiting game"—waiting for the lead to open or for edge conditions to improve. Most were only camped at the edge for one or two days, and were prepared to run at a moments notice. Some hunters never even brought their boats onto the ice.

2009 was also difficult since the muġaliq incorporated within the shorefast ice never froze solid. Near thawing temperatures arrived on April 26 and soon reached above freezing on May 18. Warm weather and the arrival of warm water (as suggested from interviews with the hunters) led to a quick deterioration of trails and cracks, and in particular to those south of Nunavaq. This sequence of events made the conditions in the South very unsafe. Some crews pulled off the ice as early as May 12 due to these unsafe conditions, but also because the larger whales were beginning to move through. Similar to 2007 and 2008, the trails off NARL and northward remained intact longer than those to the South.

On May 16 a southeast wind opened the lead for a short time (see Figures 3.1 and 3.11) and in the early hours of May 17 ABC Crew (Arnold Brower, Sr. Crew) landed an 8-m ingutuk from trail number one (see Figure 3.14), and was able to find a pan of tuvaġruaq to successfully haul up the whale. Three other crews caught whales before May 23 but experienced great difficulty in finding a suitable place to butcher because of muġaliq at the edge. One whale was struck and butchered at trail one and two were struck from the trails off Hollywood. Of these latter two, one was hauled to trail seven and the other to trail four in hopes of finding ice that would support the weight of the whales and also because the trails off Hollywood were not safe enough to permit safe passage for the large number of people required to butcher a whale. Each attempt failed and as the whales were pulled onto the ice, they would immediately break through. In all three cases they had to cut off the heads of the whales (1/3 of the whale's body) in the water and anchor it to the ice edge. These poor butchering conditions unfortunately did not allow the crews to retrieve all of the whale meat, and in one case they were only able to collect the skin and blubber (muktuk). Joe Leavitt stated that if heavier ice conditions had existed in 2009 butchering all four whales would not have been a problem.

To some members of the community the success of the whale hunt is more than just about climate and ice conditions; it is connected to the well-being of the people. Roy Ahmaogak, for instance, said, "*One of the most heartbreaking things about this year was that we weren't given the opportunity to practice traditional whaling because of the ice. Barrow and its people have been feuding and bickering at each other all this last winter. This is the reason we think the ice didn't go out this year and it stayed closed. This will make us think this coming year that we have to watch our tongue and to watch what we say to people. We are lucky to have two blanket tosses this year. It will teach Barrow and people like us*." In the end, Barrow joyously celebrated the four caught whales during two Nalukatak. Barrow then set their sights on the non-traditional fall bowhead hunt, which is done in open water with outboard engines and aluminum boats.

3.5.4 Spring 2010: East wind and a shorefast ice promontory bring favorable conditions

Through late March, the shorefast ice in the winter of 2010 maintained a fairly narrow extent at between 1 and 3 km off the village. Pack ice periodically drifted in against the shorefast ice for short periods of time but never securing attached. On March 26, several floes of multi-year ice, which had diameters on the km-scale and average thicknesses of 2.9 m, drifted in and attached to the shorefast ice about 3 km off NARL (see Figure 3.15). During the first two weeks of April, three trails were established across these smooth multi-year floes to access the lead. The narrow extent of ice to the south led to numerous short trails being built, although it was expected that there would likely be attachments of additional ice as the spring progressed.

As anticipated, pack ice came in and attached to the shorefast ice on April 15, resulting in an ice edge quite far offshore. However, this condition was short-lived when a large section of shorefast ice broke free on April 28. Through email correspondence with Whaling Captain Eugene Brower, I learned that hunters were on the ice during this event but pulled off the ice as new cracks were observed. This break-out event left a large promontory of shorefast ice (nuvuġaqpuk) extending 12 km offshore as shown in Figure 3.15—curiously reminiscent of the nuvuġaqpuk of the previous year (see Figures 3.1 and 3.14). This feature largely determined where the crews hunted in the weeks that followed. Crews traveled south as far as Monument to find open water very

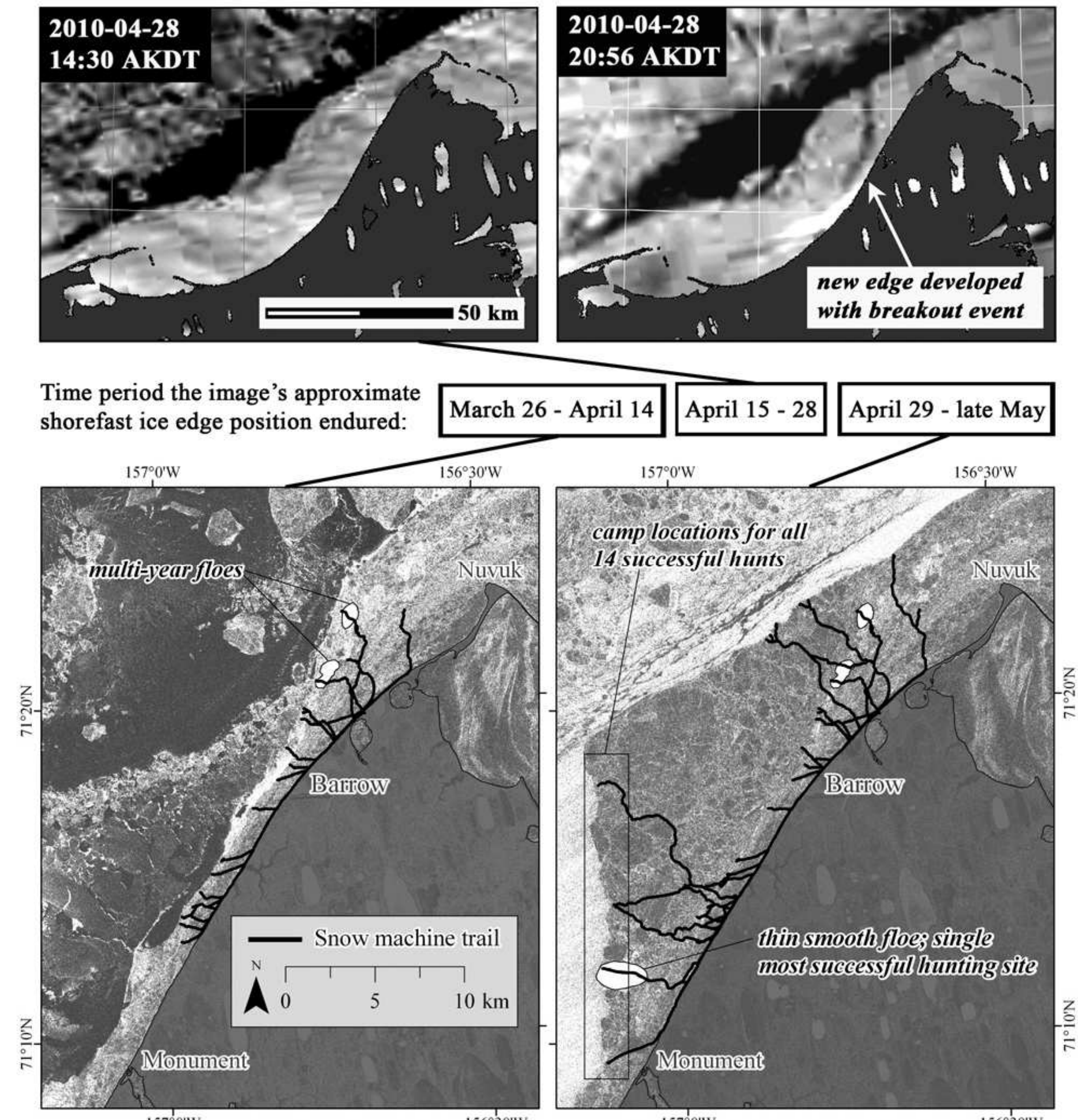


Figure 3.15 Graphical timeline of the variable shorefast ice extent that characterized the 2010 whaling season. The bottom left image shows the ice edge position that existed from March 26 to April 14 and the initial trails. The top left image shows a wider ice extent between April 15 and 28. The top right image captured the large-scale break-out event on April 28. The bottom right shows the ice extent after the break-out (April 29 - late May) and the resulting network of trails.

close to shore, while the crews further north were left with a much greater distance to travel to reach the edge.

Crews quickly extended their trails to the western-facing edge of the large promontory of ice as shown in Figure 3.15. Within the first few weeks of May, 14 whales were taken from these southern trails, and none from the trails to the north. A discussion with Joe Leavitt, a captain who landed Barrow's second whale on May 2, along with passing conversations with various other hunters, pointed to a number of reasons for the hunting success in this area. First, the ice was rather smooth and flat which made it quite navigable and provided many opportunities for places to haul up a whale. The orientation of the ice edge provided clear views of the approaching whales. Numerous hunters suggested that the large promontory of ice guided or deflected the whales away from the camps placed further north on the opposite side of the promontory. Also, it was noted that because the ice was quite thin (between 1.0 and 1.5 m at the edge), the whales were diving beneath the ice in this area. Despite the thinness of the ice, there were few or no cracks that caused concern amongst the crews.

Joe Leavitt described 2010 as "a good year for spring whaling". A persistent east wind kept the lead open for most of the hunting season. However the whale harvest did not come easy. More whales than normal were struck and lost. The strong east wind produced rough water that prevented some crews from tracking their floats that were attached to the struck whales, which resulted in the whales being lost. Leavitt suggested that some of the struck whales may have dove under the ice, never to be found.

3.5.5 Spring 2011: Obstructing shear ridge and warm May temperatures

On February 17, a localized ice shove took place during a strong (15 m/s) southwest wind. By observing image sequences from the coastal radar and webcam, it appeared as though sections of shorefast ice off Barrow became unanchored and rotated clockwise up the coast under the force of incoming pack ice. This event created a zone of compression along Barrow's coastline resulting in large ridges with sail heights upwards of around 10 m in height above sea level either on the beach or in very shallow waters. Using differential GPS, I measured 11.0 m above sea level at what appeared to be the greatest sail height of the ridges between Barrow and NARL (71°19'15.73" N, 156°42' 44.89" W; 150 m off the beach). Surprisingly, the rough ice near shore did not significantly interrupt alongshore snowmobile traffic, which typically relies on the near-shore flat ice zone (igniġnaq) to provide easy travel up and down the coast.

The real challenge for the whalers at the start of the hunting season was not the uncharacteristically rough ice, but was a strikingly prominent shear ridge (agiuppak) that developed at the ice edge. Figure 3.16 shows an aerial photo of this ridge taken by helicopter on March 23, 2011. This ridge persisted as a strikingly smooth and polished wall of ice until April 10. Moderately rough water deteriorated the wall over the course of a couple days (see Figure 3.16), revealing that it actually had little structural integrity. The whalers referred to the ice in the ridge as muġaliq, just as they had in 2009. By mid-April, approximately eight main trails extended to (or very near) the open water. However, the whalers struggled to deal with the ridge. There were few locations to place a camp or to haul up a whale.

Figure 3.16 Photos of the shorefast ice in spring 2011. *Top left*: An aerial photo (by J.C. George on March 23) of the shear ridge at the ice edge. See the photo's approximate coverage as the white grid in Figure 3.17. *Top right*: A trail traversing the shear ridge. See the location of the photo (by M.L. Druckenmiller on April 20) as the black square in Figure 3.17. *Bottom*: Both photos were taken at the same location, marked by the black triangle in Figure 3.17, two days apart, during which time waves led to rapid deterioration of the ridge. Both photos were taken by M.L. Druckenmiller on April 9 (left) and April 11 (right).

Against the whalers' wishes, the shear ridge persisted throughout the entire whaling season. The majority of crews headed to the southern most trail where a narrow band of ice accreted to the seaward side of the ridge and provided a platform for camps and butchering sites. In total, Barrow managed to land 6 whales during the season—two in early May and four others on May 21 and 22. Because so many crews concentrated in one area, the utilized trails received a lot snowmobile traffic, which when combined with the warmer temperatures of late May led to dangerous holes along the trails (similar to that shown in Figure 3.7).

The persistent shear ridge that provided poor ice edge conditions for whaling may have been linked to a regional set-up of shorefast ice along the Chukchi coast between Point Franklin and Barrow that was very stable in extent (i.e., resistant to break-out). Figure 3.17 shows the regional-scale shorefast ice extent that maintained a stable position throughout the entire whaling season. This provides an example for the observation made by Eugene Brower that Point Franklin often serves as a deflection point for pack ice moving from the west (see Section 3.2). As Point Franklin provides this deflection, a relatively wide shorefast ice cover develops across the entirety of Peard Bay, extending to Nunavaq, and providing a “guide-rail” to drifting pack ice.

3.5.6 Discussion

The initial placement of ice trails is largely in response to ice conditions, traditional practices, and crew preference. Over the course of a single whaling season, shorefast ice conditions often change considerably, requiring major shifts in hunting locations and strategies. These changes fall within five categories: (1) changes in the location and geometry of the ice edge as ice attaches and detaches, (2) the accretion of different ice types, which may be either desirable or undesirable, (3) shifts in wind and/or current conditions that change their hazard assessment of break-out events, lead conditions, and the roughness of open water, (4) deteriorating ice conditions due to warming air temperature, incursion of warmer and stronger ocean currents beneath the ice, or excessive and concentrated snowmobile traffic, and (5) the development of cracks that lead to specific areas being deemed unsafe.

The presence of muġaliq dominated the observations of hunters in 2009 and 2011. This slush ice, which forms through shear at any time throughout winter or spring, represents a type of ice that lacks the drainage of salt water that typical thermodynamic ice production promotes, thus rendering it potentially unstable and responsive to slight changes in temperature. Hunters acknowledged that this ice is common but that 2009 was remarkable because the presence of muġaliq was so widespread and air temperatures did not allow for this ice to retain its integrity late into the season. Coupling this phenomenon with an understanding that advection of warm water can lead to the destabilization of shorefast ice by melting grounded ridge keels (Mahoney et al. 2007b) and refrozen cracks, reveals that shorefast ice as a stable platform for hunting and travel is closely linked not only to climate change but to weather and oceanographic variability.

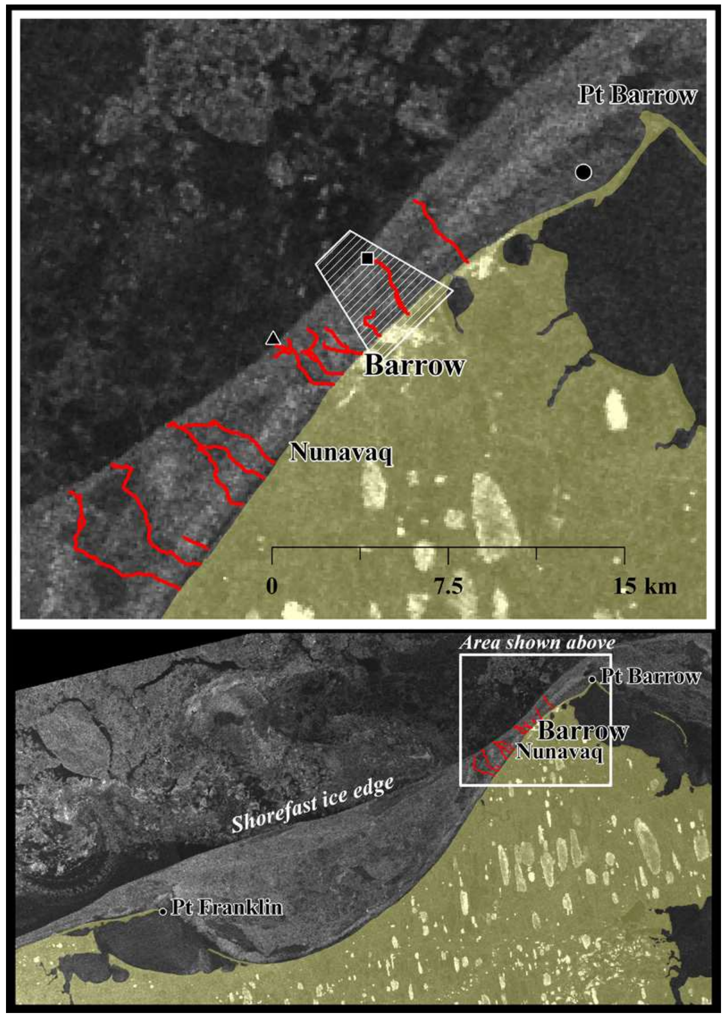


Figure 3.17 Map of Barrow's 2011 trails as of 21 April 2011. No major trails are believed to have been established after this date. *Top*: The black triangle, black square, and white grid mark the location of photos in Figure 3.16. The black circle marks the location of the 2011 sea ice mass balance site. *Bottom*: A regional-scale view shows an extent of stable shorefast ice between Point Franklin and Point Barrow. The shorefast ice edge maintained this location over the entire whaling season.

Changes in shorefast ice characteristics are much more complicated than the obvious reduction in the presence of multi-year ice. During our conversations, Arnold Brower, Sr. and Tom Brower, III both noted that shorefast ice prior to the 1980s extended much farther out, was flatter, and was composed of thicker ice than recent years. While detailed analysis of how shorefast ice characteristics have changed over time is beyond the scope of this chapter, it is clear that changes are taking place that present new challenges for the whaling community. If hunters continue struggling to find sufficiently grounded and stable ice, such as the tuvaġruaq experienced in 2008, they may increasingly have to deal with the problems encountered in 2007, 2009, and 2011—early spring break-out events close to shore or ice edge conditions that are not suitable for pulling up a whale. However, the seasonal summaries presented here span a five-year period and accordingly can only present a brief look at how present climate and ice conditions may be impacting spring whaling.

Lastly, the summaries of how the crews responded to ice conditions during these five years begs the important question of whether there is a clear and distinguishable local zonation of ice conditions along Barrow's coastline. This topic, worthy of further investigation, may underscore the fact that Barrow's ice environment allows for understanding not only how ice conditions respond to climate but also to subtleties in local and regional conditions, such as bathymetry and coastal currents. This may present an opportunity for scientists to further discover the local expert sea ice knowledge found in Barrow, which likely possess an intricate understanding of the processes that may govern a local zonation of conditions, and further lead to improved scientific monitoring that is relevant to the community's activities on ice.

3.6 Conclusions

The Barrow community continues to practice successful traditional spring whaling from shorefast ice while making observations that lend a new perspective to understanding processes that dominate the present day coastal sea ice environment. Hunters assess shorefast ice in a highly specialized manner as they consider safety, navigation, hunting strategies, and traditional knowledge and practices. Detailed characteristics of year-to-year ice conditions, which are unobservable by standard scientific monitoring programs, manifest in impacts to the whaling community. Utilizing the collaborative and experiential (as opposed to experimental) approach presented here—a type of ethnoglaciology, we are working toward an improved understanding of how to observe the local environment in a manner to track changes important to both climate study and to the community. This research may ideally begin to illustrate how strategic adaptations in the way the community uses the shorefast ice are indicative of and responsive to environmental change.

Mapping Barrow's ice trails allows us to piece together how ice characteristics spatially and temporally relate to the community's use of the ice. With an understanding of the decisions and observations hunters make before and during spring whaling, we may interpret the mapping of trail locations as a documentation of hunting strategy. The maps are providing a valuable product to the community while also serving as a useful reference tool for scientists and hunters to communicate across barriers of culture and experience. It is our hope that this project continues as a long-term monitoring effort to unite advanced scientific instrumentation and expertise, traditional knowledge, and ice use by a modern arctic whaling community.

References

Aporta, C., 2004. Routes, trails and tracks: Trail-breaking among the Inuit of Igloolik. Etud. Inuit 28(2): 9-38.

Braund, S.R., Moorehead, E.L., 1995. Contemporary Alaska Eskimo bowhead whaling villages. In: McCartney, A.P. (Ed.) *Hunting the largest animals: Native whaling in the Western Arctic and Subarctic*. The Canadian Circumpolar Institute, University of Alberta, pp 253-279.

Comiso, J.C., Parkinson, C.L., Gersten, R., Stock, L., 2008. Accelerated decline in the Arctic sea ice cover. Geophys. Res. Lett. 35, L01703, doi:10.1029/2007GL031972.

Drobot, S.D., Maslanik, J.A., 2003. Interannual variability in summer Beaufort Sea ice conditions: Relationship to winter and summer surface and atmospheric variability. J. Geophys. Res. 108 (C7).

Druckenmiller, M.L., Eicken, H., Johnson, M.A., Pringle, D.J., Williams, C.C., 2009. Toward an integrated coastal sea ice observatory: System components and a case study at Barrow, Alaska. Cold Reg. Sc. Tech. 56(2-3): 61-72.

Eicken, H., Lovecraft, A.L., Druckenmiller, M.L., 2009. Sea ice system services: A framework to help identify and meet information needs relevant for arctic observing networks. Arctic 62(2): 119-136.

George, J.C., Huntington, H.P., Brewster, K., Eicken, H., Norton, D.W., Glenn, R., 2004. Observations on shorefast ice dynamics in arctic Alaska and the responses of the Iñupiat hunting community. Arctic 57(4): 363–374.

George, J.C., Norton, D.W., Brower Jr., H., unpubl. Observations on landfast ice break-off events "Uisauniq" near Point Barrow, Alaska. North Slope Borough Department of Wildlife Management, Barrow, Alaska.

Haas, C., Gerland, S., Eicken, H., Miller, H., 1997. Comparison of sea ice thickness measurements under summer and winter conditions in the Arctic using a small electromagnetic induction device. Geophys. 62(3): 749-757.

Haas, C., 2003. Dynamics versus thermodynamics: The sea ice thickness distribution. In: Thomas, D.N., Dieckmann, G.S. (Eds.), *Sea ice—An introduction to its physics, chemistry, biology and geology*. Blackwell Science, Oxford, pp. 82-111.

Mahoney, A., Eicken, H., Gaylord, A.G., Shapiro, L., 2007a. Alaska landfast sea ice: Links with bathymetry and atmospheric circulation. J. Geophys. Res., 12, C02001.

Mahoney, A., Eicken, H., Shapiro, L., 2007b. How fast is landfast ice? A study of the attachment and detachment of nearshore ice at Barrow, Alaska. Cold Reg. Sc. Tech. 47: 233-255.

Maslanik, J.A., Fowler, C., Stroeve, J., Drobot, S., Zwally, J., Yi, D., Emery, W., 2007. A younger, thinner arctic ice cover: Increased potential for rapid, extensive sea ice loss. Geophys. Res. Lett., 34, L24501, doi:10.1029/2007GL032043.

Nelson, R., 1969. *Hunters of the northern ice.* University of Chicago Press, Chicago, 429 pp.

Nghiem, S.V., Rigor, I.G., Perovich, D.K., Clemente-Colón, P., Weatherly, J.W., Neumann, G., 2007. Rapid reduction of arctic perennial sea ice, Geophys. Res. Lett., 34, L19504, doi:10.1029/2007GL031138.

Norton, D.W., 2002. Coastal sea ice watch: Private confessions of a convert to indigenous knowledge. In: Krupnik, I., Jolly, D. (Eds.), *The earth is faster now: Indigenous observations of arctic environmental change*. Arctic Research Consortium of the United States, Fairbanks, Alaska, pp. 127-155.

Stoker, S.W., Krupnik I., 1993. Subsistence whaling. In: Burns, J.J., Montague, J.J., Cowles, C.J. (Eds.), *The Bowhead Whale*. Allen Press, Lawrence, Kansas, pp. 787.

Tremblay, M., Furgal, C., Lafortune, V., Larrivée, C., Savard, J., Barrett, M., Annanack, T., Enish, N., Tookalook, P., Etidloie, B., 2006. Communities and Ice: Bringing Together Traditional and Scientific Knowledge. In: Riewe, R., Oakes, J. (Eds.), *Climate Change: Linking Traditional and Scientific Knowledge*. Aboriginal Issues Press, University of Manitoba, pp. 123-138.

Chapter 4. Will the ice break-out? Interfacing geophysics with local and traditional knowledge using fault tree analysis*

Abstract

Shorefast sea ice is used as a platform for human activities throughout much of the Arctic, yet is often susceptible to detachment and break-out, mostly as a result of unanchoring of grounded ridges. In this chapter, the physical characteristics of arctic shorefast ice are related to its ability to resist a range of potentially destabilizing forces. Analysis suggests a sharp transition between poorly and well-anchored ridges. Drawing upon interviews, the empirical and time-tested local and traditional knowledge (LTK) of indigenous ice experts from Barrow, Alaska is summarized as it relates to key processes and considerations for assessing safety on ice. Through careful repeat observations, hunters track how different ice types and features, such as anchored ridges, evolve throughout winter and spring and contribute to stability on scales relevant to ice-use and their strategies for minimizing risk. Using fault tree analysis (FTA), which relies on deductive and Boolean logic to map causal relationships, this chapter develops a conceptual framework for understanding shorefast ice break-out events that incorporates both geophysics and LTK. A well-observed break-out event from 2007 is used to demonstrate a developed fault tree's ability to conceptually model the interaction of ice features, atmospheric and oceanic forces, and local to regional processes. While causality is replicated within the fault tree, the approach's inability to explicitly deal with the temporal aspects of natural systems must be considered. Lastly, this chapter discusses the benefits of FTA for interfacing geophysics with LTK in the context of how climate and synoptic scale weather patterns may relate to the risks posed to local ice-users.

---

* I intend to submit a condensed version of this chapter for publication in Cold Regions Science and Technology or a similar journal.

4.1 Introduction

Across the Arctic, shorefast sea ice (SFI) forms an apron of ice against the land that persists throughout much of winter and spring and serves as a seasonal platform for travel and hunting by coastal Native communities, as well as for near-shore industrial activities. In many areas, such as along the coast of Alaska's Chukchi Sea, users must consider the integrity of this platform and related threats to their safety. An important question to consider is "*will the ice break-out?*" While the laws of physics govern the answer, the human experience is often a much more accessible record to rely upon when making decisions on the ice. For an ice-user, science has short-comings in that it is often not able to deal with the heterogeneity of the ice cover and the intricacies of local environmental processes. To account for these characteristics, indigenous ice experts rely on empirical observations and vast experience. For centuries, the Iñupiat have managed to hunt from shorefast ice despite the risks of breaking-out. However, important lessons have been learned from the unfortunate times when hunters have found themselves adrift. In Iñupiaq, there is even a term meaning "an ice separation event involving people"—uisauniq (George et al. 2004).

Since Richard Nelson's seminal book, *Hunters of the northern ice* (1969), the local and traditional sea ice knowledge of the Iñupiat represents a body of expertise that scientists have consulted in various ways and with varying degrees of success. (Throughout this chapter I will use LTK to explicitly refer to local and traditional sea ice knowledge at Barrow, Alaska.) This knowledge is acquired through observational and personal trial-and-error learning on sea ice and has been traditionally shared through oral stories and instruction, often in the form of cautionary tales. Geophysicists and anthropologists alike have delved into these stories and cross-sections of LTK (to the extent to which it has been shared) in hope of finding new insight for research on arctic environmental processes, which today are most frequently considered in the context of global climate change.

One core characteristic of LTK is that it does not consider the natural world independent of the human world and almost always has a social context (Berkes and Berkes 2009). Iñupiat ice experts, who are usually experienced hunters, do not discuss ice stability as indifferent scientists do, but rather place emphasis on the importance of safety. Importantly however, hunters also do not unilaterally assess safety. Decisions of whether to go on ice are placed within a risk-reward framework. The risk of drifting out to sea with a shorefast ice break-out is weighed against the potential reward of providing subsistence foods for family and community. Nonetheless, hunters make calculated decisions about SFI stability when assessing risk. During spring whaling at Barrow, Alaska, hundreds of people can be on the ice at once. In 1997, one particular break-out event carried approximately 142 people out to sea (George et al. 2004). All were rescued by the community's search and rescue helicopter. Elders explain that hunters in the past were rarely as lucky. While break-out events have and will continue to present a significant threat to hunters, LTK has undoubtedly prevented many similar events throughout Inuit history.

Barrow, a primarily Native Iñupiat community of approximately 4,000 people, has a unique history of elders and experts sharing their LTK with scientists (Brewster 1997; Huntington et al. 2001). The topic of break-out events has been central to many discussions as it provides context for exploring areas of common understanding (Huntington et al. 2001; Druckenmiller et al. 2009). There is also longstanding (Reed 1969) and, more recently, a continuous (Druckenmiller et al. 2009) scientific record of local ice conditions. Much of the research has investigated SFI dynamics (Shapiro et al. 1987; George et al. 2004; Mahoney et al. 2007a, 2007b) and contributed to a rich, yet loosely woven, body of literature with relevance to SFI break-out events. The overarching objective of this chapter is to develop a framework for analyzing the stability of SFI and understanding break-out events that incorporates both geophysics and LTK.

This paper is organized as follows. Section 4.2 describes the coastal ice environment found near Barrow and summarizes the primary modes of SFI failure. Section 4.3 relates physical characteristics of the SFI cover to its ability to resist potentially destabilizing forces and presents a detailed overview of important geophysical factors in assessing SFI stability. Section 4.4 summarizes hunters' knowledge as it relates to key processes and considerations for assessing safety on ice. Section 4.5 presents fault tree analysis (FTA) as a method for conceptualizing SFI failure and integrating geophysics with LTK. FTA is a diagrammatic method that evaluates pathways to failure in complex systems by sequencing and combining different variables using boolean operators, such as AND or OR (Ferdous et al. 2007). I apply this approach to the thoroughly observed break-out event that took place off Barrow in 2007 (Druckenmiller et al. 2009, Chapter 2). Lastly, in reflection of key considerations for assessing failure, I discuss reasons why the "rules" of LTK so often hold true and offer perspective on how climate and environmental change relate to stability.

4.2 The coastal ice environment

Figure 4.1 (top panel) shows a cross-section of the different zones within the SFI environment. These include bottom fast ice, floating fast ice, the grounded ice zone, and floating extensions. Most literature on SFI (e.g., Shapiro and Barry 1978) does not, by definition, include extension ice as part of the SFI. Here, however, I consider extension ice to be an important part of SFI given that it is widely exploited as a platform for spring whaling. Furthermore, on timescales of human use (hours to weeks), extension ice can be just as immobile as ice within the grounded ice zone, provided seas are calm and conditions are not conducive for a break-out event. However, one difficulty with our definition arises at times when the lead is closed and the pack ice beyond the SFI is immobile. During these conditions it can be very difficult to determine where the edge of the SFI is located.

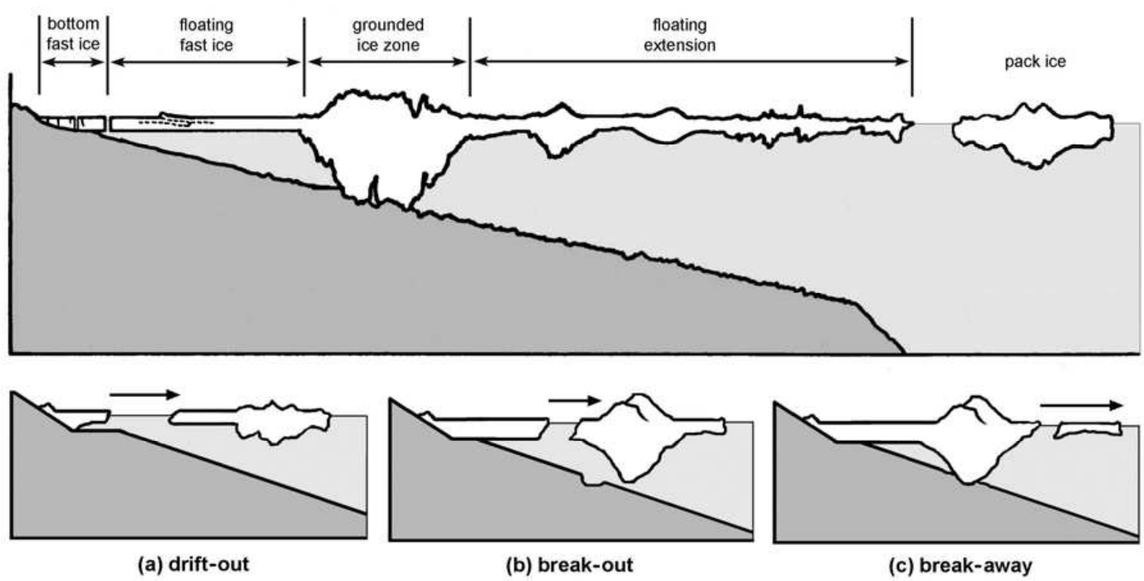


Figure 4.1 Zones of a simplified SFI environment in the Chukchi Sea (top) and modes of SFI failure (bottom). In reality, the grounded zone can be more expansive in extent with level sections of floating ice between ridges. (Adapted from Shapiro and Barry 1978)

4.2.1 Stages of shorefast ice

In consideration of how the local community uses SFI and building from discussions I have had with Joe Leavitt, a Barrow whaling captain who has advised me throughout much of my research, I describe the lifecycle of SFI as comprised of five non-discrete stages. First, is the *initiation stage*, which typically begins in late October or early November and extends into late

December or mid-January. This stage spans from the time ice is first observed along the coast (ice that either freezes in place or is advected in) to the time ice is secure enough to walk on based on both its thickness and anchoring to the coast. Mahoney et al. (2007a) found that the initiation of SFI correlates best with the onset of approximately 80% sea ice concentrations in the region (within 200 km of the coast), and less with the onset of freezing temperatures or winter-time atmospheric circulation patterns. In this stage, bottom fast ice, minor beach ride-ups or small grounded ridges in shallow water typically keep the ice in place. The ice is mostly used by seal hunters, who in Barrow represent a small cross-section of the experienced hunters.

Second, is the *ice building stage*. Through approximately late-March, the dominant grounded ridge systems develop through interaction with drifting pack ice. It is widely accepted that in order to obtain a well anchored ice cover, winter storms with strong west winds must co-occur with a significant local concentration of heavy pack ice that can collide with the SFI to build ridges (Joe Leavitt, pers. comm., 2010). Ridges can be characterized based on whether they are formed in compression or shear. In general, compression (or pressure) ridges form in discrete events while shear ridges can form over prolonged periods of time as drift ice grinds against the SFI edge. The ice drift in the shear zone typically follows the dominant ice drift direction to the NW (directly opposing the prevailing wind).

By late-March, SFI is in its *mature stage*. While generally stable by this stage, the ice continues to be mechanically thickened through deformation, thermodynamically thickened through ice growth, and adjusts in its lateral extent and thickness distribution as forces act on the ice. At this time, whaling crews begin to scout for spring whaling locations and build trails. Hunters hope for a “clean” stable edge (i.e., free of weakly attached sections of ice) in deep water where they can establish their camps in wait for the arrival of the first large wave of bowhead whales in late-April. In general, the maximum SFI extent is not reached until May (Eicken et al. 2006).

By mid-May, milder weather arrives (air temperatures near 0°C), marking the approximate start of the *deterioration stage*. During the final weeks of spring whaling, which typically ends by the third or last week in May, hunting crews increasingly avoid greater sections of the shorefast ice cover as thin spots on ice develop, especially where heavy snow machine traffic has eroded the ice from above (Chapter 3). By late May, as incident solar irradiance increases, the presence of leads may shift from representing a location of significant ice growth to a source of ocean heating (Perovich and Richter-Menge 2000), which may provide a mechanism for bottom ice melt and the weakening of nearby ridge keels. Sometime between mid-May and early June, offshore pack ice conditions in the Chukchi Sea transition from a less mobile, ice-choked wintertime state to a more mobile, highly broken springtime state, where the distance over which stress can be imparted through the ice decreases due to fractures (Eicken et al. 2006; Lewis Shapiro, pers. comm., 2011).

The final stage—*break-up*—arrives typically in the first week in June, marked by the appearance of melt ponds on the surface (Petrich et al. *in prep*.). The ice is generally trafficable through mid-June, despite hazardous conditions due to continued thermal erosion of ridge keels, interconnected melt ponds, and the melting out of refrozen cracks. In addition to the thermal component, break-up is also comprised of a mechanical component. As the general cohesion and anchoring strength diminishes, large sections of shorefast ice break-away under wind and ocean forcing, often during distinct weather events (Wadhams 1980; Petrich et al. *in prep*.).

Progression through these stages typically involves non-distinct transitions and often the progression is not limited to a set sequence. The shorefast ice cover may move from the initiation stage through to the mature ice stage, before experiencing a break-out that removes significant sections of ice from along the coastline, thus in these areas reverting back to the initiation stage (albeit under much different thermal and dynamic conditions than in fall time).

4.2.2 Modes of shorefast ice failure

Stability may be broadly viewed as the ice cover's resistance to forces capable of moving or deforming the ice. As a result, specific definitions for SFI stability must consider the type of activity or ice-use of interest, as this will define the spatial scales and sea ice parameters of importance. For example, those concerned with the bearing capacity of sea ice must consider small-scale vertical displacement and thus creep and elastic behavior. When dealing with the structures within the ice, compressive and multi-axial strength are most important (Timco and Weeks 2010). Here, with a focus on horizontal ice divergence or convergence in the SFI zone on local scales (generally of at least 10^2 m), I define stability as the ice cover's resistance to compressive, tensile, shear or flexural failure. Accordingly, assessments of stability refer to whether or not the ice will remain present in its current anchored state and areal extent, but not to whether the ice will persist as a platform that resists vertical loading. The latter is certainly a concern for ice-users, but beyond the current scope of this research.

Divergent failure (or separation) events, which may lead to a uisauniq, can be broken down into three basic categories, which are shown in Figure 1 (bottom panel). A *drift-out* event takes place when the ice detaches from a poorly anchored state with no grounded ice seaward of the tidal crack. Such events typically take place during the initiation stage of SFI development. A *break-out* event is one that includes removal of ice from within the grounded zone. The ice fails such that its anchored ridges become detached from the sea floor (or alternatively the ridge keels fail in shear). *Break-away* events involve the detachment of floating ice seaward of the grounded zone. Break-out and break-away events taking place during the mature and deterioration ice stages are the focus of this chapter since these pose the greatest threat to hunters on the ice in springtime. In general, much greater forces are required for a break-out event, which accounts for them being less common than break-away events. Also, as long as hunters are not carried away, break-away events are often desirable in that they can remove weakly attached floating extensions from the edge.

Convergent failure events, although not a focus for this chapter, also represent threats to ice-users as well as to coastal infrastructure. The compression of SFI ("ivu") by incoming drift ice to form pressure ridges in the coastal waters represents the most common type of convergent failure. Less common events included ice-pushes where either ridges pile-up onshore or ice sheets ride-up onto land, sometimes damaging community infrastructure[1] (Mahoney et al. 2004; Kovacs and Sodhi 1980). Ice push events are most common when landfast ice is not fully anchored, such as in fall or late-spring, and at times when both the coastal lead system and offshore pack ice are closed (Kovacs and Sodhi 1980).

4.3 Force balance analysis of stability

The forces acting on SFI that may lead to divergent failure include wind, ocean current, changes in buoyancy due to increases and decreases in sea-level, and impact by drifting pack ice. When evaluating whether these forces can destabilize the ice, one must consider the roughness of the ice and characteristics of the grounded zone, which includes the number of ridges, ridge sail heights and keel depths, and water depth at grounding. The following section describes how these variables are to be considered in a force balance when assuming typical ridge characteristics. Throughout this section, I present 'stability ratios' which provide a basis for evaluating how forces and ridge characteristic combine in the context of asking the question "*will the ice break-out?*".

However, before reviewing the most important factors for SFI stability in the Chukchi Sea off Barrow it is important to acknowledge how this region differs from others in the Arctic. First, SFI in the Chukchi Sea does not experience the inflow of large river drainage as is the case in the coastal waters north of Russia and in the Mackenzie Delta. Freshwater input beneath SFI can lead to a potentially destabilizing under-ice buoyancy force (Macdonald and Carmack 1991). Furthermore, river runoff can provide sensible heat to the ice underside, leading to melt. In the deltas of the Mackenzie River (Divine et al. 2004) and the Yenisey and Ob Rivers (Searcy et al. 1996), these processes are attributed to earlier spring break-up of SFI in comparison to adjacent non-estuaries. Both of these factors can be largely disregarded as important for the Chukchi Sea. Secondly, with proximity to Barrow Canyon, the coastal waters west of Barrow have a relatively steep bathymetric gradient. Studies have shown that the outer limit of SFI extent is typically found near the 20 m isobath (Barry et al. 1979; Kovacs 1976; Mahoney et al. 2007a), which implies that the SFI edge will be closer to shore with a steep bathymetric gradient. This is important as the SFI extent directly determines the magnitude of imparted stresses on ice by winds and ocean currents.

4.3.1 Frictional coupling at the sea bed

The anchoring strength of a cross-section of SFI (see Figure 4.1) is linked to the frictional coupling between grounded ridge keels and the sea bed and the amount of gouging (i.e., depth of keel penetration into the sediment). The significance of gouging is difficult to estimate, in part because it depends on the direction of both the gouging event and any force that may act to un-gouge the keel. If a ridge is being forced from a direction opposite the direction of gouging, opposing sediment resistance may be negligible. However, if it is being forced in any direction other than the direction of gouging, the sediment that piled up on the seafloor during the gouging event may resist displacement by acting as a physical, vertical barrier.

The shear stress due to frictional coupling at the sea bed, σ_{sb}, is given by (Mahoney et al. 2007b):

$$\sigma_{sb} = \frac{W_g c_f}{A_g}, \qquad [4.1]$$

where W_g is the weight of the grounded ridge accounting for buoyancy, c_f is the static friction coefficient, and A_g is the area of contact between the grounded keel and the seafloor. Shapiro and Metzner (1987) calculated c_f to be 0.50 for solid ice blocks on a gravel beach.

W_g, which I express in terms of the area-above-buoyancy, A_b (note that the area-above-buoyancy is zero for a floating ridge), for a cross section of SFI (assuming a unit width) is as follows:

$$W_g = A_b \rho_r g\,, \qquad [4.2]$$

where ρ_r is the bulk density of the ridge and g is gravitational acceleration (9.8 m s^{-2}). In order to translate a ridge surface profile into a weight above buoyancy, A_b must be expressed in terms of ridge sail height, H_s. First, A_b is given by:

$$A_b = A_r - (\rho_w / \rho_r)\, A_w\,, \qquad [4.3]$$

where ρ_w is the density of sea water (1027 kg m^{-3}), A_r is the total cross-sectional area of a grounded ridge, and A_w is the cross-sectional area of displaced water. Archimedes' law provides that:

$$\frac{\rho_r}{\rho_w} = \frac{\left(A_k / A_s\right)}{1 + \left(A_k / A_s\right)}\,, \qquad [4.4]$$

where A_k and A_s are the cross-sectional keel and sail areas, respectively. Rearranging and denoting the keel area to sail area ratio (A_k / A_s) as ψ gives:

$$\rho_r = \frac{\rho_w \psi}{1 + \psi}\,. \qquad [4.5]$$

Timco and Burden (1997) determined the typical value for ψ to be 8.0 for first-year ridges in the Beaufort Sea[2]. The value of ψ is dependent on the density of the ice blocks in the ridge and porosity in the keel and sail such that:

$$\psi = \frac{\rho_{is}}{\rho_w - \rho_{ik}} \frac{(1 - P_s)}{(1 - P_k)}, \qquad [4.6]$$

where ρ_{is} is the density of ice in the blocks of the sail, ρ_{ik} is the density of ice in the blocks of the keel, P_s is sail porosity, and P_k is keel porosity.

Timco and Burden (1997) provide mean values for typical arctic first-year ridge characteristics, as shown in Figure 4.2:

- keel depth to sail height ratio (H_k/H_s) or γ = 4.4,
- sail angle, α_s = 32.9°, and
- keel angle, α_k = 26.6°.

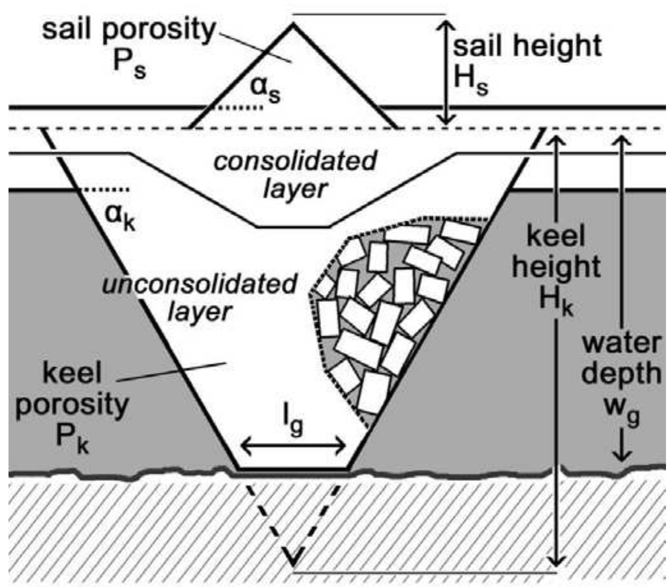


Figure 4.2 Schematic illustration of a first-year grounded ridge (adapted from Timco and Burden 1997) with the symbols used in the text. The unconsolidated layer of the keel is shown to be comprised of blocks. The dashed line represents sea-level.

Rearranging [4.5] to solve for ρ_w/ρ_r and substituting into [4.3] gives:

$$A_b = A_r - \frac{(1+\psi)}{\psi} A_w, \qquad [4.7]$$

A_r can be written as:

$$A_r = \frac{(1+\psi)}{\psi} A_k . \quad [4.8]$$

Substituting [4.8] in [4.7] gives:

$$A_b = \frac{(1+\psi)}{\psi} (A_k - A_w) . \quad [4.9]$$

Assuming the simplified triangular geometry for the ridge keel as shown in Figure 4.2, we can express the area of the keel as:

$$A_k = \frac{H_k^2}{\tan \alpha_k} . \quad [4.10]$$

Similarly, we can express the area of displaced water as:

$$A_w = \frac{H_k^2}{\tan \alpha_k} - \frac{(H_k - w_g)^2}{\tan \alpha_s} . \quad [4.11]$$

Substituting both [4.10] and [4.11] into [4.9] yields:

$$A_b = \frac{(1+\psi)(H_k - w_g)^2}{\psi \tan \alpha_s} . \quad [4.12]$$

Given than $H_k = \gamma H_s$, [4.12] can be rewritten as:

$$A_b = \frac{(1+\psi)(\gamma H_s - w_g)^2}{\psi \tan \alpha_k} , \quad [4.13]$$

where w_g is the water depth at grounding. Substituting [4.13] into [4.2] gives:

$$W_g = \frac{\rho_r g(1+\psi)(\gamma H_s - w_g)^2}{\psi \tan\alpha_k}. \qquad [4.14]$$

Using [4.6], [4.14] can be simplified as:

$$W_g = \frac{\rho_w g(\gamma H_s - w_g)^2}{\tan\alpha_k}. \qquad [4.15]$$

Assuming grounding takes place along the width of a keel at depth w_g as shown in Figure 4.2, A_g (see equation 4.1) can be expressed as a length, l_g (assuming a unit width), as follows:

$$l_g = \frac{2}{\tan\alpha_k}(\gamma H_s - w_g), \qquad [4.16]$$

Substituting [4.15] and [4.16] into [4.1], yields:

$$\sigma_{sb} = \frac{\rho_w g c_f (\gamma H_s - w_g)}{2}. \qquad [4.17]$$

The total frictional force exerted by grounded ridges, F_{sb}, is:

$$F_{sb} = W_g c_f n_g, \qquad [4.18]$$

where n_g is the number of grounded ridges. Substituting [4.15] into [4.18], and introducing the average degree of grounding, $\overline{D}_g$, gives:

$$F_{sb} = \frac{c_f n_g \rho_w g \overline{D}_g}{\tan\alpha_k}, \qquad [4.19]$$

where $\overline{D}_g$ is given by:

$$\overline{D}_g = \frac{1}{n_g}\sum_{i=1}^{n_g}\left(\gamma H_{s_i} - w_{g_i}\right)^2 . \qquad [4.20]$$

Before proceeding to the following sections, it is useful to note what this chapter has achieved thus far. By assuming a triangular geometry for ridge sails and keels (see Figure 4.2) and by using empirically derived characteristics (keel depth to sail height ratio, γ, and sail angle, α_k), the total frictional force exerted on the seabed can been determined providing that the water depth at grounding is known. This is an essential step in assessing the ability of an opposing force to un-ground a ridge keel (or a series of ridge keels) from the sea floor.

4.3.2 Shear strength of ridge keels

In addition to failure at the seabed (i.e., when the frictional force is overcome), we must also consider that the ridge keel may fail in shear. Shear strength τ_k of a ridge keel can be described by the Mohr-Coulomb failure criteria:

$$\tau_k = c + \sigma_N \tan\theta , \qquad [4.21]$$

where c is the cohesion strength, σ_N is the normal stress acting on the surface of failure, and θ is the angle of friction.

The literature has reported a large range in values for both cohesion and the angle of friction since these properties are related to a number of factors: the friction between ice blocks, the rotational and rearrangement potential of the ice blocks, the strength of the blocks themselves, and the strength of freeze bonds between blocks (Schaefer and Ettema 1986; Leppäranta and Hakala 1992; Shafrova and Høyland 2008). These properties are a function of the stress and temperature history, as well as the growth history of the parent ice sheet that provides the ice blocks.

Schaefer and Ettema (1986), Bruneau (1997), Timco et al. (2000), and Shafrova and Høyland (2008) report c values between 0 and 32 kPa and θ values between 6 and 70°. These are from predominantly laboratory scale studies; only 3 of the more than 20 studies were field-based.

Croasdale & Associates Ltd. (1995) reported that cohesion strengths under full-scale typical marine conditions may be expected between 25 to 100 kPa. As used in engineering design, Brown et al. (1995) predict lower values of 5 to 10 kPa. Leppäranta and Hakala (1992) determined shear strength values between 1.7 and 4.0 kPa for keels in the Baltic Sea, and Croasdale et al. (2001) determined values between 6 to 23 kPa with an average of 14.1 kPa for first-year keels in the Arctic.

The extent of freeze bonds (i.e., the degree of consolidation) is extremely important to understanding how the cohesion, and thus the shear strength for ridges, evolve throughout the lifetime of a ridge. Immediately after a ridge forms, the cohesion in the keel is zero since no freeze bonds exist between the blocks' points of contact. However, consolidation ensues as freeze bonds develop through atmospheric cooling and by drawing on the cold reserves of the submerged ice blocks (Marchenko 2008). During this initial stage of ridge consolidation, points of contact can freeze throughout the entire volume of the sail and keel. At the same time, a consolidated layer (i.e., a layer with zero macroscopic porosity; see Figure 4.2) begins to develop in the upper layer of the keel. This initial stage can last between a few hours (Høyland and Liferov 2005) to over 10 days (Marchenko 2008), and depends on the initial temperature of the blocks, block size, keel porosity, and the oceanic heat flux. Freeze-bonds cease to develop if the temperature of the ice blocks rises to that of freezing water at approximately -1.8 °C (Marchenko 2008). However, at the same time, the consolidation layer may continue to thicken due to cooling by the atmosphere. Timco and Goodrich (1988) found that the depth of the consolidation layer can grow up to twice as fast as that of level ice under the same ambient conditions. Marchenko (2008) found that the oceanic heat flux can actually begin to melt keels while the consolidation layer is still thickening.

Assuming that shear strength is based on a failure surface length approximately equal to the length of the keel surface in contact with the seabed, the normal stress, σ_N can be described as:

$$\sigma_N = \frac{W_g}{l_g} \text{, or by substituting [4.15] and [4.16] as:} \qquad [4.22]$$

$$\sigma_N = \frac{\rho_w g(\gamma H_s - w_g)}{2}. \qquad [4.23]$$

Substituting [4.23] into [4.21] gives:

$$\tau_k = c + \frac{\rho_w g(\gamma H_s - w_g)\tan\theta}{2}. \quad [4.24]$$

Determining which stress is first overcome with a force acting parallel to the SFI—either the shear strength of the ridge keel or the frictional stress at the seabed—is dependent on three chosen parameters: the coefficient of friction c_f between the sea bed and keel, the cohesion strength c, and the angle of friction θ. Figure 4.3 presents a contoured surface that divides shear failure at the ridge keel from a failure at the seabed where the frictional stress is overcome. It is important to note that the cohesion will extensively evolve over the lifetime of a ridge, as discussed earlier. The angle of internal friction however is mostly linked to the stress history of the parent ice sheet and the nature of the deformation process (e.g., a ridge formed in shear versus in compression). The coefficient of friction must be assigned according to the sediment type of the seafloor. In Figure 4.3, empirically derived values for c_f are provided for different sediment types and field tests from a literature review provided by Barker and Timco (2003). The highest values stem from a study where ice blocks were submerged beneath water; Utt and Clark (1980) attribute these values to lower contact pressures and smoother surfaces. The most appropriate value for the gravel-type sediment at Barrow is 0.50 (Shapiro and Metzner 1987; Mahoney et al. 2007b). However, if we assume gouging of a keel, a higher coefficient of friction is expected (Timco and Weeks 2010). If we use the typical value of internal friction for a first-year ridge of 26.6° (equal to the angle of repose; Timco and Burden 1997), Figure 4.3 suggests that ridges off Barrow will mostly fail at the seafloor by overcoming the frictional force. While I consider this the most likely case as I proceed in this chapter to examine the impact of forces on SFI, it is important to note that if we assume a slightly lower value for θ, or a slightly higher value for c_f, and consider an imparted force at a time when keel cohesion is low (i.e., immediately after ridge formation or after a considerable influx of warm water to deteriorate the freeze bonds of the keel), shear failure is probable [3].

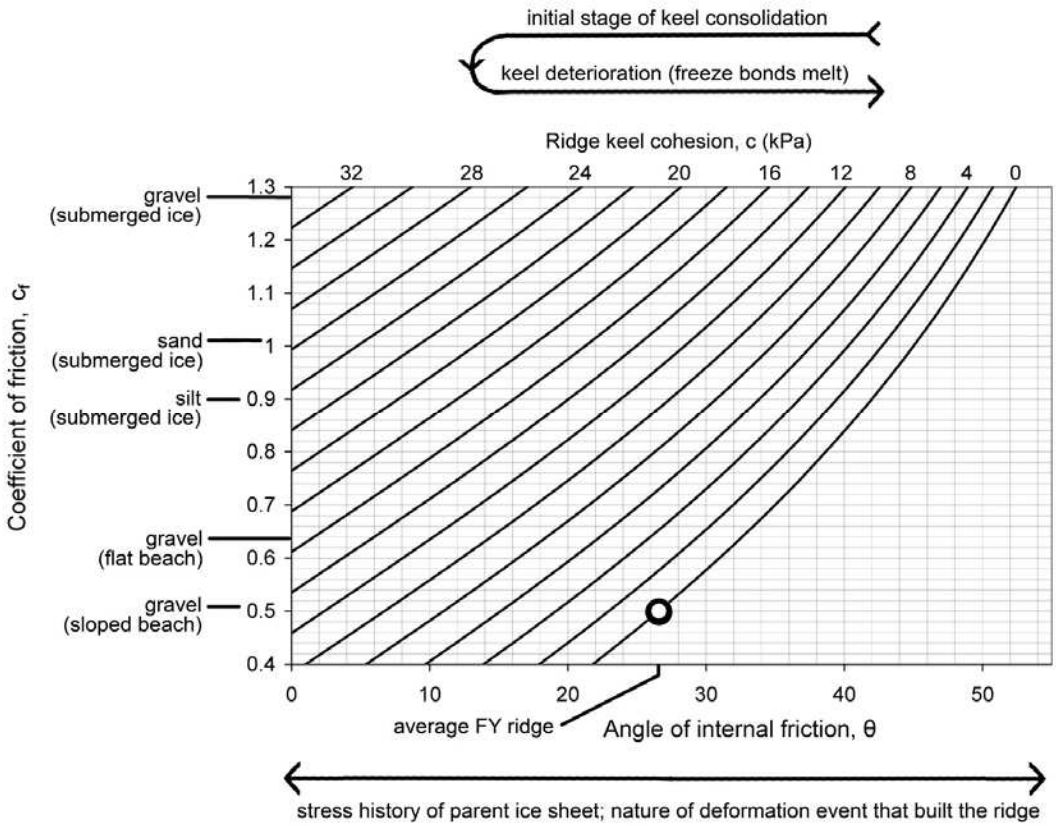


Figure 4.3 Contour plot that divides shear failure of a ridge keel from failure at the seabed. At points above the contour values for ridge keel cohesion, *c*, failure at the seabed will occur where the frictional stress is overcome. At points below the contour values, shear failure of the keel will occur. The contoured surface is representative of a 6 m ridge sail in 20 m of water depth (ρ_w=1027 kg m^{-3}; γ=4.2). Ridge keel cohesion, *c*, varies with ridge keel consolidation and the melting of freeze bonds. The average angle of internal friction, θ, for a first-year ridge in the Beaufort Sea is 26.6° (Timco and Burden 1997). Empirically derived coefficients of friction, c_f, are provided for different sediment types and field tests (Barker and Timco 2003). The black circle represents typical assumptions for first-year ridges near Barrow (α_s = 26.6°; c_f = 0.50).

4.3.3 Wind stress

The stress imparted on stationary SFI from a blowing wind, τ_a, is given by:

$$\tau_a = \rho_a C_a U_a^2 , \qquad [4.25]$$

where ρ_a is the density of the mass of air above the ice (e.g., 1.3 kg m^{-3} for dry air at -10°C) and U_a is the wind velocity in m s^{-1} at the anemometer height of 10 m. C_a is the unit-less ice-air drag coefficient, which can range from between 1.5 x 10^{-3} to 8.0 x 10^{-3} for very smooth first-year ice and extremely rough multi-year ice, respectively (Guest et al. 1994). For typical SFI off Barrow in springtime, the value is most likely to range between 3.1 x 10^{-3} (rough FY ice) to 4.2 x 10^{-3} (very rough FY ice).

The drag coefficient can be split into skin friction drag, due to the small-scale roughness of undeformed ice, and form drag, due to the influence of larger-scale ridges. Banke et al. (1976) developed the following equation:

$$C_a = C_{10} + (C_f \overline{h}_s N/2), \qquad [4.26]$$

where C_{10} represents skin friction drag (1.9 x 10^{-3} for arctic ice in the Beaufort Sea; Banke and Smith, 1973), C_f represents the form drag (0.3 for FY ridges to 0.4 for MY ridges), $\overline{h}_s$ is the mean ridge height, and N is the mean number of ridges per unit length in the wind direction.

To consider how frictional coupling at the sea bed can oppose an offshore wind, we must balance forces. Assuming the stress exerted by the wind is uniformly applied over the ice surface, the force exerted by an offshore wind, F_a, is given by:

$$F_a = \tau_a L_T, \qquad [4.27]$$

where L_T is the total extent of SFI. Substituting [4.25] into [4.27] gives:

$$F_a = \rho_a C_a U_a^2 L_T. \qquad [4.28]$$

Balancing [4.28] with [4.19] and solving for the minimum mean number of grounded ridges per unit downwind distance, N_g (equal to n_g/L_T), necessary to counter an offshore wind gives:

$$N_g = \frac{\rho_a C_a U_a^2 \tan\alpha_k}{c_f \rho_w g \overline{D}_g}. \qquad [4.29]$$

Similarly, the minimum extent of grounding E_g (the total length of ice in contact with the sea floor over the entire extent of SFI) required to counter an offshore wind is given by:

$$E_g = \frac{2F_a\left(\gamma\overline{H}_s - \overline{w}_g\right)}{c_f \rho_w g L_T \overline{D}_g}, \qquad [4.30]$$

where $\overline{H}_s$ and $\overline{w}_g$ are the mean sail height of grounded ridges and the mean water depth at grounding, respectively.

With respect to wind forcing, the transition between stable and unstable ice is very abrupt. Figure 4.4 plots the extent of grounding versus the keel depth to sail height ratio for different roughnesses and wind speeds. In practical terms, there is a fine line between stably and unstably grounded ridges. This fine line is determined by water depth or rather the water depth to sail height ratio. If interpreting Figure 4.4 such that the boundary between a low and a high required degree of grounding (i.e., between stable and unstable grounded ridges) is marked by the approximate region where the curves begin to steepen, a critical water depth to sail height ratio that may indicate grounding exists around 4.2, which is approximately 95% of the keel height to sail height ratio of 4.4.

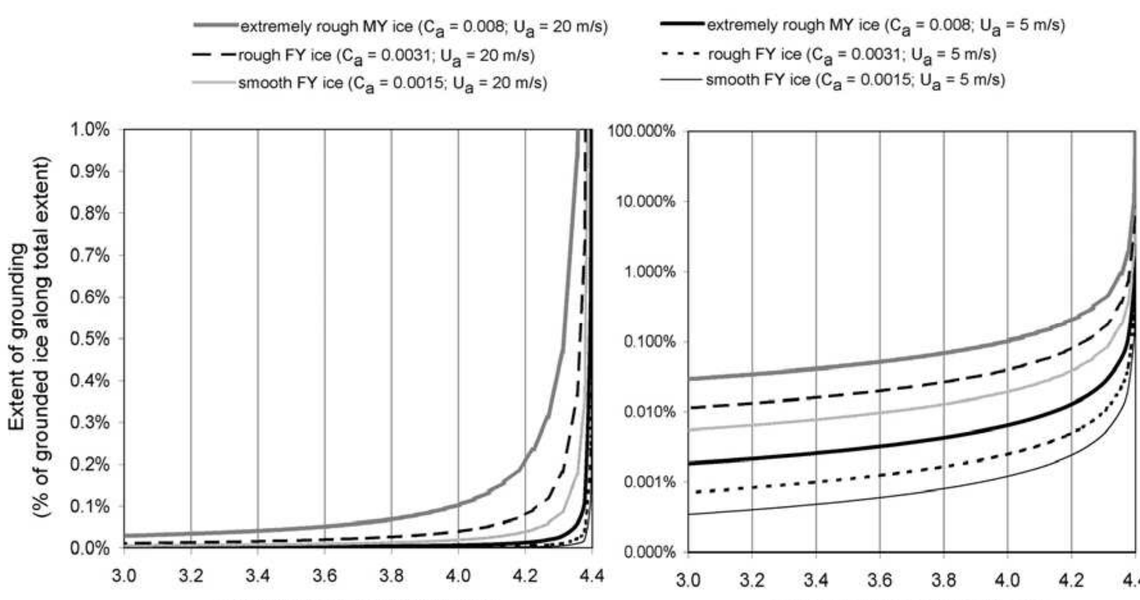


Figure 4.4 Water depth to sail height ratio versus the required extent of grounding for different ice roughness (C_a = 0.0015 to 0.008) and wind speeds (u_a = 5 and 20 m/s). On the left is a normal-normal plot up to 1%. On the right is a log-normal plot up to 100%. Calculations assume a keel depth to sail height ratio of 4.4, an average grounded sail height of 4 m, and a total shorefast ice extent of 10 km (ρ_w=1027 kg m^{-3}; c_f = 0.5).

It is important to note that we have assumed ridge characteristics based on floating ridges. While this is likely valid for estimating the area-above-buoyancy when a pre-formed floating ridge becomes grounded, it is not necessarily valid for ridges that form in-situ. Vaudrey (1980) found that sail heights and keel depths for grounded ridges are not as well correlated as floating ridges (R = 0.25 versus 0.93). The reason is simple. When a ridge is floating, the weight of the sail balances the buoyancy of the keel. In the case of ridge formation where the keel depth reaches the seafloor, the sail height is no longer limited by buoyancy. Vaudrey (1980), who surveyed both floating and grounded ridges, found a keel depth to sail height ratio of 5.5 for floating ridges, yet did not suggest this value to be the same as the critical water depth to sail height ratio that would indicate grounding. My analysis of their data on floating and grounded ridges suggests that a water depth to sail height ratio to indicate grounding would have to be 4.4, which is 80% of their keel depth to sail height ratio of 5.5.

To evaluate whether a given wind will overcome the frictional coupling between the keel and the sea bed, I consider the ratio of F_{sb} to F_a, which we may denote using [4.19] and [4.28] as S_1 such that:

$$S_1 = \frac{F_{sb}}{F_a} = \frac{c_f n_g \rho_w g \overline{D}_g}{\rho_a C_a U_a^2 L_T \tan \alpha_k} \,. \qquad [4.31]$$

Simplifying this ratio (ρ_a=1.3 kg m^{-3}, α_k = 26.6°, c_f = 0.5, ρ_w = 1027 kg m^{-3}) gives:

$$S_1 = 7750 \frac{n_g \overline{D}_g}{C_a U_a^2 L_T} \,. \qquad [4.32]$$

If $S_1 > 1$ the wind will not overcome frictional seabed coupling and if $S_1 < 1$ it will.

4.3.4 Current stress

Just as the ice cover can be forced by the wind, it can also be forced by ocean currents. The stress imparted on ice by the ocean, τ_w, is given by:

$$\tau_w = \rho_w C_w U_w^2 \,, \qquad [4.33]$$

where U_w is the current velocity in m s^{-1}at the bottom of the logarithmic boundary layer (approx. 1-3 m below the ice; 10% of total boundary layer). C_w is the ice-water drag coefficient, which is controlled by under-ice roughness and, like C_a, can be broken down into both skin friction and form drag. However, compared to ice-air interaction, form drag in ice-water interaction is much more significant given that the oceanic boundary layer, which is approximately 30 m thick, is much thinner than the atmospheric boundary layer, which is usually 1000 m thick (Wadhams 2000). A large range in values has been measured, from 7.8 x 10^{-3} for smooth floes in Bering Strait (Reynolds et al. 1985) to 20 x 10^{-3} (McPhee 1979) for ice in the central arctic pack. Leppäranta (2005) gives a value for the ratio C_a/C_w of 0.24 for arctic sea ice. Therefore, if for Barrow we consider a value for C_a of 4.2 x 10^{-3} for very rough FY ice, then it is appropriate to use a value for C_w of 17.5 x 10^{-3}.

The mean flow through Barrow Canyon is 20 cm s^{-1} from the SW[4], and measurements have shown velocities as high as 50 to 100 cm s^{-1} at 18 m depth (Weingartner et al. 2005). While velocities in the canyon are not necessarily representative of those in the coastal waters, Wilson et al. (1982) also measured coastal currents near Point Barrow of up to 50 cm s^{-1}. SIZONET moorings in 2010 have shown velocities upward of 70 cm s^{-1} may be expected[5]. With these values, we can expect a stress from current upwards of 8.8 kPa.

Assuming the stress exerted by the current is uniformly applied over L_T , the force exerted by a current, F_w, is given by:

$$F_w = \tau_w L_T \,. \qquad [4.34]$$

Substituting [4.33] gives:

$$F_w = \rho_w C_w U_w^2 L_T \,. \qquad [4.35]$$

Balancing the frictional coupling at the seabed, equation [4.19,] with the force applied by an opposing current, [4.35], the ratio of F_{sb} to F_w or S_2 is:

$$S_2 = \frac{F_{sb}}{F_w} = \frac{c_f n_g g \overline{D}_g}{C_w U_w^2 L_T \tan\alpha_k} \,. \qquad [4.36]$$

Using typical values ($\alpha_k = 26.6°$, $c_f = 0.5$, g = 9.8 m s^{-1}) gives:

$$S_2 = 9.8 \frac{n_g \overline{D}_g}{C_w U_w^2 L_T} \cdot \qquad [4.37]$$

If $S_2 > 1$ the current will not overcome frictional seabed coupling and if $S_2 < 1$ it will.

4.3.5 Changes in sea-level

Increases in local sea-level reduce the stability of the ice cover as F_{sb} decreases (see equations 4.19 and 4.20). Conversely, ridge keels are more stably grounded as sea-level decreases. To evaluate how a change in sea-level may impact the SFI cover's resistance to wind and current forcings, we must first adjust the average degree of grounding $\overline{D}_g$, equation [4.20], such that:

$$\overline{D}_g{}' = \frac{1}{n_g} \sum_{i=1}^{n_g} \left(\gamma \overline{H}_s - \left(\overline{w}_g + \Delta w_d \right) \right)^2 , \qquad [4.38]$$

where $\overline{D}_g{}'$ represents a modified average degree of grounding that account for a change in sea level, Δw_d. Accordingly, S_1 and S_2, equations [4.32] and [4.37], respectively, may be rewritten as:

$$S_1' = 7750 \frac{n_g \left(\overline{D}_g{}' \right)^2}{C_a U_a^2 L_T} \text{, and} \qquad [4.39]$$

$$S_2' = 9.8 \frac{n_g \left(\overline{D}_g{}' \right)^2}{C_w U_w^2 L_T} , \qquad [4.40]$$

where S_1' and S_2' likewise represent modified stability ratios that account for Δw_d.

It is important to note that Barrow has a very low tidal range. In spring, the tidal variation in the Chukchi Sea ice is about 12.5 cm (Hunkins 1965). Therefore, we are most concerned with pressure or wind driven changes in sea-level, including storm surges.

Ekman dynamics, which dictate that the direction of induced surface currents will be to the right of the wind forcing, can work to either increase or decrease local sea-level. Upwelling, and the decrease in local sea-level, are particularly strong in the western Beaufort and Chukchi Seas. Local strong easterly winds, which develop with strong sea-level pressure (SLP) gradients between the Aleutian Low and the Beaufort High (Cassano et al. 2006), drive upwelling along the Alaskan and Beaufort and Chukchi continental slopes (Yang 2006; Pickart et al. 2009). The intensity of upwelling winds in the Chukchi Sea diminishes in late fall and early winter with the inhibiting presence of heavy pack ice (Pickart et al. 2009). Pickart et al. (2009), who used a mooring array across the Beaufort shelf-break at approximately 152°W to detect upwelling, measured upwelling wind stresses at Point Barrow up to 0.5 Pa, which corresponds to approximately a 10 m s^{-1} wind blowing across rough first-year ice. Upwelling events were defined by easterly winds that led to either a pronounced weakening of the eastward Alaskan Coastal Current or a reversal from the east and a pronounced decrease in deep water salinity (as warm salty Atlantic water is presumably upwelled onto the shelf). Johnson (1989) was one to first note that wind forcing can lead to reversals from the dominant NE flow direction. Nearshore, coastal upwelling leads to not only a decease in coastal sea-level, but also warmer more saline waters in the nearshore region.

At Barrow, an upwelling (alongshore) wind blowing from the NE can lead to offshore flow in the upper layers and decrease sea-level at both the coast and ice edge. The greatest decrease is at the ice edge resulting in a cross-shore sea-level slope, which causes a geostrophic flow under the ice in the direction of the wind (Kasper 2010). Kasper (2010) used modeling to show that a 7 ms^{-1} upwelling wind blowing for 10 days along a uniform SFI cover of 25 km in extent results in cross-shelf sea surface slopes of 3 x 10^{-7}. Decreases in sea-level are linear with time and are also a function of ice-ocean coupling, such that a rougher under-ice surface leads to less of a sea-level drop beneath the ice. The stress τ_t imparted on the ice cover by the sea surface slope is given by (Leppäranta 2005):

$$\tau_t = -\rho_i z_i g\beta \,, \qquad [4.41]$$

where z_i is ice thickness and β is the slope. Even in the case of extreme upwelling developing a sea surface slope across the extent of SFI (e.g., $\beta = 3\text{x}10^{-7}$; Kasper 2010), the developed stresses are on the order of 0.01 Pa, which are quite negligible at values that are an order of magnitude below the wind stress.

While upwelling winds may not produce a sea surface slope that has a significant effect on the ice extent, the associated drops in sea-level can be quite significant for the stability of floating extension ice, which will be discussed in the following section. Through modeling, Kasper (2010) showed decreases in depth up to 1.3 m (7 m s^{-1} wind sustained for 10 days along a 25 km wide SFI cover). During observed upwelling, Weingartner et al. (2009) observed sea-level fluctuations beneath SFI in the Beaufort Sea of 0.5 m or more during winter.

Ekman dynamics can also work to increase local sea-level through onshore transport. For example, a wind blowing from the SW will force the upper ocean to move toward the SE, raising sea-level along the SW-NE trending coastline at Barrow. This was evident during a documented breakout event in 2007 (Druckenmiller et al. 2009), which will be discussed later in Section 4.5.2.

Storm surges at Barrow, typically associated with extreme and sustained westerlies, have been observed to raise sea level by 0.4 m in late-spring (Hunkins 1965) to 3 m in summer (Lynch et al. 2004). Extreme westerlies are associated with a low pressure system north of Barrow, originating from either a Polar-low or frontal cyclone that moves eastward from over Siberia and the East Siberian Sea (Cassano et al. 2006). Given that large fetch is required (i.e., a vast extent of open water), storm surges are much less of a concern during winter and springtime, when hunters are on the ice. However, there is greater potential for concern during the freeze-up period, before regional ice concentrations increase. At this time, surface waves likely play a role in the initiation stage of SFI formation as they may determine whether young ice persists and has the ability to be later thickened as part of the SFI, either through deformation or thermodynamic growth. Squire (1993) has shown that a portion of the energy of a wave incident on SFI penetrates beneath the ice, developing ice-coupled waves that may lead to fractures in the ice. Even in winter and spring, after fetch has been reduced, hunters have observed ice-coupled waves traveling beneath floating extensions of new ice (Harry Brower, Jr., pers. comm., 2008).

4.3.6 Failure in flexure

With a drop in sea-level, cracks can form where floating extension ice meets the grounded zone as the flexural strength of the ice is overcome. We may consider the floating ice as a beam uniformly loaded by its own weight as the supporting buoyancy force drops. The flexural strength of a floating sea ice sheet is given by (Langhorne 2004; Timco 2008):

$$\sigma_f = \frac{6W_b l}{bz_i^2}, \quad [4.42]$$

where W_b is the weight above buoyancy for the length of the floating extension L, l is the length between the fracture point and the place where the load is applied ($L/2$) of the ice sheet, b is the unit width, and z_i is the ice thickness. With a drop in water depth, Δw_d, W_b is given by:

$$W_b = \rho_w b \Delta w_d g L. \quad [4.43]$$

Rearranging equations [4.42] and [4.43], and solving for the maximum length of an extending ice sheet that can endure the drop in sea-level gives:

$$L = \left(\frac{\sigma_f z_i^2}{3\rho_w \Delta w_d g} \right)^{0.5}. \quad [4.44]$$

Flexural strength may range between 400 and 700 kPa, and is related to brine volume fraction, ν_b (Langhorne 2004; Timco and Weeks 2010) by the following:

$$\sigma_f = 1.76e^{-5.88\sqrt{\upsilon_b}}. \quad [4.45]$$

With equation [4.44] we can determine at what length an extension will break given a certain ice thickness, brine volume fraction, and drop in sea-level. For example, assuming a floating extension of ice of 1.0 m in thickness experiences a drop in sea-level of 0.25 m, and using σ_f= 700 kPa, the extension ice will crack providing the extension is at least 10 m in extent. However, it is important to note that this approach is only valid up until the flexural length scale of sea is reached, which is between 20 m and 2 km (Fox 2000). The flexural length scale for sea ice is determined by its flexural rigidity, which is related to the Elastic modulus and Poisson's ratio (Vaughan 1995; Fox 2000)[6].

Although even minor drops in sea level can lead to cracks developing through flexure, Langhorne (2004) found that if given adequate time to refreeze (before being forced offshore), a crack will develop a higher flexural strength than the host ice sheet, which is assumed to be linked to crystal structure and orientation in the healed crack.

4.3.7 Failure in tension

Sudden drops in sea-level that lead to cracks at the seaward edge of the grounded ice zone are also an important factor in the break-away of floating extensions in that they decrease the tensile strength of the ice on the larger scale.

With wind blowing across the SFI, the tensile stress per unit width of ice σ_t is given by (Timco 2008):

$$\sigma_t = \frac{\tau_a L_T}{\bar{z}_i}, \qquad [4.46]$$

where $\bar{z}_i$ is the average ice thickness of the floating extension. If we assume that tensile failure will not take place shoreward of the grounded zone, but rather within the floating extensions, equation [4.46] can be written as:

$$\sigma_t = \frac{\tau_a (L_T - x)}{\bar{z}_i}, \qquad [4.47]$$

where x is the distance between the coast and outermost seaward edge of the grounded zone. A similar expression can be derived for a current acting on the ice. S_3 and S_4, which relate to a stable extension's tensile strength when facing an offshore wind or current can be defined as:

$$S_3 = \frac{\tau_a (L_T - x)}{\sigma_t \bar{z}_i}, \text{ and} \qquad [4.48]$$

$$S_4 = \frac{\tau_w (L_T - x)}{\sigma_t \bar{z}_i}. \qquad [4.49]$$

If $S_3 > 1$, the extension will fail under the applied wind stress. Likewise, if $S_4 > 1$ the extension will fail under the applied current stress. Timco and Weeks (2010) give empirically-derived values of 200 to 800 kPa for the tensile strength of first-year ice on the block scale. Yet on the large scale (the scale of interest here) values may be around 20 kPa (Timco 2008) or 25 kPa (Tremblay and Hakakian 2006). Tensile strength, the maximum tensile stress before failure, is inversely dependant on both temperature and porosity. Let us consider a floating extension of rough FY ice were the average thickness is 1 m stressed by a gale force wind of 20 m s^{-1}. In this scenario (σ_t = 20 kPa, ρ_a=1.3 kg m^{-3}, C_a = 3.1 x 10^{-3}), the extension would have to be at least 12 km wide.

4.4 Iñupiat ice experts assess safety

Nelson (1969) wrote that "the characteristics and behavior of shorefast ice are so generally predictable that they have figured greatly into the hunting and travel techniques of Eskimos." The Iñupiat managed the risk of uisauniq events through a sophisticated understanding of the interaction of local variables. As is the case of most bodies of LTK, Iñupiat sea ice knowledge has not been developed with the intention of being precisely communicated in writing. Here, I present only a summary approximation of LTK on SFI stability based on approximately 25 interviews, many informal discussions, and literature (Norton 2002; George at al. 2004; George et al., unpubl.).

In my experience of talking with hunters about ice conditions and asking the question "*Will the ice break-out?*", I have observed two levels of assessment. First, they assess the local ice cover on the larger scale, often describing the current year in reference to past observations. It is in the context of these types of observations that hunters (usually of ages between 40 and 80) tend to talk about the significant differences between the present conditions and that of the past. The second type of assessment is one that identifies specific ice features and/or hazards that are relevant to their safety. Spending much time on, and traveling great distances across SFI, hunters are able to not only identify features in one location, but observe their spatial distribution or continuous coverage over kilometers, such as can be the case with shear ridges, refrozen cracks, rafted ice sheets, etc. These assessments are not made solely by individuals, but result from efficient exchanges within the social network of the whaling crews. When specific potential hazards are of concern, hunters on the ice often use VHF radios to consult elders or other experienced hunters. Radios allow specific assessments to span an area greater than the individual's sphere of observation.

Table 4.1 summarizes the LTK of the most important considerations when assessing the risk of SFI failure. These factors have been divided into four different categories: (1) ice features, (2) forcing, (3) indicators, and (4) processes.

Table 4.1 LTK in the Barrow region of the most important factors or warning signs to consider when assessing the risk of break-out or break-away events (sources: formal interviews and informal discussions with Barrow whalers; George et al., unpubl.).

Ice feature	Description
Accretion boundary	Boundary feature (e.g., crack) where ice has added on to SFI; often the same places where the ice will later break-away
Active crack (nutaqqutaq*) shoreward of grounded zone	Active crack in the SFI, kept open by either slight shifting of ice or by warming air or water temperatures
Iiguaq*	Section of ice that is weakly attached to the SFI
Muġaliq*	Slush or brash ice that forms through shear and the incorporation of snow; may either comprise large sections of SFI or represent narrow bands of ice at attachment boundaries; rapidly looses integrity when warmed
Ridge height	The higher the ridge, the more likely the ridge is grounded.
Sediment in the ridges	Sediment in the ridges is often seen as sign that the ridge is anchored
Cracks around ridges	Indicate that the ridge is not rising and falling with sea level and is therefore grounded
Thickness of level ice	A thicker ice cover leads to fewer but larger, more anchored ridges
Multi-year ice	Thick multi-year ice incorporated in SFI adds to the anchoring strength, especially when broken into large ridges
SFI edge geometry	Critical in determining whether a glancing collision from pack ice will detach sections of SFI. A smooth edge (i.e., consistent SFI extent along the coast) is more likely to lead to shearing at its outer boundary.
Forcing	**Description**
Tuuq*	Refers to a glancing collision by pack ice that results in the removal of SFI sections; means "to chisel"
Katak*	Sudden drop in sea level where the flat extensions ice near grounded ridges cracks and may break-away; means "to fall"
Sudden sea level rise	Can un-anchor grounded ridges; most likely with a south wind
Strong offshore wind	Can cause unsecure ice to detach; can lead to a katak*
Strong offshore current	Particularly dangerous condition where the current flows out from beneath (perpendicular to) the ice edge; can cause unsecure ice to detach and can break-up ridge keels

Table 4.1 continued

Strong current	Can cause unsecure ice to detach
Tsunamis	Submarine earthquakes and/or landslides are assumed to have led to a number of tsunamis in the past that have destabilized SFI.
Indicator	Description
Ice drifting against a strong wind	When drift ice is observed moving in the opposite direction of a strong wind, a dangerously strong current exists.
Reversal in current direction	A time to be overly cautious is when the current direction shifts (e.g., current from the NE reversing to a current from the SW).
Rise in current	A strong surface current can be predicted based on first detecting a strong current near the sea floor. Over a day or so, the current speed will increase at progressively shallower depth and eventually high current speeds reach up to the underside of the SFI.
Palusaqniq*	Weather system that may potentially destabilize the SFI that begins with winds out of the SE that continue to swing around to the SW where the wind direction leads to dangerous increases in sea level and tends to bring pack ice in toward the coast.
Moon phase	Moon phase leads to increased high tides during the spring tides (i.e., during the new or full moon)
Ridges that don't move during seasonal extremes	The best indicator if a ridge is well-anchored is whether its position remains unchanged throughout strong winds or currents or pack ice collisions.
Muġaala	Blocks of ice from ridge keels detach and emerge in the open lead, indicating keel deterioration; means "to throw-up" (see Chapter 3)
Process	Description
Prolonger periods of cold air temperatures	Increase the overall anchoring strength
Warm air temperatures	Lead to the overall weakening of SFI, mostly by weakening refrozen cracks and muġaliq*
Warm water arriving in May	Qaisagnaq*, the current from the SW, intensifies in May and brings warm water; leads to the overall weakening of SFI (ridge keels, level ice, and refrozen cracks)

* Iñupiat terminology.

4.4.1 Ice features

SFI incrementally and variably extends seaward through a series of attachment and break-away events, mostly throughout the first three stages of the ice year until a maximum extent is reached in May (Eicken et al. 2006). The boundary within the SFI of each attached section represents a line of fusion between two morphologically different sections of ice. Often these accretion boundaries are clearly marked by (1) a discrete transition between two ice sections of different surface characteristics, e.g., roughness, (2) a crack that may or may not completely refreeze or remains active with internal shifting of SFI, (3) a shear or compression ridge, or (4) a boundary of predominantly slush ice that piles up (muġaliq), often due to extensive shear motion. Iñupiat hunters identify sections of weakly attached ice as iiguat (Druckenmiller et al. 2010, Chapter 3; George et al. 2004). These areas are typically identified either because their accretion boundary appears susceptible to detachment or they are thin relative to level first-year ice. As mentioned previously, thin attachments can breakup when penetrated by long wavelength surface gravity waves (Squire 1993), made possible during times of large areas of open water in the region. Accretion boundaries are monitored throughout the season as likely locations for failure.

Local ice experts observe ridges for indication of anchoring. The Iñupiaq word for a grounded ridge is kisitchat, which literally translates to "anchor". General ridge height and size are considered alongside an understanding of how water depth varies along their coastline. They do not apply a strict rule of thumb to determine whether a ridge of a certain height is grounded. They look for the presence of sediment attached to the outside of ridge blocks as a sign that the ridge keel reached the seafloor during its formation[7]. Cracks around the ridges also indicate that it is not rising and falling with sea-level and is therefore grounded.

Hunters likely also recall memory of past conditions to produce relative assessments of how well the ice cover may be anchored. Hunters today see a significant decrease in the presence of multi-year ice, and relate this observation to differences in how the ice cover is anchored. In the past when level SFI was thicker, presumably through the presence of more multi-year ice floes, there were fewer, but much larger ridges than today. In general, hunters acknowledge that when ice is thicker, larger ridges develop.

Another important characteristic of the SFI cover that hunters observe is the shape or geometry of the ice edge—a characteristic that is nowadays more easily observed through satellite imagery. A smooth and consistent edge allows drifting pack ice that may rub against or obliquely strike the edge to pass without breaking away significant sections of SFI. On the contrary, an angled or protruding ice edge may provide a point of collision with pack ice moving parallel to the SFI edge, resulting in a break-out or break-away event. This action by pack ice is termed tuuq, which means "to chisel".

4.4.2 Forcing

In addition to observing the ice cover, local experts pay close attention to wind and current. Periods when the current is very strong, especially when observed flowing out from under the ice in an offshore direction, are times to be very cautious of break-out and break-away events (George et al., unpubl.). Hunters routinely monitor currents by observing ice drift directions and the deflection of a sounding line dropped from the edge.

Wind is very easily monitored (especially in comparison to currents) and may ultimately be the most important locally observed variable in influencing the assortment of forces that affect SFI stability. In most descriptions of conditions where risk of a failure is high, wind speed and/or direction is mentioned as a contributing factor. A strong offshore wind is known to both force the ice but also to drop sea-level. Katak, which means "to fall," is the Iñupiaq term used to describe a sudden drop in sea-level where the flat ice near grounded ridges cracks and may lead to a break-out (George et al., unpubl.; Norton 2002). A strong offshore wind can also open the lead and develop rough water, which may act to "chip away" (iiawwaqtuk) small sections of the outermost shorefast ice edge. Sudden increases in sea-level can destabilize the SFI, and are mostly attributed to south winds. Hunters observe such increases in sea-level by water coming up through cracks, such as those near ridges or the tide crack that forms along the beach.

Although observing signs of forces is critical to risk assessment, George et al. (unpubl.) found through many conversations with Barrow hunters and through examining various case studies of notable break-out events that involved people, that many actually took place under calm conditions. There are two possible explanations for this. First, it could be a sampling bias since hunters are more likely to be on the ice during a break-out under calm conditions than they are to be on the ice during a break-out under extreme conditions. Second, it may relate to a time delay between the preconditioning of ice for a break-out and the arrival of a force great enough to cause the break-out. If sufficient preconditioning occurs (e.g., the melting of grounded ridge keels), the required force for a break-out may be minimal and interpreted by hunters as calm conditions. In discussing break-out events, hunters also note the unusual; specifically, the occurrence of tsunamis (George et al., unpubl.)[8]. Unusual events are important to a people that spend a large amount of time on sea ice and possess an oral history that emphasizes such events.

4.4.3 Indicators

Local experts use various indicators to efficiently predict and monitor potentially dangerous currents. Given that the direction of drift ice is both guided by wind and current velocities, hunters identify dangerously strong currents by observing ice drifting against a strong wind. Joe Leavitt has explained that an arrival of strong current can be predicted based on first detecting a strong current near the sea floor. Over a day or so, the current speed will increase at progressively shallower depth and eventually high current speeds reach the underside of the SFI. Leavitt also explained that a reversal in current direction is another important warning of potentially unstable conditions. I will address this observation in more detail in Section 4.5 and 4.6.

Palusaqniq is the Iñupiaq term that describes the arrival of a weather pattern that begins with winds out of the SE that continue to swing around to the SW where the wind direction leads to dangerous increases in sea-level and tends to bring pack ice in toward the coast. Hunters also attribute increased sea-level to lunar tides with the highest occurring during the new and full moon phases (George et al., unpubl.).

In terms of assessing the stability of grounded ridges or the attachment strength of extension ice, hunters observe the wind and weather conditions that the shorefast ice endures throughout the season. For example, a ridge that remains unmoved and unchanged throughout strong winds or currents or in spite of a significant impact from pack ice is likely well-anchored. While winter storms are important for establishing grounded ridges (as discussed in Section 4.2.1), they also provide observant hunters with a means for "testing" the stability of ridges that may have already developed. However, this method of assessing stability begins to fail as warm air and water temperatures arrive in spring. Hunters often observe the weakening in the anchoring of ridges near the lead when ice blocks from the keels detach and emerge in the open lead. Hunters associate this process (muġaala) with the arrival of warm water from the SW. Beyond this general explanation, I never heard local experts discuss other potential sources of heat to the ocean, such as by solar heating through an open lead along the SFI.

4.4.4 Processes

Hunters acknowledge that wind and current alone do not usually lead to break-out or break-away events (George et al., unpubl.). It is generally necessary that some level of preconditioning take place, which is most important to consider at the accretion boundaries (mentioned in Section 4.4.1) and at grounded ridge keels. The accretion boundaries fail when structural integrity diminishes with increasing air temperatures, and in particular when such warming is coincident with pack ice interaction or other dynamic forces. When analyzing sea ice growth, science quantifies the duration and intensity of low temperatures in terms of freezing degree days (the sum of the average daily degrees below zero Celsius for a specific time period). Local ice experts consider low temperature history in a more qualitative manner as they evaluate the healing of cracks and the solidification of slush or brash ice that is present within accretion boundaries. I have also heard hunters speak of the strengthening of ridges with cold temperatures, but this may be logically assumed rather than actually observed. The arrival of warm water is often attributed to the strengthening of the current from the SW (Qaisagnaq) in May.

While Table 4.1 summarizes LTK in manner that may complement the detailed discussion of the geophysics in Section 4.3, it does not provide a framework for comprehensively evaluating the factors that govern whether the ice will break-out or break-away. The next section presents an approach in this direction.

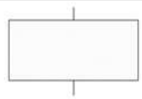
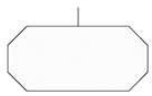
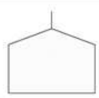
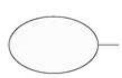
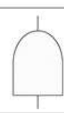
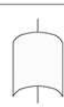
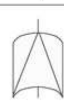
4.5 Fault tree analysis

In this section, I introduce fault tree analysis (FTA) as a way to evaluate failure using perspectives from both geophysics and local knowledge. FTA identifies potential pathways to a precisely defined top-level failure event using deductive logic to combine a series of lower level events. The goal is to reveal the causal relationships between system components and to describe the behavior of the system (Ferdous et al. 2007). While FTA has found most use in the fields of safety and operational engineering where systems are man-made (AIChE 2000; Ferdous et al. 2007), it has been applied to natural systems in a few cases (Barnthouse and Suter 1986; Hayes 2002). To the best of my knowledge, this work is the first to use this approach to combine science with local and traditional knowledge.

4.5.1 Constructing the fault tree

To construct a fault tree, I define the top-level failure event as a SFI failure during winter or spring, which may be either a break-out or break-away event as defined in Figure 4.1. Table 4.2 presents the names and descriptions of the symbols used to develop the fault tree. Forces on shorefast ice are represented by either intermediate or basic (bottom-level) events based on the level of causality defined in the fault tree. Input variables represent the quantifiable variables discussed in Section 4.3. Indicator events are those that may be used to predict the occurrence of a force, and are largely taken from both Section 4.3 and Table 4.1. The two primary gates used in FTA are AND and OR gates. With an AND gate, output (i.e., the higher-level event) occurs if all inputs occur together, while with an OR gate, output occurs if one or more inputs occur. Formulation gates identify relevant equations from the text.

Table 4.2 Fault tree analysis symbol names and descriptions

Symbols	Symbol name	Description
	Top level event	Specific failure event that guides the development of the fault tree
	Intermediate event	Event may exist between all types of events or gates
	Undeveloped event	Bottom-level event that is not developed further due to lack of information or beyond the scope of this work
	Basic event	Bottom-level event where information in known
	Transfer-out event	Event is developed further in a related fault tree
	Transfer-in event	Event is linked to an overarching fault tree
	Indictor event	Indicates an observation that typically occurs in connection with an event
	Input variable	Indicates an important input variable that controls a gate's operation
	AND gate	Output occurs if all inputs occur
	OR gate	Output occurs if any inputs occur
	Exclusive OR gate	Output occurs if only one input occurs
	Formulation gate	Identifies relevant equation when available in the text

For Barrow's SW to NE oriented coastline, the directionality of specific wind forcing as used throughout the fault tree (unless specifically noted otherwise) is as follows: An alongshore upwelling wind is from the N to E quadrant, an offshore wind is from the E to S quadrant, an alongshore downwelling wind is from the S to W quadrant, and an onshore wind is from the W to N quadrant. The same directionality is used when referencing currents. The direction of current flow follows the atmospheric convention (i.e., direction is given as the direction from which the current is flowing).

Figures 4.5 through 4.11 present individual sections of a larger connected fault tree. Figure 4.5 establishes that SFI failure occurs if a break-out or a break-away occurs. Two events are necessary for a break-out: insufficient anchoring strength (see Figure 4.6) and a destabilizing force. A destabilizing force may occur either with an offshore wind, an offshore current, a rise in sea-level accompanied by an offshore force (see Figure 4.7), or a collision with pack ice (Tuuq; see Figure 4.8). Immediately, I must recognize that explicitly defining the directionality of forces is a particular challenge in constructing this fault tree. For example, an offshore wind, which is here designated as from a direction ranging from E to S, will act directly against the SFI cover's ridges if they are linear and roughly parallel to the coast. However, experience has shown that this is not always the case (see Chapters 2 and 3). Ridges can form in an orientation that is perpendicular to the coast, such that an alongshore wind may be normal to the ridge line. This is also problematic as we consider the mean coastal currents acting on the ice. As will be discussed later, the currents off Barrow largely fall within only two main directions—either from the SW or from the NE—both of which are parallel to the coast. Therefore, an assumption of linear ridge systems that are strictly parallel to the coast largely negates the potential for current forcing from the two primary directions. However, this assumption is valid for assessing the influence of tidal currents and storm surges, which may involve strong on- or offshore components. Nonetheless, for the purposes of demonstrating the usefulness of FTA to SFI stability, I assume linear ridge systems parallel to the coast.

Figure 4.6 establishes what contributes to an insufficient anchoring strength. At the top level, two important indicators taken from LTK are shown. Observations that a ridge has previously shifted under a significant force, such as strong winds, or the lack of visual evidence of grounding (i.e., no cracks around the grounded ridges or sediment on the underside of ice blocks[6]) provides indication to hunters that a ridge may not be well anchored. The remainder of this figure establishes that a ridge will either fail in shear or the frictional coupling between the keel and seabed will be overcome (see Figure 4.3). In both cases, the degree of grounding is an essential factor to consider.

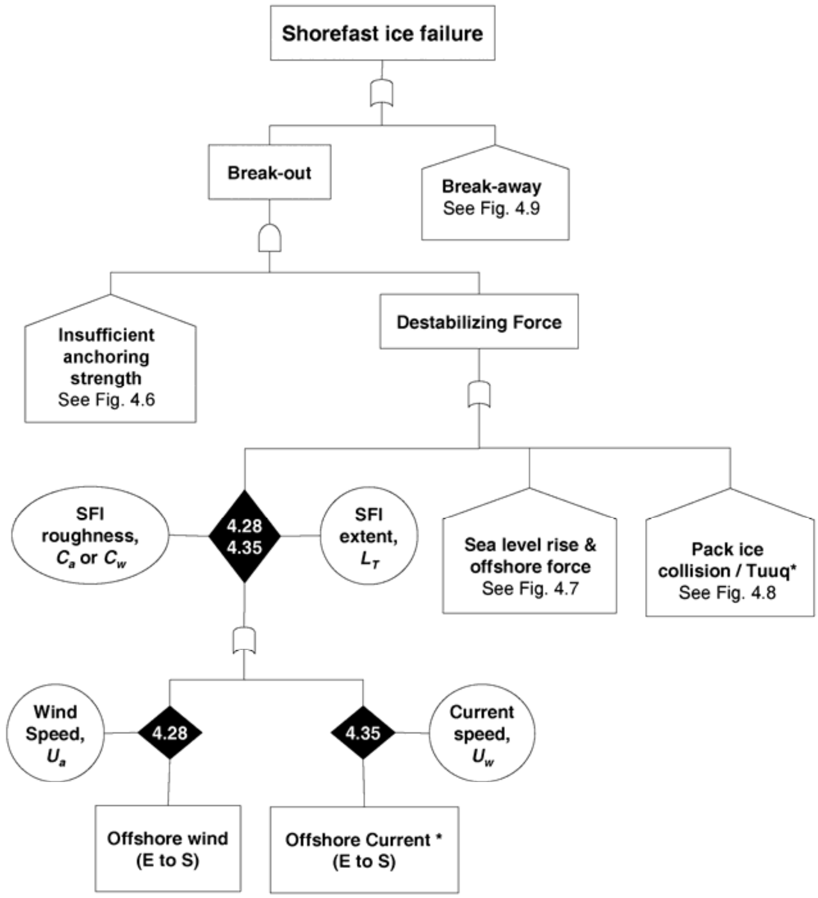


Figure 4.5 Top-level of the fault tree for SFI failure (connects with Figures 4.6, 4.7, 4.8, and 4.9). Asterisks (*) indicate factors from Table 4.1.

Figure 4.7 presents the scenario for the co-occurrence of a rise in sea-level and an offshore force. Implicit is the assumption that a rise in sea-level alone will not lead to a break-out event without a force to move the ice away from the coast. Two scenarios are possible, either a pack ice collision or an offshore south wind, both of which can occur alongside a rise in sea-level due to downwelling winds. Here, an offshore wind is limited to a south wind since it must also be from a direction that can lead to downwelling. In Figure 4.7, I include the highly rare observation of tsunamis leading to break-outs. Although such a rare event is not considered in the decision-making process of hunters when assessing risk, it has been a factor attributed to past events that have led to the break-out of hunters[7], and thus demonstrates that his approach is conceptually capable of incorporating a range of scenarios despite their low probability.

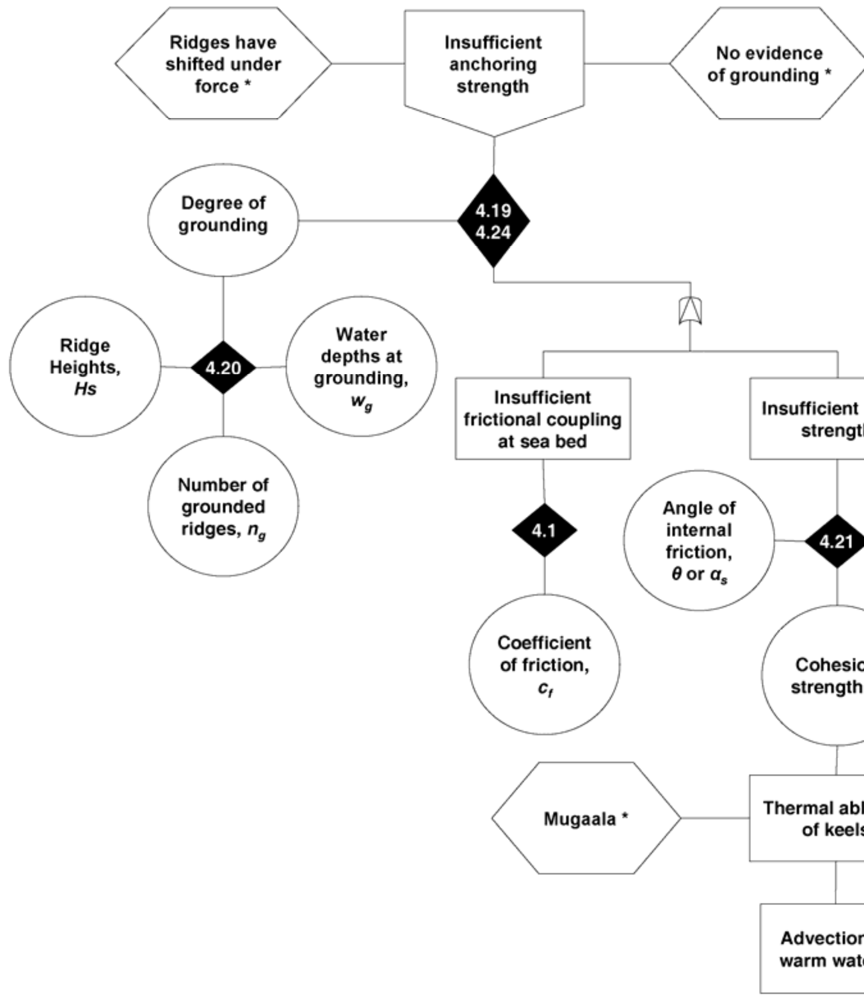


Figure 4.6 Fault tree segment for insufficient anchoring strength (connects back to Figure 4.5). Asterisks (*) indicate factors from Table 4.1.

Figure 4.8 describes what is necessary for a pack ice collision (or tuuq). There must exist (1) a vulnerable SFI geometry, i.e., an angled or protruding ice edge that provides a surface for contact, (2) a strong alongshore wind or current, and (3) drifting ice adjacent to the SFI edge. The latter may arise from either concentrated pack ice near shore that is brought in by sustained onshore winds or downwelling, or the proximity of heavy floes, such as individual multi-year floes or large consolidated drifting ridges. Note that the fault tree does not consider ice shoves where the pack ice pushes directly against the SFI, but rather defines an impact as one that is oblique to the SFI edge.

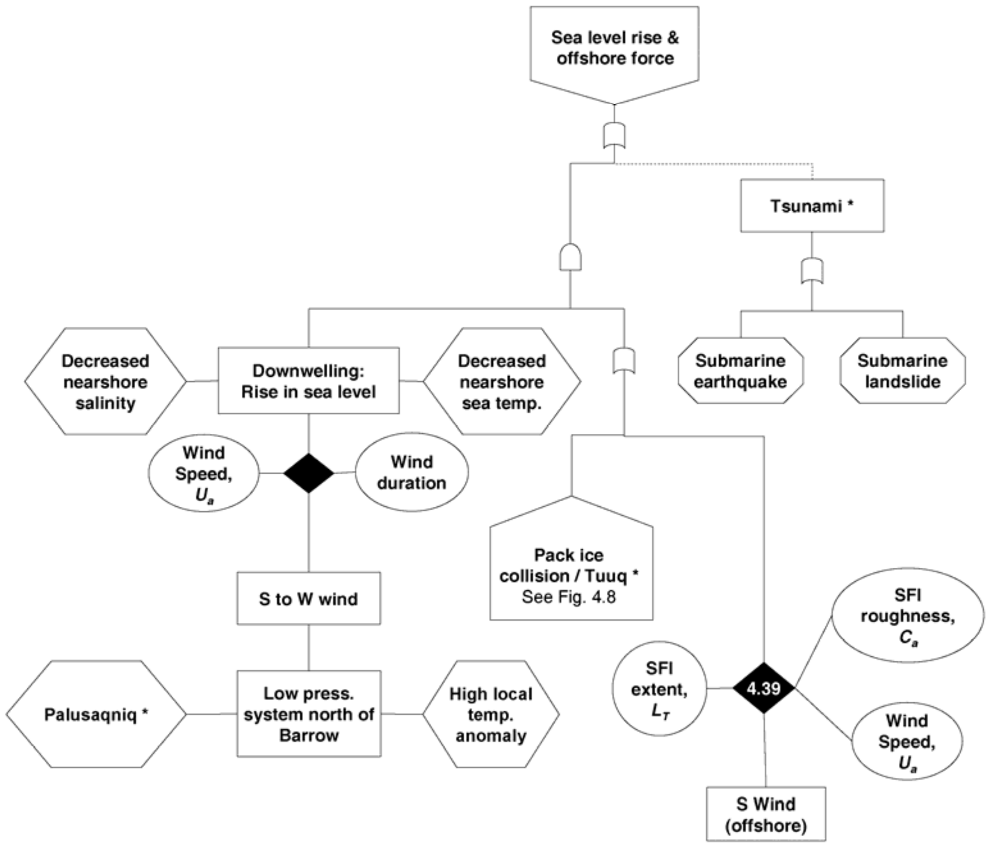


Figure 4.7 Fault tree of a sea-level rise contributing to a SFI break-out (connects back to Figure 4.5 and forward to Figure 4.8). Asterisks (*) indicate factors from Table 4.1.

Figure 4.9 represents the different pathways that may lead to a break-away event. An iiguaq (or weak attachment; see Figure 4.10) must co-occur with a destabilizing force. The force may be either an offshore wind or current that directly imparts a force on the ice, a collision with pack ice, or surface waves that develop in an open lead that provides sufficient fetch.

Figure 4.10 presents the different scenarios that may lead to an iiguaq (or weak attachment) at the outmost boundary of the SFI. Here, I present "false shorefast ice" as not necessarily a type of weak attachment, but rather as ice that remains present along the edge under periods of pinning by pack ice or stagnant winds and currents but that is not actually attached. This highlights the importance of the practice by local experts of observing the history of SFI and the weather and ocean conditions under which it has endured. Weak attachments are present for two main reasons—either there is a crack shoreward of the grounded zone or there is muġaliq (refrozen

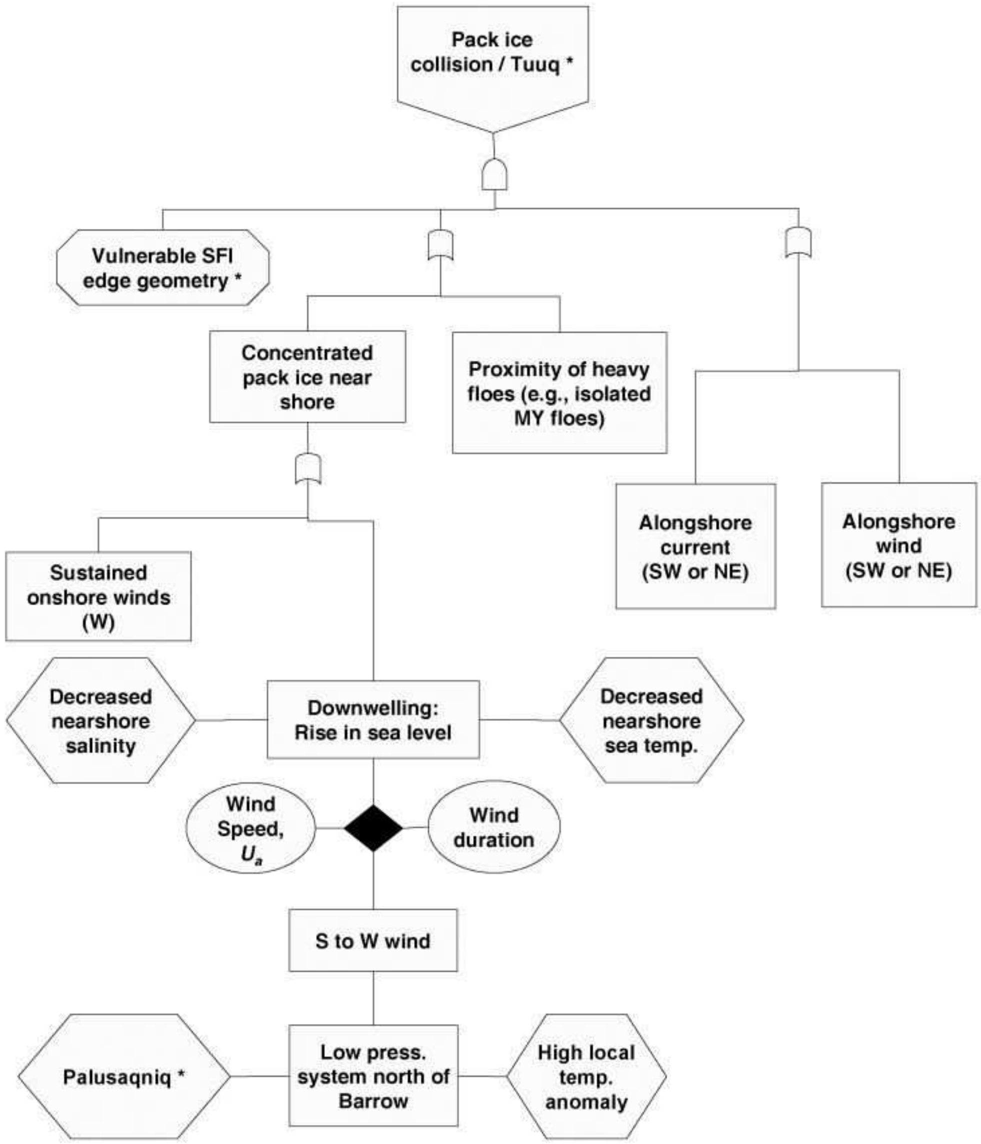


Figure 4.8 Fault tree of a pack ice collision contributing to a SFI break-out (connects back to Figures 4.5 , 4.7, and 4.8). Asterisks (*) indicate factors from Table 4.1.

brash ice and slush) at the accretion boundary. Decreases in the tensile strength of both of these features are vulnerable to increasing air temperatures, radiative forcing, and the advection of warm water. However, cracks can also remain active under the influence of dynamic forcing as well, such as sea-level fluctuations that crack floating ice at where it attaches to the grounded zone.

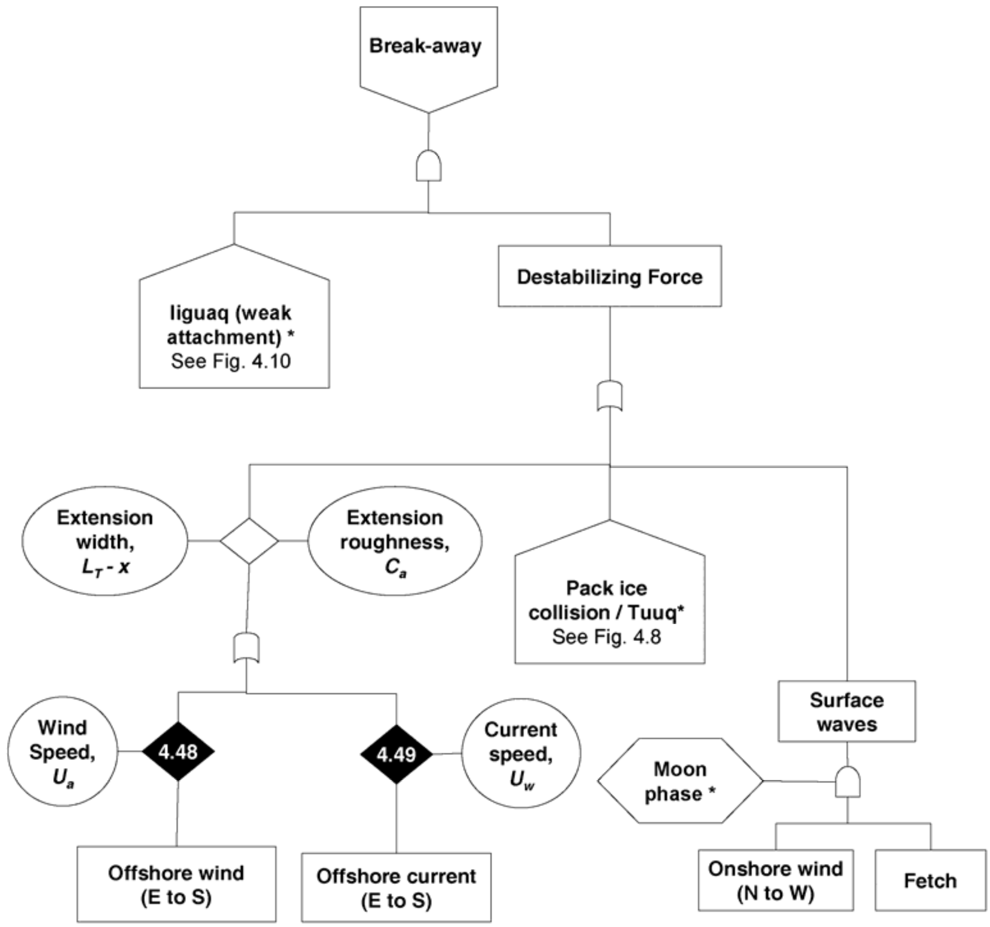


Figure 4.9 Fault tree of a SFI break-away event (connects back to Figure 4.5 and forward to Figures 4.8 and 4.10). Asterisks (*) indicate factors from Table 4.1.

Lastly, Figure 4.11 summarizes the controlling variables that lead to a drop in sea-level due to upwelling. As noted earlier in Section 4.3, indicators of upwelling include increased nearshore salinity and sea temperatures. As an additional indicator, I consider the reversal in current (see Table 4.1) that hunters acknowledge as an important warning sign of a break-away event. An explanation for this may relate to the observation by Johnson (1989), mentioned previously, that strong upwelling winds can lead to a reversal in the Alaskan Coastal Current from an easterly direction to a westerly direction. In this sense, perhaps a reversal in current may predict a katak event that may break-away floating extensions.

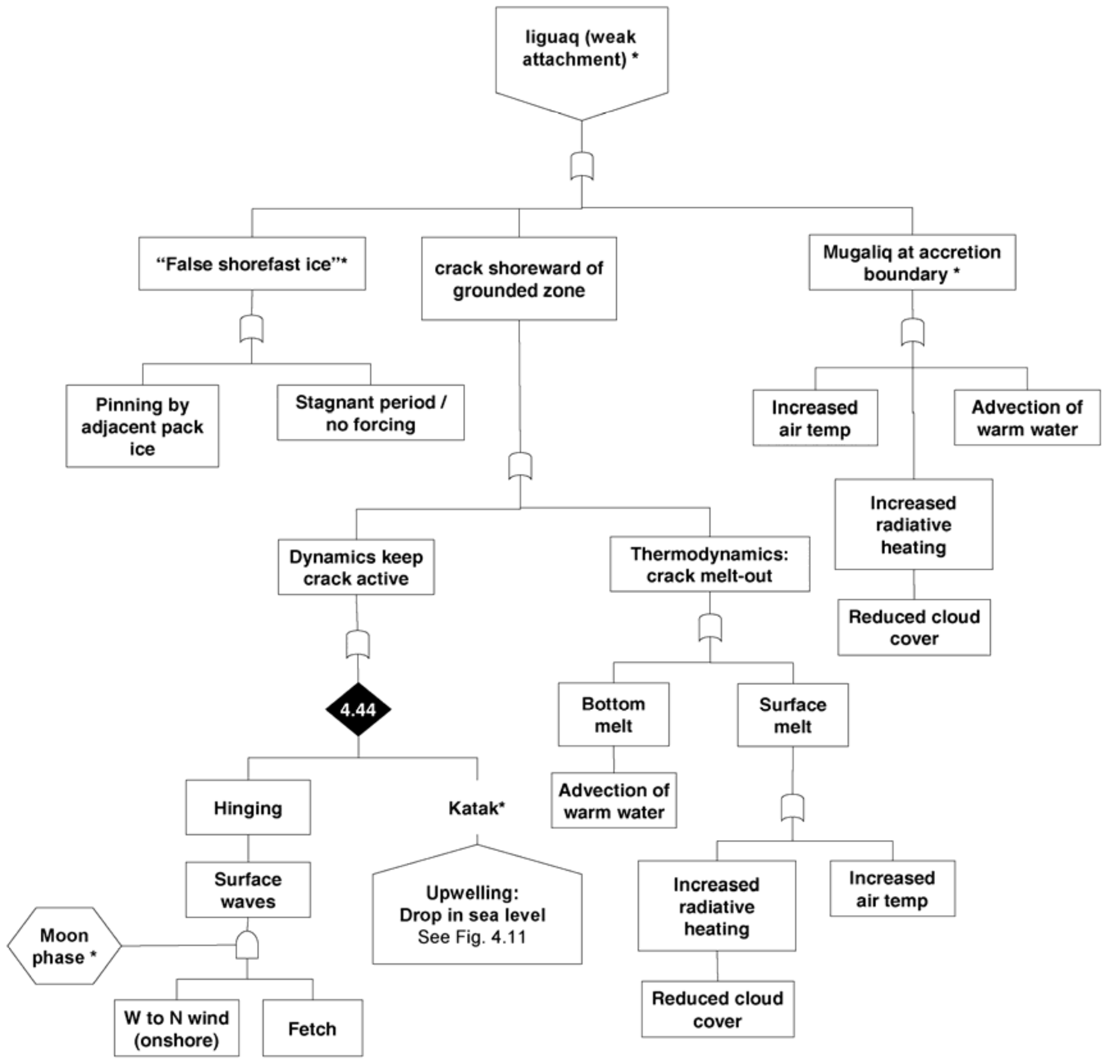


Figure 4.10 Fault tree of an liguaq that will condition a SFI break-away event (connects back to Figure 4.9 and forward to Figure 4.11). Asterisks (*) indicate factors from Table 4.1.

4.5.2 Evaluating a break-out event from 2007

To illustrate how the constructed fault tree can work to evaluate the reasons for specific break-out or break-away events, I examine the break-out event that took place in 2007, which was previously described in detail by Druckenmiller et al. (2009, Chapter 2, refer to Figures 2.3 to 2.6). What makes this particular case study unique is that the event was observed in detail by the various components of the Barrow Sea Ice Observatory. On March 28, pack-ice drifting from the SW collided with (tuuq) a protrusion in the SFI edge, resulting in a break-out and rigid-body

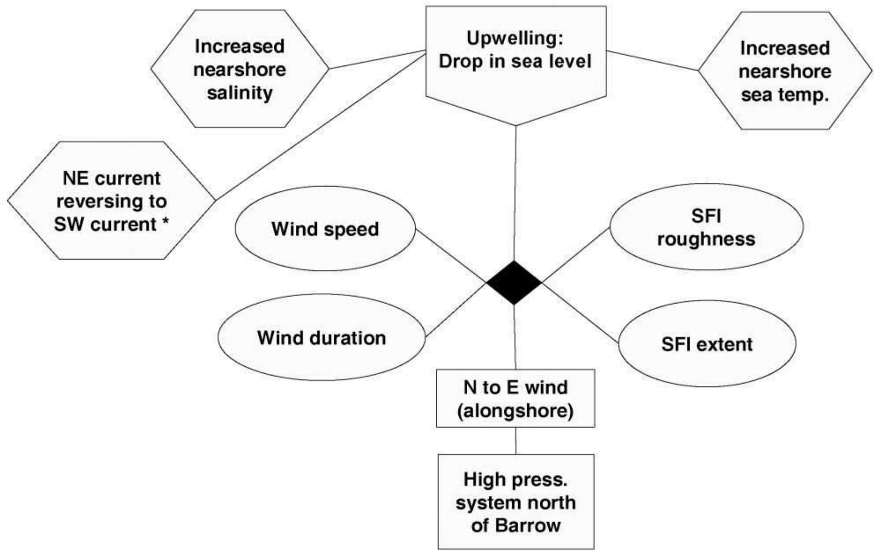


Figure 4.11 Fault tree of a drop in sea-level through upwelling contributing to a SFI break-away event (connects back to Figure 4.10). Asterisks (*) indicate factors from Table 4.1.

rotation of an approximately 8 km^2 section of ice. Luckily, no people were on the ice. A coastal radar captured the dynamic sequence of events by tracking ice drift locations at 4 min resolution before, during, and after the break-out. Satellite imagery provided additional information of ice extent and the concentration of adjacent pack ice. A sea-level gauge showed an increase in sea level in the ten days prior to the event along with a marked increase in water temperature. Local weather data revealed sustained SW winds during the period of increased sea level and a significant peak in air temperature following the recovery from a period of low SLP. Local observations by Joe Leavitt provided insight into the anchoring strength of the ice that broke-out.

Figure 4.12 presents the contributing factors to this break-out event by extracting events and pathways from the overarching fault tree of Figures 4.5 to 4.11. Joe Leavitt's written observations indicated that the pressure ridges in the region that broke-out had not endured recent forcing because they had "changed" (moved) during a west wind in the days prior to the event. This indicates insufficient anchoring strength; however, no information on sail heights in the region was available. Two events contributed to the destabilizing force. First, at the time of the event there was a moderately strong east wind at 7 m s^{-1}. While the wind may have contributed to the export of SFI after failure, it is unlikely that such a wind triggered the failure. Through analysis of the radar imagery, the event clearly appeared to be initiated by the oblique pack ice collision at the “vulnerable” location on the SFI edge. The near-shore pack ice concentration increased in the ten day prior to the event through a sustained SW wind that resulted in increased sea-level through downwelling (as observed from the sea-level gauge). A strong current from the SW, which was apparent through the tracking of ice floes in the radar data as moving against a strong wind, likely drove the pack ice along the shorefast ice edge and significantly contributed to the energy imparted on the SFI during the collision.

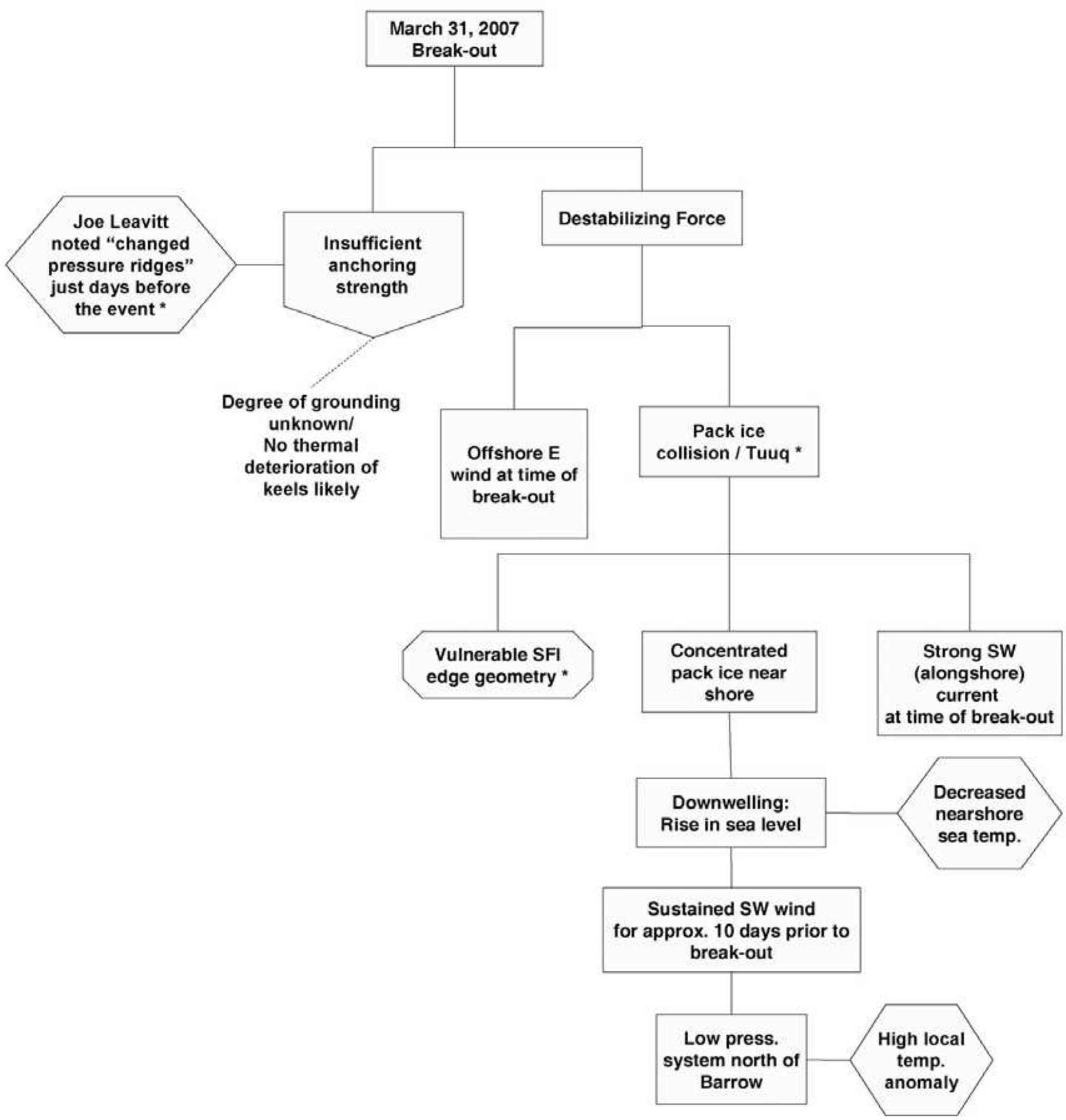


Figure 4.12 Fault tree for the March 31, 2007 break-out event. Asterisks (*) indicate factors from Table 4.1.

4.5.3 Considerations for quantitative FTA

The fault tree in Figures 4.5 to 4.11 has been developed such that wind and current directions are the basic events in most cases. These variables are central to risk assessment by experienced local ice experts. The overarching goal has been to construct a conceptual model for SFI failure, as a detailed probability assessment is beyond the scope of this paper and potentially even beyond current possibilities given the absence of necessary datasets. However, it is informative to at least consider the general probabilities of the wind and current vectors based on available wind and current data from Barrow. Figure 4.13 presents wind and current roses (directions and speed probabilities) for the period March 1 to May 1, 2010, which represent the months when the whaling community spends a lot of time on the ice. The current velocities have been averaged over the top 40 m of the water column, approximately 90% of total depth. During this period the dominant wind directions were out of the E or NE. However, all 8 sectors provided for periods of heavy winds of greater than 8.8 m s^{-1}. Unsurprisingly, the dominant current directions and intensities were either from the SW or NE. While current flow was observed in both the on- and offshore directions at different times, they were largely at very low speeds, and readings in these instances may have been influenced from the presence of either drifting pack ice or SFI above the mooring.

Figure 4.14 presents the probabilities of the wind and current events from the sections of the overarching fault tree that deal with a break-out. While this crudely distilled version of the fault tree clearly overlooks many other factors, it provides perspective on what pathways to failure are most probable based on available wind and current forces, and may assist in the design of a refined fault tree for quantitative analysis. Probabilities, P, are given for wind and current in particular directions regardless of strength, and probabilities P' are given for above average winds (> 5.2 m s^{-1}) and currents (>16.6 cm s^{-1}). Figure 4.14 reveals that the sequence of events that led to the 2007 break-out are quite likely to occur. Both strong offshore winds (E to S: P=0.51; P'=0.27) and down-welling winds (S to W: P=0.16, P'=0.02) have significant probabilities of occurrence.

Figures 4.12 and 4.13 highlight two particular challenges, if not disadvantages, when using a fault tree to describe a natural system. First, FTA does not allow for temporality. For example, in the chain of events outlined in Figure 4.12 for the 2007 break-out, an east wind as an offshore force and a SW wind as a mechanism for concentrating pack ice along the SFI are both present.

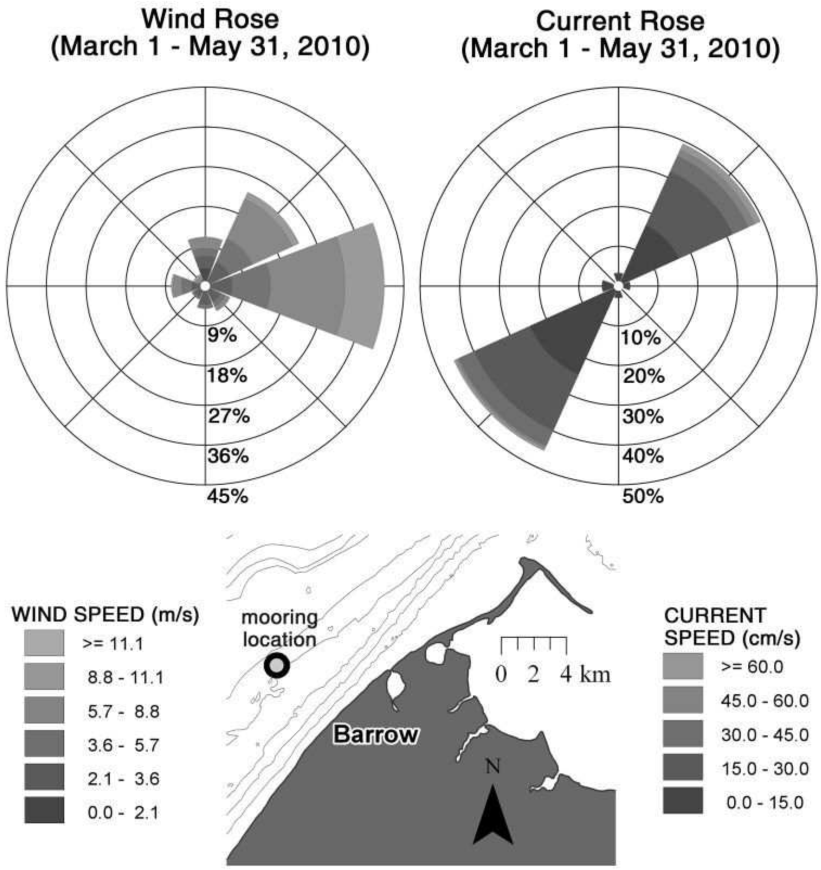


Figure 4.13 Wind and current roses for Barrow during March, April and May 2010. Hourly measured wind and current speeds are shown for the direction they are moving from. The map at bottom shows the location of the mooring at 5 km off Barrow's coastline at between 40 and 50 m water depth (contours are at every 10 m). The mooring was beyond the SFI for the first half of this time period (until April 15) and beneath the SFI during the remainder of the period. (Source: Quality Controlled Local Climatological Data obtained from NOAA's National Climatic Data Center; W Post-W Rogers Airport; Station #27502).

This makes sense when considering that the sequence of events necessary for a break-out event transpire over time; however, it is problematic for straightforward probability analysis.

Furthermore, a general rule in fault tree development is that all basic events should be independent (Butler and Martensen 1989). In probability theory, the probability that two independent events will co-occur is the product of their individual probabilities [$P(AB) = P(A)P(B)$]; however the probability that two completely dependent events will co-occur is the probability that only one will occur [$P(CD) = P(C) = P(D)$]. While, this obviously is a concern for how different probabilities for wind vectors may be dealt with when

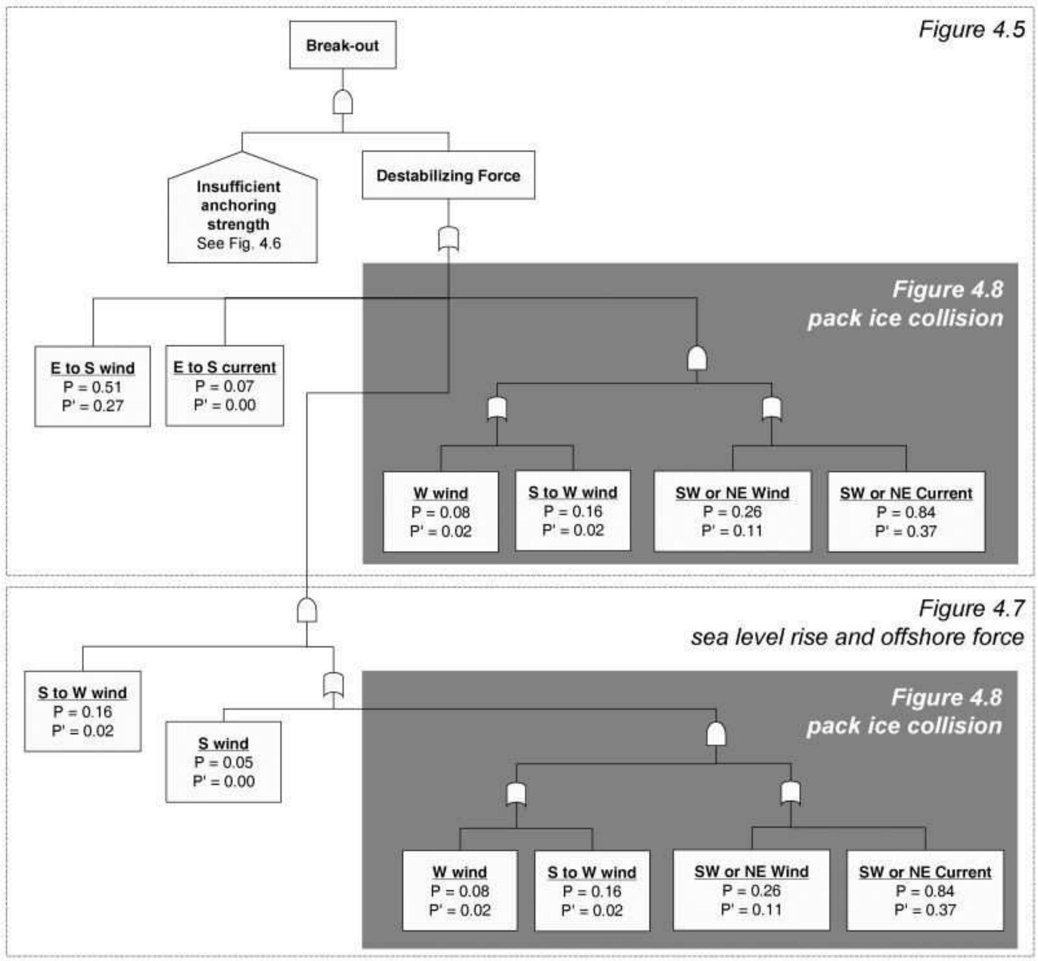


Figure 4.14 Spring probabilities (March 1 to May 31) for the wind and current directions that provide the basic level events in the fault tree for a SFI break-out. P = the total probability of occurrence for the given wind or current direction. P' = the probability for an above average wind (>5.2 m/s) or above average current (>16.6 cm/s) for the given directions. Based on wind and current data from 2010.

combined with an AND gate, it must also be a concern for combinations of wind and current vectors. It is understood that atmospheric and oceanic circulations are correlated in the Arctic. Nikiforov and Shpaikher (1980) found a correlation coefficient upwards of 0.80 for the upper 200 m of the ocean. Thorndike and Colony (1982) found that geostrophic winds account for 70% of the variability in ice drift velocities. Using a mooring array off Point Barrow from 7 August to 7 September 2001, Wilson et al. (1982) found that currents are well correlated with atmospheric pressure gradients (R = 0.81 to 0.85) and with local winds (R = 0.65 to 0.72).

For the sake of comparison and to demonstrate an approach that may account for the correlation between wind and current in a fault tree, I performed vector correlation for one year's worth of wind and current data from Barrow (August 5, 2009 to July 29, 2010). Using a method of vector correlation that simultaneously considers speed and direction and is invariant under coordinate system transformation (Crosby et al. 1993; Hooper 1959), I defined wind and current as two dimensional vectors, $\vec{W}_1$ and $\vec{W}_2$ respectively, such that

$$\vec{W}_1 = u_1 i + v_1 j \text{ , and} \qquad [4.50]$$

$$\vec{W}_2 = u_2 i + v_2 j \text{ .} \qquad [4.51]$$

If $\vec{W} = \begin{pmatrix} \vec{W}_1 \\ \vec{W}_2 \end{pmatrix}$, the four-dimensional covariance matrix for $\vec{W}$ is written as:

$$\Sigma_W = \begin{pmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{pmatrix} = \begin{bmatrix} \sigma(u_1,u_1) & \sigma(u_1,v_1) & \sigma(u_1,u_2) & \sigma(u_1,v_2) \\ \sigma(v_1,u_1) & \sigma(v_1,v_1) & \sigma(v_1,u_2) & \sigma(v_1,v_2) \\ \sigma(u_2,u_1) & \sigma(u_2,v_1) & \sigma(u_2,u_2) & \sigma(u_2,v_2) \\ \sigma(v_2,u_1) & \sigma(v_2,v_1) & \sigma(v_2,u_2) & \sigma(v_2,v_2) \end{bmatrix}. \qquad [4.52]$$

The resulting correlation parameter is given as

$$\rho_v^2 = Tr\left[(\Sigma_{11})^{-1}\Sigma_{12}(\Sigma_{22})^{-1}\Sigma_{21}\right]. \qquad [4.53]$$

Since the correlation is performed in two dimensions, values for ρ_v^2 may range between 0.0 for no correlation and 2.0 for a perfect correlation. Figure 4.15 reveals that the correlation parameter calculated on the scale of a day range between close to 0 and upwards of over 1.3. On the scale of a week, a month, and a year the average values are 0.42, 0.36, and 0.30, respectively. Surprisingly, these values do not match with those found by the previously mentioned studies. Perhaps, this is due to proximity of the mooring to the coast or the influence of coastal ice in decoupling surface winds and ocean flow.

4.6 Summary and discussion

The search for causality is inherent to LTK. It is through observance of cause and effect that rules develop as to how to be safe on sea ice. The “rules” used in real world decision making are rarely well-documented, yet this is necessary as we consider how interfacing science with local knowledge may improve the assessment of hazards and environmental monitoring. Here, I have introduced FTA for its advantages of diagrammatically and conceptually describing SFI break-out and break-away events. I have shown that it is capable of pairing the LTK of experienced ice experts with the types of variables that geophysics identifies as critical to SFI stability. In the context of answering the question “*will the ice break-out?*”, what have we learned from these two different bodies of knowledge? As the broader context is considered, additional important questions emerge: Who may ultimately benefit from this approach? What lessons may be gleaned in regards to how long-term trends in climate may impact SFI stability, hazard evaluation, and ice-use? In this final section, I address these questions and consider the important next steps for advancing this research.

4.6.1 Specific lessons regarding SFI stability

If representative assumptions can be made regarding geometric ridge characteristics, such as the keel angle (which also provides for a valid assumption of the angle of internal friction), the keel depth to sail height ratio provides a means to assess a ridge’s degree of grounding. In consideration of the work by Vaudrey (1980) and the assumption that weakly grounded ridges with only minor contact with the sea floor will remain anchored for only short periods when sufficiently forced by winds or currents, I suggest a water depth to sail height ratio that can be used to indicate stably grounded ridges must be 80-95% of the assumed keel depth to sail height ratio for floating ridges. This relates to the finding that there is a sharp transition between well and poorly anchored ridges. In other words, there is only a narrow range of contact between the seabed and ridge keels that would permit the stress from strong winds or currents from un-grounding keels.

This finding explains why the LTK of hunters is effective in reliability assessing whether the ice in an area is securely anchored. The sharp transition in anchoring strength allows local experts to rely upon observations of the conditions (e.g., high winds) under which a ridge or grounded zone endures. Furthermore, if hunters can find visual evidence that ridges are grounded (e.g., cracks at the base of a ridge), they can reliably infer stability. Although I acknowledged earlier that the reversal in current (see Table 4.1) that hunters rely on as a warning sign of a break-out event may relate to upwelling, I offer here a second explanation. It may relate to the earlier discussion (see Section 4.3.1) on the direction of gouging that takes place when keels contact the sea floor. If a keel gouges the sea floor under a certain current direction, say from the NE, the opposing sediments will effectively result in a high coefficient of friction. Once the current force shifts to a direction opposite the direction of gouging, say from the SW, the effective coefficient of friction immediately decreases because the direction of force is away from the piled up sediment that is within the groove on the sea floor (assuming that sediment does not fill in behind, on the opposite side of the keel's grounding front). This may further point to local experts' reliance on the weather and forcing history of the ice cover to reveal anchoring strength. This strategy however, breaks down once air and water temperatures increase and the cohesion strength of ice keels is diminished.

Assessing whether a floating extension is safe is much more difficult. This obviously factors into the general risk avoidance practiced by the hunters in Barrow during springtime whaling. Crews ensure access to the grounded zone through carefully routed trails and forethought into multiple options for escape. Extension ice of thicknesses comparable to level first-year ice (approx. 1.5 m) may fail in flexure given drops in sea-level that may be expected under typical upwelling (Δw_d = 0.5 m; Weingartner et al. 2009). For determining how resistant extension ice is to failure, there are seemingly no straight forward rules within LTK, which is to be expected of an empirical-based, highly nuanced knowledge. The ice's strength properties can vary considerably even before air and water temperatures provide indication. New cracks can develop and greatly reduce its larger-scale tensile strength. Alternatively, if cracks refreeze, flexural strength may actually increase. As a result of these difficulties for assessment, hunters routinely rely on real-time monitoring during periods of concern. A young hunter may be placed at an active crack and instructed to monitor it. If the crack begins to separate the crew members on the seaward side of the crack can be notified to evacuate.

4.6.2 Stability and atmospheric circulation

This leads to an important topic not discussed thus far. Beyond what happens at the local scale, SFI stability is also related to arctic atmospheric pressure patterns in so far as they control synoptic scale weather and in turn drive local wind velocities. The Arctic Oscillation (AO) describes opposing non-seasonal atmospheric pressure variations between the Polar Regions and mid-latitudes. When the AO is in the negative phase positive SLP anomalies dominate in the Arctic Basin with negative SLP anomalies at mid-latitudes, thus promoting more stable weather and colder temperatures in the Arctic. The opposite is true when the AO is in the positive phase; atmospheric pressure over the pole is reduced and positive SLP anomalies develop at mid-latitudes. As a result, transport of warm air into the Arctic is enhanced and more cyclones develop. The AO has been in the positive phase between 1979 and 1988, in the negative phase between 1989 and 1995, largely neutral between 1995 and 2008 (Comiso 2006; Thompson and Wallace 1998), and strongly negative in 2009 and 2010.

The strength and spatial scale of the Beaufort Gyre (BG), a prevailingly anticyclonic oceanic circulation in the Beaufort Sea, is driven by the prevailingly anticyclonic arctic circulation patterns. Proshutinsky and Johnson (1997) and Proshutinsky et al. (2002) describe the two seasonal circulation regimes of the BG. In wintertime (September to May), anticyclonic circulation is strongest and greatest in extent as both winds and geostrophic currents circulate clockwise around a Beaufort High. This anticyclonic circulation leads to elevated sea-levels in the central region of the BG while decreasing sea-level along the coast through upwelling. In summertime (June to August), as atmospheric pressure decreases and anticyclonic winds weaken or become cyclonic, the anticyclonic circulation of the BG weakens, and occasionally reverses to a cyclonic pattern (Asplin et al. 2009). In the case of cyclonic atmospheric circulation, downwelling takes place and raises sea-level along the coast. Therefore, when the AO is positive, a weaker BG is expected, especially in summer. When the AO is negative, a stronger BG is expected.

Given that atmospheric pressure patterns control winds, which in turn control upwelling and downwelling in the coastal regions, it is expected that atmospheric pressure patterns play a role in SFI stability during spring whaling (April to May). Mahoney et al. (2007a) looked for such a correlation with the timing of Barrow's spring break-up in June but found a greater link with air temperature and thawing degree days than with atmospheric circulation patters. These findings however are not very applicable as we consider stability prior to break-up and the onset of thawing. Furthermore, Mahoney et al. (2007a) concluded that for coastal regions with steep bathymetry gradients (such as found along the Chukchi Sea relative to the Kara Sea, for example) atmospheric circulation patterns play less of a role in defining the extent of stable SFI than bathymetry. Given that their definition of stable SFI relied on the lack of detectable horizontal displacement over a 20 day period, their work largely implies that floating extensions were likely overlooked in areas of their study. The work presented here suggests that with a positive AO a period of increased potentially destabilizing scenarios may develop as the probability of a dangerous rise in sea level increases with more downwelling. More important however, is that increased pack ice concentrations are likely in the waters adjacent to Barrow's SFI, presenting greater opportunity for break-out or break-away events that are initiated through direct pack ice interaction.

4.6.3 Framework for two way sharing

Inherent to FTA is the general idea that there are essentially an infinite number of ways for a system to succeed, but a finite number of ways for a system to fail (Butler and Martensen 1989). Therefore, we will be most efficient in learning about a system by examining the ways in which it fails. The empirical-based knowledge of indigenous sea ice experts has developed in this very fashion—by observing and experiencing SFI break-out events over centuries. Throughout this chapter (and thesis) I have used the word "expert" to describe local people that possess a sophisticated understanding of sea ice. In doing so, I assume they base their decisions on a detailed mental model of how the sea ice environment predictably behaves. To what extent that model is explicit, consciously relying on a set of assumptions that can be articulated, or implicit—largely based on "intuition"—has largely remained unexplored. Furthermore, it is a challenge to understand whether or not the explicit assumptions that a hunter is able to communicate to researchers are solely reliable in the real world, or whether it is the non-communicable "intuition" that has led the Iñupiat to repeatedly well-demonstrate their unsurpassable local ice expertise.

Very often research that seeks to "interface" local knowledge with science is charged with seeking to only validate LTK. Naturally, this often offends those experts on the LTK side of the interface since the opposite approach of LTK validating science is rarely seen. In spite of this, I contend that this process, which may first appear as "validation" of LTK by science, is essential to moving forward as partners in problem-solving (e.g., in developing ways to better monitor SFI stability). However, we must look at this in a much different light. When LTK is not "validated", it means that science has simply not yet reached the appropriate level of understanding. Very often the reason for this is that the proper context for discussion has yet to arise. FTA provides the necessary context by focusing on the practical nature of their knowledge. Accordingly, such efforts must recognize the utility associated with science being able to understand LTK.

4.6.4 Potential uses of FTA

In the field of engineering, FTA is most typically used to pinpoint system components that contribute to failure and either improve or replace them. In considering SFI, nature is the design engineer, leaving us powerless to change the system. However, FTA can still identify the components of the system that lead to failure so that we may improve our understanding of the how ice features and forces interact. For example, FTA may reveal how the indicators that LTK uses to assess SFI stability can inform monitoring strategies. Clearly a greater emphasis must be placed on observing the stress and temperature history of the ice cover, as opposed to simply relying on isolated observations of ridge characteristics. While applying this in an operational context may first seem daunting, it is important to reflect on the lessons learned in this chapter. Figure 4.4 was mostly discussed in the context of how the ratio of water depth at grounding to sail height relates to a rapid transition between well and poorly anchored ridges. It can also be interpreted such that it requires only take a few large ridges to sufficiently anchor the SFI cover. In a monitoring context, narrowing the most important stabilizing components of an ice cover to specific ridges may allow for more detailed studies of how critical ice features evolve throughout the spring season.

A second potential use of FTA is as an educational resource. In summer 2008, I sat in the home of Tom Brower, III, a Barrow whaling captain, and listened to him recount how he had broken off from the shorefast ice four times in his lifetime. Brower summarized the inherent risk of the hunt: *"There is no easy spring whaling. If someone says it's easy, they haven't gone through hard times yet. A young whaling captain hasn't seen the experience that we have being broken off and coming back. It's just a matter of time."* As mentioned previously, there is no substitute for real-life experience in learning practical lessons. However, it is important to reflect on some other important realities facing indigenous communities in the Arctic. Hunters today spend less time on sea ice compared to the generations before them. Accordingly, active hunters today do not have the same breadth or detail to their local knowledge and experience. Also, the use of technology (global positioning systems, satellite imagery, computers, etc.) is ever-increasing. For these reasons, the use of a well-developed fault tree that encompasses a range of important considerations in assessing SFI stability may serve as a potentially useful tool to complement the traditional learning of young hunters. This information would be most appropriate as a learning tool for when they are *off the ice*, and not as a decision-support tool when they are *on the ice*. As mentioned earlier, one of the primary disadvantages of FTA is its inability to properly account for the temporal dimension of cause and effect relationships. Although, even if it could, it would be no substitute for a skilled hunter's ability to process the many environmental signals they face when assessing safety. On the ice so many more considerations must be taken into account than can ever be incorporated into a fault tree (e.g., the amount of time required to reach safer ice in an emergency).

Quite different from the way local hunters make decisions regarding ice safety, are the strategies used by industrial operations in the Arctic. Although they may face similar risks and ultimately may be forced to make similar decisions (e.g., get off the ice!), industry personnel typically do not possess the same level of expertise or have nearly as much experience as local ice experts. As a result, their decision making process is much less organic and typically must follow a fairly rigid checklist. The fault tree approach, if tailored in scope and according to monitoring capabilities, could provide a very useful tool to those assessing hazard in an operational setting.

4.6.5 Next steps

The FTA approach presented here was tested using the late-March 2007 break-out event. In this specific example, the observed contributing factors and indicators by both local experts and geophysical monitoring were closely replicated in the existing fault tree. Analyzing additional events is important as they may not yield such close agreement; yet will provide a means for adapting and expanding the fault tree. Further in depth analysis of multiple SFI break-out events alongside accurately measured ridge characteristics may also allow for the eventual development of stability indices that add further usefulness to FTA and contribute toward probabilistic capabilities.

With each break-out or break-away event analyzed, the opportunity to further engage with local ice experts exists. The entire fault tree developed here is likely too academic and abstract to properly use as the sole topic of conversation with hunters. However, focusing on specific events and presenting the level of detail as that in Figure 4.12 may find great interest amongst them. Furthermore, Table 4.1 is by no means a comprehensive list of LTK as related to assessing SFI stability. Although it is based on a wide range of interviews, there seems to always exist new lessons from LTK as unique local ice conditions develop with each passing year. Lastly, as long-term trends are observed in coastal sea ice conditions off Alaska, which are exclusively linked to regional and global scale processes, a fault tree may be used to communicate these changes and the resulting implications for SFI stability to local experts.

Notes

1. In 1937, a particular ride-up event rode over the steep 9 m high bluffs at Barrow, resulting in deaths and destroyed structures (Kovacs and Sodhi 1980).
2. To arrive at $\psi = 8.0$, the same as Timco and Burden (1997), Leppäranta and Hakala (1992) used the following values: $\rho_{is} = \rho_{ik} = 880$ kg m^{-3}, $k_s = 19\%$, $k_k = 29\%$, and ρ_w =1027 kg m^{-3} (for surface water in the Baltic Sea).
3. Timco and Burden (1997) reported a standard deviation of 13.4° about the mean of 26.6° for the typical value of internal friction for a first-year ridge.
4. Throughout this chapter I describe the direction of current flow using the atmospheric convention (i.e., direction is given as the direction from which the current is flowing).
5. A mooring of the Seasonal Ice Zone Observing Network (SIZONet) was deployed at approx. 5 km offshore of Barrow between August 2009 and July 2010. See location in Figure 4.13.
6. The flexural length of sea ice, l_c, is equal to $\sqrt[4]{D/\rho_i g}$, where D is the flexural rigidity, which is related to the Elastic modulus, E, and Poisson's ratio, υ, by $D = Eh^3 / 12(1-\upsilon^2)$ (Fox 2000).
7. It is unclear how carefully hunters discriminate between sediment in ridges that sticks to ice blocks during ridge building and sediment that attaches to the underside of level ice as it grows under turbulent conditions. At Barrow, I have observed both sediment at the base and throughout level ice when analyzing ice cores and in ice blocks at the very top of ridges. The most likely cause of the latter is that the sediment was within the parent ice sheet as a result of growth in shallow turbulent waters.
8. Pete Sovalik (UAF Oral History Tape H88-26-03) recounted an incident near Cross Island in November (year not given) when he and a few others were set adrift for five days after an unexpected large wave broke away a section of shorefast ice: "It was good weather. Fine, calm and sunshine…The ice on the other side of the lead looks funny. Moving up and down...I start wondering what happened that things look like that. Finally,

in the middle of the lead big waves show up. Big waves. It was fast. Waves coming toward me like that. I'm too late….I don't know what [caused it], maybe an earthquake? I couldn't travel anymore. The ice was all broken; smashed up like paper….About four or five hours steady pretty well up and down like that. Getting smaller, smaller, smaller. Finally it stopped. The water calmed down.". Sovalik and the others were adrift for five days before they were able to find their way back to land across a tightened ice pack.

9. The branches in the fault tree leading from an offshore wind and an offshore current converge prior to the level of the other forces because their formulations have two input variables in common, SFI roughness and extent. Therefore, this approach to constructing the tree avoids repetition of these input variables.

List of symbols

Symbols are listed in the order as they appear in the text. Units are provided in parenthesis, along with values when referring to a specific constant used in the text.

σ_{sb} shear stress due to frictional coupling at the sea bed, (Pa)
W_g weight of a grounded ridge, accounting for buoyancy, (N)
c_f static friction coefficient
A_g area of contact between a grounded keel and the seafloor, (m^2)
A_b ridge area-above-buoyancy, (m^2)
ρ_r ridge bulk density, (kg m^{-3})
g gravitational acceleration, (9.8 m s^{-2})
H_s ridge sail height, (m)
ρ_w density of sea water, (1027 kg m^{-3})
A_r total cross-sectional area of a grounded ridge, (m^2)
A_w cross-sectional area of displaced water by a grounded ridge, (m^2)
A_k cross-sectional area of a ridge keel, (m^2)
A_s cross-sectional area of a ridge sail, (m^2)
ψ keel area to sail area ratio (A_k / A_s)
ρ_{is} density of the ice blocks in the sail, (kg m^{-3})
ρ_{ik} density of the ice bocks in the keel, (kg m^{-3})
P_s sail porosity
P_k keel porosity

γ	keel depth to sail height ratio (H_k / H_s)
α_s	sail angle, (°)
α_k	keel angle, (°)
w_g	water depth at grounding, (m)
l_g	length of contact area between a grounded keel and the seafloor, (m)
F_{sb}	frictional force exerted by grounded ridges, (N)
n_g	number of grounded ridges along a cross sectional SFI profile
$\overline{D}_g$	average degree of grounding grounded ridges along a cross sectional SFI profile, (m^2)
τ_k	shear strength of a ridge keel, (Pa)
σ_N	normal stress, (Pa)
c	cohesion strength, (Pa)
θ	angle of friction, (°)
τ_a	wind stress (Pa)
ρ_a	density of air, (1.3 kg m^{-3} for dry air at -10°C)
U_a	wind velocity at the anemometer height of 10m, (m s^{-1})
C_a	ice-air drag coefficient
C_{10}	skin friction drag
C_f	form drag
$\overline{h}_s$	mean sail height, (m)
N	mean number of ridges per unit downwind distance, (m^{-1})
F_a	force exerted by an offshore wind, (N)
L_T	total extent of shorefast ice, (m)
N_g	mean number of grounded ridges per unit downwind distance, (m^{-1})
E_g	extent of grounding; total length of ice in contact with the sea floor over L_T, (%)
$\overline{H}_s$	mean sail height of grounded ridges, (m)
$\overline{w}_g$	mean water depth at grounding, (m)
S_1	F_{sb} / F_a
τ_w	stress imparted on ice by the ocean, (Pa)
U_w	current velocity at the bottom of the logarithmic boundary layer, (m s^{-1})
C_a	ice-water drag coefficient

F_w	force exerted by a current, (N)
S_2	F_{sb} / F_w
$\overline{D}_g{}'$	average degree of grounding that account for a change in sea level, (m^2)
Δw_d	change in sea level, (m)
S_1'	F_{sb} / F_a accounting for change in sea level Δw_d
S_2'	F_{sb} / F_w accounting for change in sea level Δw_d
τ_t	stress due to sea level tilt (Pa)
z_i	ice thickness, (m)
β	sea surface slope
σ_f	flexural strength, (Pa)
l	length between the point flexural fracture and the point where the load is applied, (m)
L	length of floating extension that fails in flexure, up until the flexural length of sea ice, (m)
ν_b	brine volume fraction
l_c	flexural length of sea ice, (m)
D	flexural rigidity, (Pa m^3)
E	Elastic modulus, (Pa)
υ	Poisson's ratio
x	distance between the coast and outermost seaward edge of the grounded zone, (m)
S_3	ratio of wind stress to tensile strength of a floating extension
S_4	ratio of current stress to tensile strength of a floating extension
ρ_v^2	vector correlation parameter

References

AIChE, 2000. Guidelines for chemical process quantitative risk analysis, Second edition. American Institute for Chemical Engineers, New York, USA.

Asplin, M.G., Lukovich, J.V., Barber, D.G., 2009. Atmospheric forcing of the Beaufort Sea ice gyre: Surface pressure climatology and sea ice motion. J. Geophys. Res., 114, C00A06, doi:10.1029/2008JC005127.

Banke, E.G., Smith, S.D., 1973. Wind stress on arctic sea ice. J. Geophys. Res., 78(33): 7871-7883.

Banke, E.G., Smith, S.D., Anderson, R.J., 1976. Recent measurements of wind stress on arctic sea ice. J. Fish Res. Bd. Canada, 33, 2307-2317.

Barker, A., Timco, G.W., 2003. The friction coefficient of a large ice block on a sand/gravel beach. 12th Workshop on the hydraulics of ice covered rivers, Edmonton, AB, June 19-20.

Barnthouse, L.W., Suter II, G.W., 1986. Users manual for ecological risk assessment. National Technical Information Service, Springfield Virginia, ORNL-6251.

Barry, R.G, Moritz, R.E., Rogers, J.C., 1979. The fast ice regimes of the Beaufort and Chukchi Sea coasts, Alaska. Cold Regions Science and Technology 1, pp. 129-152.

Berkes, F., Berkes, M.K., 2009. Ecological complexity, fuzzy logic, and holism in indigenous knowledge. Futures 41: 6-12.

Brewster, K., 1997. Native contributions to arctic sciences at Barrow, Alaska. Arctic 50(3): 277-288.

Brown, T.G., Cheung, M.S., Croasdale, K.R., Wright, B.D, 1995. Advice on design ice loads for the Northumberland Strait Bridge piers. Report to Public Works and Government Services Canada, Charlottetown, PEI, 124 pp.

Bruneau, S., 1997. Development of a first-year ridge keel load model. Doctoral dissertation, Memorial University of Newfoundland, St. John's, Newfoundland, Canada.

Butler, R.W., Martensen, A.L., 1989. The fault tree compiler: Program and Mathematics. NASA Technical Paper 2915, Scientific and Tech. Info. Div., NASA, Hamton, VA.

Cassano, E.N., Lynch, A.M., Cassano, J.J., Koslow, M.R., 2006. Classification of synoptic patterns in the western Arctic associated with extreme events at Barrow, Alaska, USA. Clim. Res., 30: 83-97.

Comiso, J. C., 2006. Abrupt decline in the Arctic winter sea ice cover. Geophys. Res. Lett., 33, L18054, doi:10.1029/2006GL027341.

Croasdale & Associates Ltd., 1995. Ice load models for first-year pressure ridges and rubble fields – Phase 1 report. Joint Industry Government Project, Partly sponsored by the National Energy Board (PERD) and Public Works Canada.

Croasdale, K.R., Bruneau, S., Christian, D., Crocker, G., English, J., Metge, M., Ritch, R., 2001. In-situ measurements on the strength of first-year ice ridge keels. 16th International Conference on Port and Ocean Engineering Under Arctic Conditions, Ottawa, Canada, August 12–17, 2001, vol. 3, pp. 1445–1454.

Crosby, D.S., Breaker, L.C, Gemmill, W.H., 1993. A proposed definition for vector correlation in geophysics: Theory and application. American Meteorological Society, 10: 355-367.

Divine, D.V., Korsnes, R., Makshtas, A.P., 2004. Temporal and spatial variation of shore-fast ice in the Kara Sea. Continental Shelf Res. 24, 1717-1736.

Druckenmiller, M.L., Eicken, H., Johnson, M., Pringle, D., Williams, C.C., 2009. Toward an integrated coastal sea ice observatory: System components and a case study at Barrow, Alaska. Cold Reg. Sci. Technol. 56: 61-72.

Druckenmiller, M.L., Eicken, H., George, J.C., Brower, L., 2010. Assessing the shorefast ice: Iñupiat whaling trails off Barrow, Alaska. In: Krupnik, I., Aporta, C., Gearheard, S., Kielsen Holm, L., Laidler, G. (Eds), *SIKU: Knowing our ice*. Springer-Verlag, New York, pp. 202-228.

Eicken, H., Shapiro, L.H., Gaylord, A.G., Mahoney, A., Cotter, P.W., 2006. Mapping and characterization of recurring spring leads and landfast ice in the Beaufort and Chukchi Seas. U.S. Dept. of the Interior, Anchorage, Alaska, OCS Study MMS 2005-068.

Ferdous, R., Khan, F.I., Veitch, B., Amyotte, P.R., 2007. Methodology for computer-aided fault tree analysis. Process Safety and Environmental Protection 85(1): 70-80.

Fox, C., 2000. Scaling laws for flexural waves in floating ice. In: Dempsey, J.P. (Ed.), *Scaling Laws in Ice Mechanics and Ice Dynamics*. Proceedings of the IUTAM Conference, University of Alaska Fairbanks, 13-16 June 2000.

George, J.C., Huntington, H.P., Brewster, K., Eicken, H., Norton, D.W., Glenn, R., 2004. Observations on shorefast ice dynamics in arctic Alaska and the responses of the Iñupiat hunting community. Arctic 57(4): 363–374.

George, J.C., Norton, D.W., Brower Jr., H., unpubl. Observations on landfast ice break-off events "Uisauniq" near Point Barrow, Alaska. North Slope Borough Department of Wildlife Management, Barrow, Alaska.

Guest, P.S., Davidson, K.L., Overland, J.E., Frederickson, P.A., 1994. Atmosphere-ocean interactions in the marginal ice zones of the Nordic Seas. In: Smith, W.O., Grebmier, J.M. (Eds.), *Arctic oceanography: Marginal ice zones and continental shelves*. Amer. Geophys. U., Washington, pp. 51-95.

Hayes, K.R., 2002. Identifying hazards in complex ecological systems. Part 1: fault-tree analysis for biological invasions. Biological Invasions, 4: 235-249.

Hooper, J.W., 1959. Simultaneous equations and canonical correlation theory. Econometrica, 27: 245-256.

Høyland, K.V., Liferov, P., 2005. On the initial phase of consolidation. Cold Reg. Sci. Tech. 41: 49–59.

Hunkins, K.L., 1965. Tide and storm surge observations in the Chukchi Sea. Limno. Oceanogr. 10(1):29-39.

Huntington, H.P., Brower Jr., H., Norton, D.W., 2001. The Barrow Symposium on Sea Ice, 2000: Evaluation of one means of exchanging information between subsistence whalers and scientists. Arctic 54(2): 201-206.

Johnson, W. R., 1989. Current response to wind in the Chukchi Sea: A regional coastal upwelling event. J. Geophys. Res., 94, 2057–2064.

Kasper, J., 2010. Modeling winter circulation under landfast ice: The interaction of winds with landfast ice. Doctoral thesis, University of Alaska Fairbanks, Fairbanks, Alaska.

Kovacs, A., 1976. Grounded ice in the fast ice zone along the Beaufort Sea coast of Alaska. CRREL Report 76-32, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Kovacs, A., Sodhi, D.S., 1980. Shore ice pile-up and ride-up: Field observations, models, and theoretical analysis. Cold Reg. Sci. Tech. 2: 209-288

Langhorne, P.J., 2004. The flexural strength of partially refrozen cracks in sea ice. Proceedings of the 14^{th} Int'l Offshore and Polar Eng. Conf., Toulon, France, May 23-28, pp. 819-824.

Leppäranta, M., 2005. *The drift of sea ice*. Springer-Verlag, New York, 300 pp.

Leppäranta, M., Hakala, R., 1992. The structure and strength of first-year ice ridges in the Baltic Sea. Cold Reg. Sci. Tech. 20: 295–311.

Lynch, A.H., Curry, J.A., Brunner, R.D., Maslanik, J.A., 2004. Toward an integrated assessment of the impacts of extreme wind events on Barrow, Alaska. Bull. Am. Meteorol. Soc. 85: 209–221.

Macdonald, R.W., Carmack, E.C., 1991. The role of large-scale under-ice topography in separating estuary and ocean on an arctic shelf. Atmosphere-Ocean, 29(1): 37-53.

Mahoney, A., Eicken, H., Shapiro, L., Grenfell, T., 2004. Ice motion and driving forces during a spring ice shove on the Alaskan Chukchi Coast. J. of Glacio. 50(169): 195-207.

Mahoney, A., Eicken, H., Gaylord, A.G., Shapiro, L., 2007a. Alaska landfast sea ice: Links with bathymetry and atmospheric circulation. Journal of Geophysical Research, 112, C02001, doi:10.1029/2006JC003559.

Mahoney, A., Eicken, H., Shapiro, L., 2007b. How fast is landfast ice? A study of the attachment and detachment of nearshore ice at Barrow, Alaska. Cold Reg. Sc. Tech. 47: 233-255.

Marchenko, A., 2008. Thermodynamic consolidation and melting of sea ice ridges. Cold Reg. Sci. and Tech. 52: 278-301.

McPhee, M.G. (1979) The effect of oceanic boundary layer on the mean drift of pack ice: application of a simple model. J. Phys. Oceanogr. 9(2): 388-400.

Nelson, R., 1969. *Hunters of the northern ice.* University of Chicago Press, Chicago, 429 pp.

Nikiforov, Ye.G., Shpaikher, A.O., 1980. *Features of the formation of hydrological regime large-scale variations in the Arctic Ocean*. Gidrometeoizdat, St. Petersburg, Russia, 269 pp.

Norton, D.W., 2002. Coastal sea ice watch: Private confessions of a convert to indigenous knowledge. In: Krupnik, I., Jolly, D. (Eds.), *The earth is faster now: Indigenous observations of arctic environmental change*. Arctic Research Consortium of the United States, Fairbanks, Alaska, pp 127-155.

Perovich, D.K., Richter-Menge, J.A., 2000. Ice growth and solar heating in springtime leads. J. Geophys. Res. 105(C3): 6541-6548.

Petrich, C., Eicken, H., Zhang, J., Krieger, J., In prep. Coastal sea ice melt and break-up in northern Alaska: process and possibility to forecast.

Pickart, R.S., Moore, G.W.K., Torres, D.J., Fratantoni, P.S., Goldsmith, R.A., Yang, J., 2009. Upwelling on the continental slope of the Alaskan Beaufort Sea: Storms, ice, and oceanographic response. J. Geophys. Res. 114, C00 A13, doi: 10.1029/2008JC005009.

Proshutinsky, A.Y., Johnson, M.A., 1997. Two circulation regimes of the wind-driven Arctic Ocean. J. Geophys. Res., 102(C6), 12493-12512.

Proshutinsky, A., Bourke, R.H., McLaughlin, F.A., 2002. The role of the Beaufort Gyre in arctic climate variability: Seasonal to decadal climate scales. Geophys. Res. Let. 29(23): 2100.

Reed, J.C., 1969. The story of the Naval Arctic Research Laboratory. Arctic 22(3): 185-194.

Reynolds, M., Pease, C.H., Overland, J.E., 1985. Ice drift and regional meteorology in the southern Bering Sea: Results from MIZEX West. J. Geophys. Res. 90(C6), 11967-11981.

Schaefer, J.A., Ettema, R., 1986. Experiments on freeze-bonding between ice blocks in floating ice rubble. Proceedings of the 8th IAHR Ice Symposium, Iowa City, IA, Vol. I, 401-413.

Searcy, C., Kenneson, D., Stringer, W., 1996. A river-coastal sea ice interaction model: Mackenzie River Delta. J. Geophys. Res., 101(C4): 8885-8894.

Shafrova, S., Høyland, K.V., 2008. The freeze-bond strength in first-year ice ridges. Small-scale field and laboratory experiments. Cold Reg. Sci. Tech. 54: 54-71.

Shapiro, L.H., Barry, R.G. (Eds.), 1978. The sea ice environment. In: Weller, G., Norton, D., Johnson, T. (Eds.), Interim synthesis report: Beaufort/Chukchi. Outer Continental Shelf Environmental Assessment Program, National Oceanic and Atmospheric Administration, Boulder, CO, 54 pp.

Shapiro, L.H., Metzner, R.C., 1987. Coefficients of friction of sea ice on beach gravel. In: Shapiro, L.H., Barnes, P.W., Hanson, A., Hoskins, E.R., Johnson, J.B., Metzner, R.C. (Eds.), Mechanical properties of sea ice deformation in the near shore zone. OCSEAP Final Report, Research Unit 265, pp. 520-527, U.S. Dept. of Commerce, NOAA.

Shapiro, L.H., Barnes, P.W., Hanson, A., Hoskins, E.R., Johnon, J.B., Metzner, R.C. (Eds.), 1987. Mechanical properties of sea ice deformation in the near shore zone. OCSEAP Final Report, Research Unit 265, pp. 360-584, U.S. Dept. of Commerce, NOAA.

Squire, V.A., 1993. The breakup of shore fast sea ice, Cold Reg. Sci. Tech., 21: 211-218.

Thompson, D.W., Wallace, J.M., 1998. The Arctic oscillation signature in the wintertime geopotential height and temperature fields, Geophys. Res. Lett., 25, 1297-1300.

Thorndike, A.S., Colony, R., 1982. Sea ice motion in response to geostrophic winds. J. Geophys. Res., 87, 5845-5852.

Timco, G.W., 2008. Why does ice fail the way it does? Proceedings 19th IAHR Symposium on Ice, Vol. 2, pp. 557-577, Vancouver, B.C. Canada.

Timco, G.W., Goodrich, L.E., 1988. Ice rubble consolidation. Proceedings of the 9th International Symposium on Ice, Sapporo, Japan, Aug. 23-27, IAHR Comm. On Ice Problems, Vol. 1, pp. 427-438.

Timco, G.W., Burden, R.P., 1997. An analysis of the shapes of sea ice ridges. Cold Reg. Sci. Tech. 25: 65-77.

Timco, G.W., Croasdale, K., Wright, B., 2000. An overview of first-year sea ice ridges. Technical Report HYD-TR-047, PERD/CHC Report 5-112, August 2000, 157 pp.

Timco, G.W., Weeks, W.F., 2010. A review of the engineering properties of sea ice. Cold Regions Science and Technology 60(2): 107-129.

Tremblay, L.-B., Hakakian, M., 2006. Estimating the sea ice compressive strength from satellite-derived sea ice drift and NCEP reanalysis data. J. Phys. Oceanogr., 36: 2165–2172.

Utt, M.E., Clark, R.A., 1980. Coefficient of friction between submerged ice and soil. American Society of Mechanical Engineers. Petroleum Division Journal, No.80-PET-41, pp. 1-4.

Vaudrey, K.D., 1980. Beaufort Sea first-year ice feature survey–1979, Volume 1: Field Investigation. Gulf Research and Development Company, Houston, Texas.

Vaughan, D.G., 1995. Tidal flexture at ice shelf margins. J. of Geophys. Res. 100(B4): 6213-6224.

Wadhams, P., 1980. Ice characteristics in the seasonal sea ice zone. Cold Reg. Sci. Tech. 2: 37-87.

Wadhams, P., 2000. *Ice in the oceans*. Gordon and Breach Science Publishers, Amsterdam, 351 pp.

Weingartner, T., Aagaard, K., Woodgate, R., Danielson, S.L., Sasaki, Y., Cavalien, D., 2005. Circulation on the north central Chukchi Sea shelf. Deep-Sea Res., 52: 3150-3174.

Weingartner, T.J., Danielson, S.L., Kasper, J.L., Okkonen, S.R., 2009. Circulation and water property variations in the nearshore Alaskan Beaufort Sea (1999-2007). US Dept. of Interior, Minerals Management Service, Alaska Outer Continental Shelf Region, Anchorage, Alaska.

Wilson, D.E., Pace, S.D., Carpenter, P.D., Teas, H., Goddard, T., Wilde, P., Kinney, P.J., 1982. Nearshore coastal currents, Chukchi Sea, summer 1981. OCSEAP Final Report RU 531, U.S. Dep. of Cornmet., NOAA, Juneau, AK.

Yang, J., 2006. The seasonal variability of the Arctic Ocean ekman transport and its role in the mixed layer heat and salty fluxes. J. Clim.19: 5366-5387.

Chapter 5. Trails to the whale: Reflections of change and choice on an Iñupiat icescape*

Abstract

Shorefast sea ice, which is present along Alaska's arctic coastline from late fall through early summer, provides a platform for subsistence hunting by coastal indigenous communities, and represents a unique area for interdisciplinary research of community-environment interactions in a changing arctic. At Barrow, Alaska, trails are built each spring across the shorefast ice to connect the community to leads in ice choked waters where hunters wait for the migrating bowhead whales. Building on community-based efforts, a systematic ice trail mapping and monitoring project developed. Using electromagnetic induction sounding, surveys of continuous ice thickness were performed along the trails just prior to spring whaling, providing a multi-year dataset for quantitative analysis of trail characteristics. This paper summarizes findings from four consecutive spring seasons (2008 to 2011). Relationships between ice conditions and hunter strategies that ultimately guide trail placement and risk assessment are explored. Trail surveys provide a meaningful and consistent approach to monitoring the mass balance and thickness distribution of shorefast ice. Collaboration with the community has allowed geophysical-based monitoring to interface with local knowledge and ice-use to produce both useable science-based resources for hunters and a baseline for assessing future environmental change. With intention of sustaining this project in the long-term, this chapter discusses ways to engage Barrow's young hunters in the monitoring effort to improve access to traditional learning and interaction with elders.

* I intend to submit this chapter as two separate journal articles for publication; one likely to the special issue of Polar Geography titled "The human geography of arctic sea ice" and another to Cold Regions Science and Technology.

5.1 Introduction

In the Arctic, coastal indigenous peoples' unparalleled familiarity with sea ice stems from the fact that it provides both a physical pathway and barrier to many of their most important food sources. For nine Iñupiat communities in Alaska (see Figure 5.1), the traditional springtime hunt of the bowhead whale (*Balaena mysticetus*) remains important to their subsistence cultures. Aside from the communities of Gambell and Savoonga on St. Lawrence Island and Little Diomede Island, most traditional spring whaling is done from the edge of shorefast ice. Ice trails—expressions of traditional knowledge, risk assessment, and hunting strategy—are built each spring across the ice to connect the communities to leads in ice choked waters where they 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 bowheads. The village sits just 15 kilometers south of Point Barrow (or Nuvuk, the location of one of the historical Iñupiat settlements). The migrating whales, which over-winter in the Bering Sea, are destined for summer feeding in the Beaufort Sea, as shown in Figure 5.1. They must round Point Barrow, often passing within striking distance of hunters. The annual development of a persistent flaw lead system along Alaska's Chukchi coast (Eicken et al. 2006) provides an efficient travel corridor for the whales.

Today, in accordance with the regulations of the International Whaling Commission, Barrow receives more strike permits from the Alaska Eskimo Whaling Commission than any of the eleven member communities[1]. In recent years, around 50 whaling captains have been granted licenses to hunt in spring. Over the last ten years Barrow has landed around 10 whales each spring, and regularly has additional harvests during the open-water fall hunt.

While Barrow's geography presents obvious advantages, the dynamic local ice environment presents significant challenges as hunters rely on shorefast ice as a platform for travel, camping, and butchering whales. Figure 5.2 presents photos of both a hunting crew from Barrow establishing a camp on the ice and an aerial view of the shorefast ice off the village in spring 2010. This hunt, like many others, relies on the predictable timing of nature—the weather, ocean currents, ice, and whales. Ice conditions largely determine where, when, and how people travel, assess safety, and make decisions. In Barrow, hunters are seeing the arrival of new ice conditions that are unlike those experienced in previous decades and described in the stories of elders. In this chapter, I propose that the placement of whalers' ice trails provides an encoded reflection of how ice conditions guide the community's use of ice and interaction with its environment while

Figure 5.1 Map of Alaskan indigenous whaling communities and sea ice extent. Barrow is the only community to practice both spring and fall whaling. The black dashed and solid lines represent the winter time (March) maximum sea ice extent in 1979 and 2010, respectively. The red dashed and solid lines represent the summer time (September) minimum sea ice extent in 1979 and 2010, respectively (passive microwave satellite imagery obtained from the National Snow and Ice Data Center's digital media archive). The thick grey line with arrowheads shows the approximate migration path of the bowhead whale population over the course of early spring through late fall as it travels from the Bering Sea to the Beaufort and back to the Bering Sea (AWMP 2006).

pursuing the primary objective of safely striking, retrieving, and butchering 20-40 ton whales to feed the community. The long-term monitoring of trails may shed light on how changing conditions are impacting the hunt and driving subtle forms of adaptation. While Barrow regularly constructs the largest network of spring ice trails, other whaling communities, such as Wales, Point Hope, and Wainwright, also regularly construct multiple trails to support the hunt.

Figure 5.2 The whaling community of Barrow. A whaling crew moves their boat out to their safe camp (naŋiaqtuġvik) landward of a major grounded ridge line (top). The shorefast ice and lead system can be seen off the community of Barrow (bottom). Photos by M.L. Druckenmiller taken in April 2010.

"*Why do you want to map our trails? Don't you know they melt and go away each year?*" asked a hunter during a meeting of the Barrow Whaling Captains Association (BWCA). It was March 2007 and I wasn't sure if his question to me was rhetorical or evidence of his suspicion that I, a migratory scientist, didn't understand the least bit about their local environment. I am thankful that there were whalers at the meeting who assisted in properly articulating the project's intent such that the Captains saw no harm in approving the research.

During the previous spring, I had accompanied Hajo Eicken to Barrow for my first opportunity to step foot on arctic ice and to set a direction for my doctoral research. Through meetings with Craig George, a whale biologist with the North Slope Borough (NSB), and Richard Glenn, a local whaler with an M.S. degree in geophysics, the idea quickly emerged that I should map and research the ice trails that the hunters build each spring. Originally, the suggestion to monitor ice trails emerged from discussions at the 2000 Barrow Symposium on Sea Ice, which was a three-day gathering of over 30 Iñupiat ice experts and scientists to explore areas for collaborative sea ice research and understanding (Huntington et al. 2001).

In 2001, trail mapping began when George collected hand-drawn sketches of trails and ice features from Warren Matumeak, a Barrow elder, whaling captain, and retired director of the North Slope Borough (NSB) Department of Wildlife Management. George additionally worked with Tommy Olemaun to map trails using a handheld GPS (global positioning system) device. Figure 5.3 is a map based on both Matumeak's sketches and the GPS-tracks. Through 2006, George kept a record of general trail locations, occasionally using GPS; however a thorough and systematic approach had not yet developed. Building on existing efforts and ideas, a refined plan for a more comprehensive trail mapping project emerged and began in spring 2007.

This project is not the first to map ice trails used by indigenous peoples in the Arctic. In the Canadian Arctic, Aporta (2004; 2009), Tremblay et al. (2006), 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. Gearheard et al.'s (2010) work 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 developing a collaboration with Inuit residents near Qaanaaq, Greenland, to incorporate scientific instrumentation (similar to that used in this study) into sleds to be pulled by local dog teams. During usual times of travel, such as hunting, these onboard systems will measure ice thickness and local weather variables.

With these efforts recognized, there are three key aspects of my project that make it unique. *First*, the approach includes detailed surveys of continuous ice thickness and topography measurements, providing a multi-year dataset for quantitative analysis of trail characteristics. *Secondly*, these measurements are combined with various data collected by the Barrow Sea Ice Observatory (Druckenmiller et al. 2009, Chapter 2) to better understand the contributions of both dynamics and thermodynamics to the ice thickness distribution and to produce information resources for the community. *Thirdly*, relative to the spatial extent and roughness of the trails in

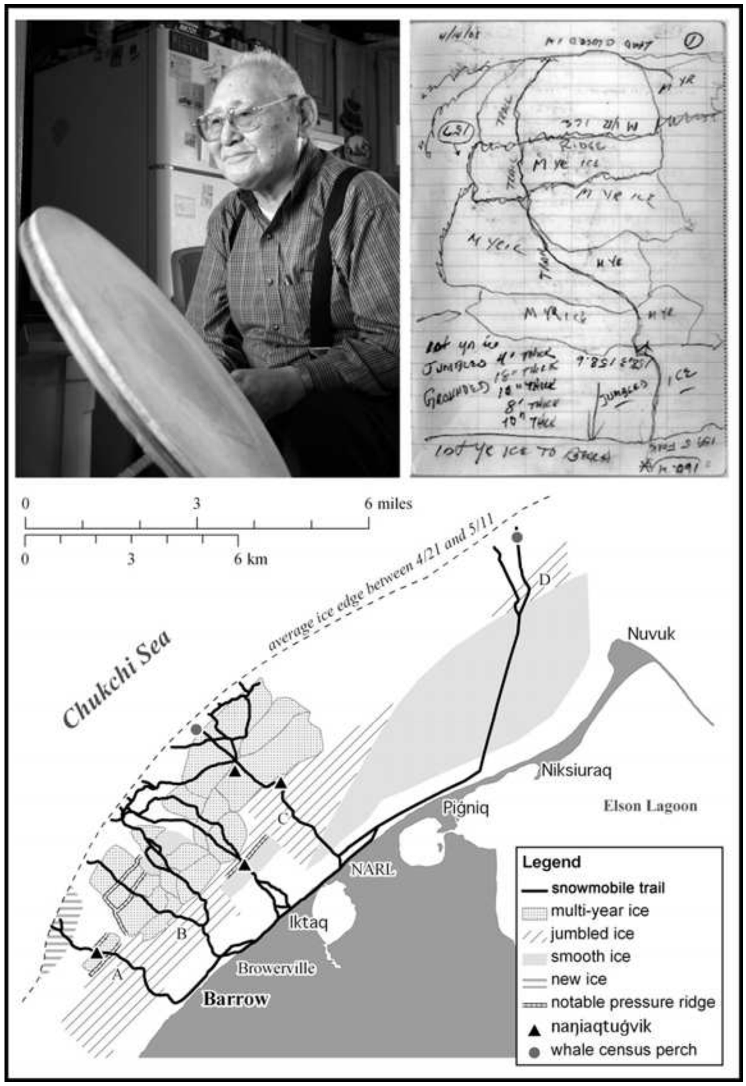


Figure 5.3 Warren Matumeak's 2001 trail map. Barrow Elder Warren Matumeak (top left; photo by Shari Gearheard) traveled the trails with a notebook, making detailed sketches of ice conditions (sample sketch shown at top right) and the locations of whaling safe camps (naŋiaqtuġvik). Matumeak's sketches, along with the GPS tracks collected by Craig George and Tommy Olemaun, were used to create the trail map shown. The feature of the ice cover that Matumeak most noted was the presence of multi-year ice floes. In the map the location of letters "A" and "B" signify areas where Matumeak observed grounded jumbled ice. "C" marks an area of jumbled first-year ice that had some islands of what appeared to be second-year ice. "D" marks an area of jumbled first-year ice of different sizes, including some very thin ice (sikuliaq).

the previously mentioned projects, the trails off Barrow traverse a very narrow stretch of highly deformed shorefast ice. The highly dynamic nature of the icescape makes for more dangerous conditions. While there are year-to-year similarities between Barrow's trail networks, each year presents significantly different conditions, unlike in the Canadian Arctic (Aporta 2004; 2009). Furthermore, over the last few decades elders and hunters in the region have reported substantial longer-term changes in the morphology and stability of the ice, making the passing of reliable knowledge onto younger generations difficult (Norton 2002). Barrow's trails are not typically placed with precise predetermined destinations in mind. Rather, they develop in response to encountered conditions to connect the community with safe and strategically placed hunting camps at the edge. These camps are often moved throughout the season as ice conditions and the location of whale sightings change (Druckenmiller et al. 2010, Chapter 3).

This paper summarizes findings of the trail mapping and monitoring project during four consecutive spring seasons (2008 to 2011)[2]. In doing so, I reveal how collaboration with the community has allowed me to combine geophysical-based monitoring with local knowledge and ice-use to document human-environment interaction, which may serve as a baseline for assessing future change. As the project evolved, my answer to the important question of "*why do you want to map our trails?*" naturally evolved. I explore the lessons and benefits of this project along three primary themes:

- Learning from indigenous ice experts (Section 5.3),
- Tracking ice conditions and community use of ice (Section 5.4), and
- Resources for the community (Section 5.5).

Much of the core emphasis of this paper is placed on Section 5.4. A framework for analysis is presented with the intention that this monitoring project continue in the long-term, thus providing many years of data and observations for inter-comparison. Lastly, I end with specific conclusions, as well as reflect on ways this work is connected to some of the most important and pressing issues facing subsistence hunting by a modern arctic community. This project, which has been driven by a university-research program, may be ripe for an opportunity to engage Barrow's youth.

5.2 Partnering to monitor ice conditions and use

Barrow has a long history of local experts partnering with researchers (Albert 1988; Brewster 1997; Druckenmiller et al. 2009, Chapter 2). Local people understand that by engaging with science they play a role in documenting and elevating their knowledge in the context of problems that concern their community and way of life. Furthermore, their involvement can tailor specific research to focus on questions they feel are important. At the 2000 Barrow Symposium on Sea

Ice local experts expressed a strong interest in seeing research address questions related to shorefast ice safety concerns (Huntington et al. 2001). Elders and hunters shared with scientists their insight into the key variables and processes to monitor in this regard[3]. As a result, the suggestion to monitor the trails emerged.

The community's interest in shorefast ice safety has also guided the efforts of the Barrow Sea Ice Observatory (BSIO), which developed over the last decade or so into an ongoing monitoring effort by Hajo Eicken and the Sea Ice Group at the Geophysical Institute of the University of Alaska Fairbanks. With input from the BWCA and the NSB Departments of Wildlife Management and Planning and Community Services, the BSIO has sought to ensure community relevance of its broader mission to monitor the coastal and regional waters near Barrow (Druckenmiller et al. 2009, Chapter 2). Table 5.1 summarizes the various components of the Observatory, which includes the trail monitoring effort which I have led.

Table 5.1 Components of the Barrow Sea Ice Observatory (adapted from Druckenmiller et al. 2009, Chapter 2)

Component	Observed variables and processes
Satellite imagery	Shorefast ice stabilization, shorefast ice extent, lead occurrence, ridging, multi-year ice concentration
Coastal radar (2005-present)	Ice drift, shorefast ice stabilization, ridging, shorefast ice break-out events
Coastal webcam (2005-present)	Presence of first ice, melt pond formation, snow cover, break-out events, open water
Mass balance site (1999-present)	Ice thickness, snow thickness, water-ice-snow-air temperature profile, relative humidity, ice salinity
Sea-level measurements (2006-present)	Tidal, storm surge, and wind driven sea-level fluctuations
Oceanographic moorings (2009-2011)	Current velocity, drift ice keel depths, water temperature
Regular observations by local ice experts (2006-2011)	Key events in the annual evolution of the ice cover, dynamic events, etc.
Ice trail surveys (2007-2011)	Ice thickness and surface elevation, trail location
Hunter interviews (2007-2011)	Ice associated hazards, shorefast ice stabilization, ice cover trafficability, influence of weather and currents, etc.

Each spring, prior to the start of whaling, I received permission from the BWCA to map and survey the trails. The general rule has been that I would stay clear of whaling activity and perform measurements before active hunting (i.e., crews camped on the ice with their boats and hunting equipment) or during periods when it was on hold[4]. The vast majority of surveys were performed in the days prior to the first arrival of passing whales (typically in mid-April; George et al. 2004a) and when the lead was closed. Occasionally, especially when mapping newly built trails in early May, surveys were performed on trails when crews were actively hunting. In these situations, I ended the surveys a couple hundred meters or so from the camps at the edge.

The primary piece of equipment used to survey ice along trails was an electromagnetic-induction device (9.8 kHz Geonics EM-31 conductivity meter), which measures apparent electrical conductivity of the underlying half-space. Because sea ice has a negligible conductivity (approx. 20 mS/m) in comparison to that of seawater (approx. 2500 mS/m), the EM induction technique may be used to indirectly measure ice thickness. By placing the EM-31 on the surface of the ice (or a known distance above since air or snow also have a negligible conductivity), 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 determined (see Appendix A for more details). Measurements are accurate to within a few percent of total thickness when surveying level un-deformed ice up to 3 m in thickness (Haas et al. 1997). Despite accuracy decreasing over rough, thicker ice, surveys across the entire extent of shorefast ice provide useful information regarding the ice thickness distribution, especially when looking to make year-to-year comparisons. A differential Global Positioning System (DGPS) capable of cm-scale accuracy was used to survey the vertical location of the surface[5]. In 2008, this equipment was placed on a small plastic sled, attached to a waist harness, and laboriously hauled across the ice by foot. In 2009, I used a large wooden sled, and by 2010 invested in the durable Ultra High Molecular Weight (UHMW) polyethylene sled shown in Figure 5.4, which is ideal for transporting the delicate EM-31 instrument.

When encountering hunters on the ice, I always explained the reason for my presence and asked whether it was okay to proceed. Responses ranged from general indifference to polite encouragement to complete the surveys. Frequently, hunters were interested in discussing their observations of ice conditions. More often though, they simply offered a clear warning that I must be alert and cautious—watching for bears and not venturing onto unsafe ice[6]. Since I was often

Figure 5.4 Ice survey sled with EM-31 and DGPS. This 4-m Ultra High Molecular Weight (UHMW) polyethylene sled has been used since spring 2010 to haul the survey system along trails using a snowmobile. The nearby metal of the snowmobile, which is approx. 1.5 m from the end of the instrument, does not influence measurements.

mapping the trail before active hunting began, I mostly encountered the younger members of the whaling crews since they provide most of the labor that goes into building trails. Occasionally, I suspended the surveys to help with and to learn how to build a proper ice trail. Trail maps were produced, similar to that shown in Figure 5.5, and provided to the community throughout the seasons. The maps helped to promote good relations and project-recognition amongst the whaling crews.

After each whaling season, I visited whaling captains and other hunters to discuss the impact of ice conditions on the hunt. These interviews were semi-directed (Huntington et al. 2009) and addressed the hunter's choice of trail and hunting locations, safety concerns, assessments of how resistant the ice was to a break-out, and the influence of the season's weather and ocean currents. All discussions were in English, but often addressed commonly used Iñupiaq terminology (see Appendix B) for ice features and weather conditions. Hardcopy maps of the trails and satellite imagery were used to help ensure that we were speaking of the same trails and ice features.

5.3 Learning from indigenous ice experts

Having traveled the trails each spring, I was able to ask specific questions about current ice conditions and why the crews chose certain areas. I quickly learned that the placement of trails is related to much more than ice conditions. Learning how whaling crews make decisions is

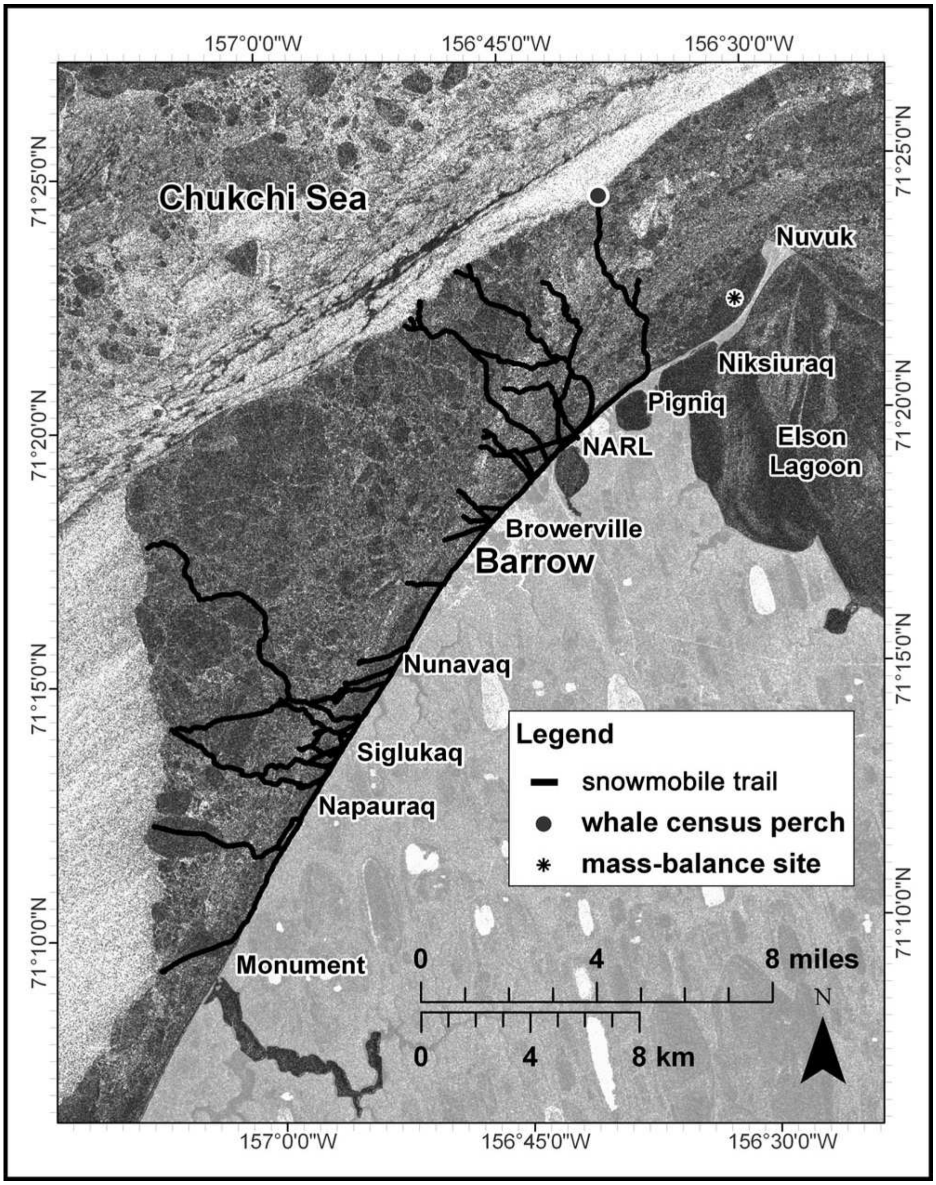


Figure 5.5 Map of the 2010 ice trails. This map is an example of the type of information provided to the community during the whaling season. The actual maps provided are in color and include navigational information such as trail names and GPS waypoints. The relatively short trails between NARL and Sigļukaq are those that were abandoned after the shorefast ice edge advanced in mid-April. The satellite image from May 1, 2010 is a 12.5-m resolution synthetic aperture radar scene from the European Remote Sensing Satellite*,* ERS-*2*, provided by the Barrow Area Information Database (BAID)[7].

necessary to understand the significance of the data being collected and to develop useful tools for the community. The strategies employed by whalers throughout the season as they construct their network of trails, monitor ice and weather conditions, and observe whale migration behavior was the subject of a previous publication (Druckenmiller et al. 2010, Chapter 3), which developed as a direct result of this project. Trails are placed with five primary considerations in mind: safety, access to whales, availability of preferred ice types, convenience, and tradition. These general factors, which guide where and across what types of ice hunters travel, are summarized in Table 5.2 and later explored more quantitatively in Section 5.4. Druckenmiller et al. (2010, Chapter 3) presented this trail monitoring project as a way to maintain detailed year-to-year summaries of how specific ice conditions relate to hunting successes and challenges; therefore, such topics will not be a focus here.

Table 5.2 Ice trail and hunting camp placement considerations (Druckenmiller et al. 2010, Chapter 3).

General considerations	Examples
Assessments of safety	- Is the ice well anchored? - Is the trail quickly navigated in case of an emergency? - Is the trail wide enough for two snowmobiles to pass? - Is there potential for secondary access/escape trails? - Is there a good location for the Naŋiaqtuġvik (safe camp)? - Can dangerous areas (e.g., cracks or thin ice) be avoided?
Access to whales	- Is the camp in a good location to see surfacing whales (e.g., in an embayment at the ice edge)? - Will the ice edge shape funnel or deflect whales to or from camp? - Does camp provide a good view of the water in the direction of the arriving whales? - Is the water deep enough for whales to dive? - Is the camp remote enough to prevent village noise from disturbing the whales?
Availability of preferred ice types	- Is there multi-year ice for drinking water? - Is the ice edge level and thick enough to haul up a whale? - Is the ice edge suitable for launching a boat? - Are high ridges nearby to serve as whale lookouts and landmarks when returning to camp in a boat?
Convenience	- How much trail construction effort is required? - What is the travel time between camp and the village? - Are other crews nearby in case of needed assistance?
Tradition	- Where are traditional hunting locations (e.g., good places to see whales)? - What crews often build trail and establish camps together? - What areas does traditional knowledge consider more dangerous (e.g., north of Nuvuk)?

While I remained a visitor to the Arctic with comparatively little experience on ice, my time traveling the trails provided me an elevated status with the hunters in comparison to the typical visiting scientist looking to discuss local and traditional knowledge. The maps provided evidence that I had been well-exposed to ice conditions of the given year. Local experts shared their knowledge and experience on topics relating to variability, long-term change, and how their community has interacted with ice, historically and today.

In 2009, Whaling Captain Tom Brower, III recalled that: *"Captains from Barrow used to band together to build a trail straight off Barrow. Then together the crews would build escape routes. In the older days, there were fewer trails. The trails were wider so dog teams could pass each other. Plus the ice was flatter in those days."* Brower estimated that once they built a trail straight out from his grandfather's house in Browerville[8] in 1969 or 1970 that was over 25 miles long, which was the furthest he remembered. Similar to Tom Brower, III, other hunters have commented that when they were younger (prior to satellite coverage) the ice edge used to be much further out, and the shorefast ice close to the coast used to be much smoother than now (A. Brower Sr., pers. comm., 2007; L. Brower, pers. comm., 2010). Stories such as these indicate that Barrow's whalers have already successfully dealt with changes to their ice environment over the last several decades.

Studies in this region have shown that the extent of stable shorefast ice is typically near the 20-m isobath (Barry et al. 1979; Kovacs 1976; Mahoney et al. 2005). However, past studies of sea-floor gouging in the Beaufort Sea Shelf using sidescan sonar and underwater photography reported gouging in depths up to 75 m in the Mackenzie Bay (Pelletier and Shearer 1972) and over 100 m in the Beaufort Sea Shelf north of Alaska (Reimitz and Barnes 1974). The highest gouge densities were found within the 50-m contour (Pelletier and Shearer 1972) and believed to be less than 100 years old at the time of study (Reimitz and Barnes 1974). While gouging is not a direct proxy for grounding, it is reasonable to assume the potential for grounding exists in areas where gouging is prevalent. Assuming that grounded features off Barrow extended to depths of 50 m, it is conceivable that hunters of the decades and centuries prior to 1970 may have been hunting much further out in comparison to today. For Alaska's Chukchi coast, Mahoney et al. (2007) showed through a comparison of the period 1999-2003 to the 1970s that the formation of shorefast ice is occurring approximately 1 month later. Coupling this finding with the general observation that thick multi-year ice is less abundant in shorefast ice (thus reducing material for massive grounded ridge systems in deep water) may account for the observation by hunters that the shorefast ice of today is not as far out as when they were young men. As for the ice being smoother in the past, this may have been simply due to the shorefast ice being thicker and less prone to developing into rubble fields.

When discussing the 2001 shorefast ice cover with Craig George (see Figure 5.3), Warren Matumeak noted that: *"We had a whole lot more multi-year ice this year than in past years. I'm referring to the ice offshore off the village. 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]. Maybe it was one piece that broke up into several pieces. I haven't seen this many [piqaluyuk] sections before."* Documented observations like these are extremely valuable to consider as the presence of multi-year ice during whaling continues to steadily decline in recent years (Jacob Adams, pers. comm., 2008; Roy Ahmaogak, pers. comm., 2009; Druckenmiller et al. 2010).

Indigenous experts' ability to recall the past allows for a critical perspective on how local ice conditions may be changing—one that is often difficult to communicate to those who do not share their same knowledge and experience. They place great importance on accurate explanations and are often hesitant to speculate or to even generally discuss impacts from climate change. During interviews, I had multiple exchanges that took the following form. First, the whaling captain told a story, recalling a specific environmental condition he encountered that posed a challenge to the hunt. My preconditioned thought immediately questioned whether this may be something specific occurring more frequently with climate change. I would ask "how common are conditions like these?", and he would answer "not too common, but it happens every so many years." Perhaps it was something he had not seen before, but remembered being mentioned by his elders. As a visitor to the community, you get the feeling that the hunters of the northern ice have truly seen it all, which makes it extremely insightful when an elder whaling captain actually suggests that something is new. The recognition of an exception or an outlier relies on a massive inventory of knowledge related to the "baseline" ice condition.

The hunters are first to admit that their personal descriptions of their observations and understanding of traditional knowledge may be different from a response offered by another hunter. Because local and traditional knowledge is highly nuanced, I expect to find 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 empirical knowledge into words. However, their understanding and interaction with the environment transcends personal experience. While discussing ice conditions, hunters express their inseparable relationship to a place of layered past experiences and described in the stories told by their elders

(Nuttall 1991; Sejersen 2004). The ice trails they build each spring traverse an ice environment that has shaped their knowledge, memory, stories, and history.

5.4 Tracking ice conditions and use

If hunters placed their trails in the same locations each year, independent of ice conditions, trail monitoring would provide a record of ice conditions in specific localities and the project could serve as a strictly physical-science endeavor to track inter-annual variability. Similarly, if the whaling crews sought a single ice type and placed their trails wherever the ice could be found, trail monitoring would provide great detail on the spatial distribution of ice morphology without an essential consideration of human and social-aspects. Clearly, neither of these is true of the way Barrow's whaling crews choose the location of their trails and hunting locations. Rather, locations vary and are a reflection of the choices hunters make as ice conditions change from year to year.

However, what does remain largely consistent from year to year is the assortment of strategies the whalers use, as presented previously in Table 5.2. (In this context, adaptation may take place when strategies evolve over longer timescales.) However, the idea that the community possesses the ability to modify their strategies based on ice conditions should not detract from reality, which is that hunting from sea ice involves compromising with the environment. In some years, conditions are not ideal for whaling (Druckenmiller et al. 2010, Chapter 3) and the hunters must simply do the best they can.

This section describes the variability in ice conditions and community ice-use and presents a framework for year-to-year comparison.

5.4.1 Beginning the record with whale harvest data (1980-2006)

Springtime whaling in Barrow is largely based along a stretch of coastline that extends over 30 kilometers from Nuvuk in the North to occasionally beyond Monument[9] in the south (see Figure 5.6). Since the mid-1970's, with permission by the whalers biologists with the NSB have visited the butchering sites of whales to retrieve biological samples. The locations of butchering sites have been recorded and are used here to approximate the general spatial extent of the area used during the hunt. This data is not representative of the exact range of hunting sites since it depends on successful hunts, but since the time period is large it is likely a very good proxy. Whales are hauled onto the ice for butchering at the same locations as the whaling camps, unless strong currents or deteriorating ice conditions force a crew to pull a whale to an alternative haul out site. Figure 5.6 shows the individual locations of butchering sites for whales taken between 1980 and 2006 and the directional distributions for the early, mid, and late-periods of the whaling seasons. The earliest crews on the ice typically base their hunt relatively close to town, most likely to simply minimize travel distance. As the season progresses the hunting community extends its range as more crews begin their hunt and spread-out in search of good hunting sites. However, clearly space between crews and distance to the village are not the only factors that guide where the crews base their hunt.

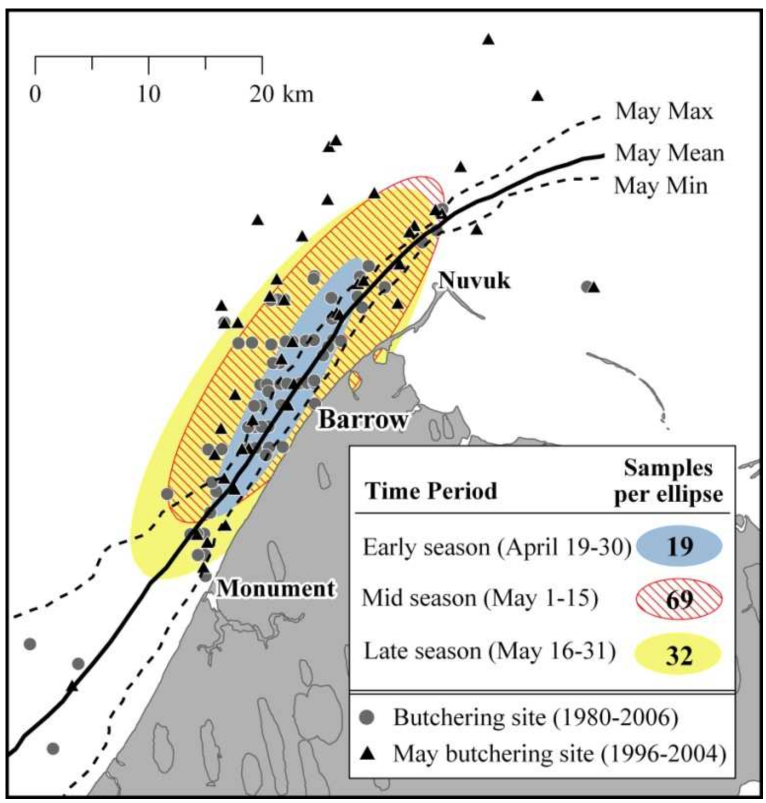


Figure 5.6 Shorefast ice extent and the spatial distribution of Barrow's springtime whale butchering sites. The minimum, mean, and maximum stable shorefast ice extents are from the month of May from 1996 through 2004. Butchering sites for the period over which the ice extents are determined are shown as triangles to distinguish these from all other butchering sites (1980-2004). Standard deviation ellipses (standard distances based on two standard deviations)[10] show directional distribution of butchering sites during the early, mid, and late season. Harvest data provided by NSB Department of Wildlife Management. Data points represent harvest site locations that were well-documented; more whales have been harvested over this time period than is shown here. Shorefast ice extent data from Eicken et al. (2006).

Figure 5.6 also shows the extent of stable shorefast ice for May—the month when the vast majority of whales are harvested—averaged for years 1996 to 2004. Here, stable shorefast ice was determined using satellite imagery and a method developed by Mahoney et al. (2005), which bases the definition of stability on the lack of detectable horizontal displacement over a 20-day period. The average butchering sites are mostly beyond even the maximum stable extent. This is expected as crews regularly base their hunt in deeper water well beyond the 20-m isobath that marks the average extent of stable shorefast ice in the Alaska's Beaufort and Chukchi Seas (Barry et al. 1979; Kovacs 1976; Mahoney et al. 2005). Camps are often placed on extended floating shorefast ice (iiguaq), which is highly vulnerable to breaking out and/or colliding with drifting pack ice (George et al. 2004b; Druckenmiller et al. 2010). In these situations, options for quick retreat to safer ice are critical.

Figure 5.7 uses the butchering site data to approximate the spatial extent of the hunting areas used by select individual whaling crews. This shows that while some crews have a wide range in select hunting sites, many others prefer to hunt in roughly the same location each year. For example, crew 6 (with a sample of 15 harvests) prefers to base their hunt between Barrow and Nuvuk.

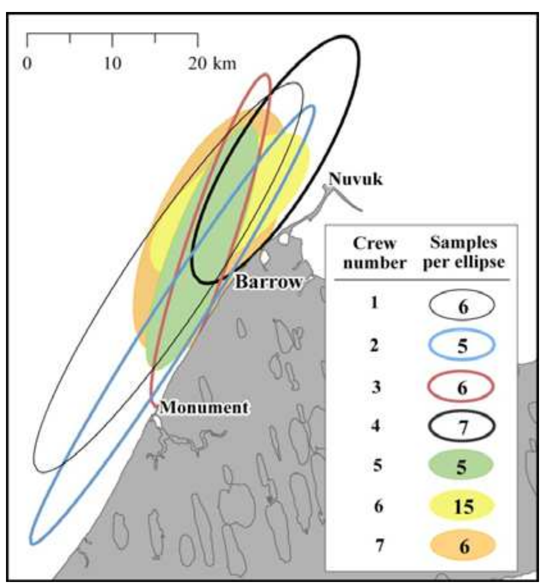


Figure 5.7 Spatial extent for hunting areas used by select individual whaling crews. Standard deviation ellipses (standard distances based on two standard deviations)[10] show directional distribution of harvest sites for seven different whaling crews based on a varying number of data points for each. Actual crew names are withheld; the designated crew numbers are arbitrary. Harvest data provided by NSB Department of Wildlife Management.

5.4.2 Summary of ice trail survey data (2008-2011)

As the EM-31 is dragged along the surface of trails, it measures the apparent conductivity of the underlying half-space, which is then transformed during post-processing to the distance between the instrument and the ice-water interface as discussed above and in Appendix A. Therefore these indirect measurements actually reflect the total layer thickness of ice and snow, and not specifically ice thickness. If it were possible to continuously measure the depth of an unaltered snow surface along the trails, snow depth would be subtracted from the total thickness to arrive at a more accurate estimate of ice thickness. However, these surveys are performed along trails that have often already experienced heavy snowmobile traffic that significantly disturbs and depresses the snow cover. *Therefore, I neglect snow depth*[11] *and present total layer thickness measurements as measurements of ice thickness unless otherwise noted.*

The EM-31 and DPGS were set to log at 1 second increments such that driving at speeds between 5 and 10 mph led to a measurement at approximately every 3 m. Data was sub-sampled to 5-m spacing. Water depths were assigned to each measurement using a bathymetry of 5-m resolution[12]. Here, I analyze the ice thickness and water depth data only. The surface elevation dataset, acquired for years 2008 to 2010, is discussed in Appendix A.

Figure 5.8 presents the locations and probability density functions (PDFs) of ice thickness for the four year period. The EM-31 conductivity measurements were transformed to total layer thickness using the following transformation equations for years 2009 to 2010 and 2011, respectively: $Z_t = 8.72 - 1.22\ln(\sigma_a - 12.4)$ and $Z_t = 8.49 - 1.21\ln(\sigma_a - 14.9)$. See Appendix A for how these empirically-derived transformation equations were developed.

The 2010 dataset does not include ice thickness measurements from the early season trails, which can be seen in Figure 5.4 as those not extending to the ice edge, since they were abandoned and not used during the active whaling season. Table 5.3 summarizes the ice thickness distributions and compares these to measurements made at the mass balance site (Druckenmiller et al. 2009, Chapter 4) on April 12 of each year, which is the average date for the trail surveys. Years 2008 and 2010 have thickness modes representative of thin ice (i.e., ice less than average first-year ice thickness), while 2009 and 2011 do not. Thin ice modes appear in the PDF for a given year with only one or two trail surveys that traverse such ice. As discussed in Chapter 3, these areas of thin ice in 2008 and 2010 represented very successful hunting sites for many crews.

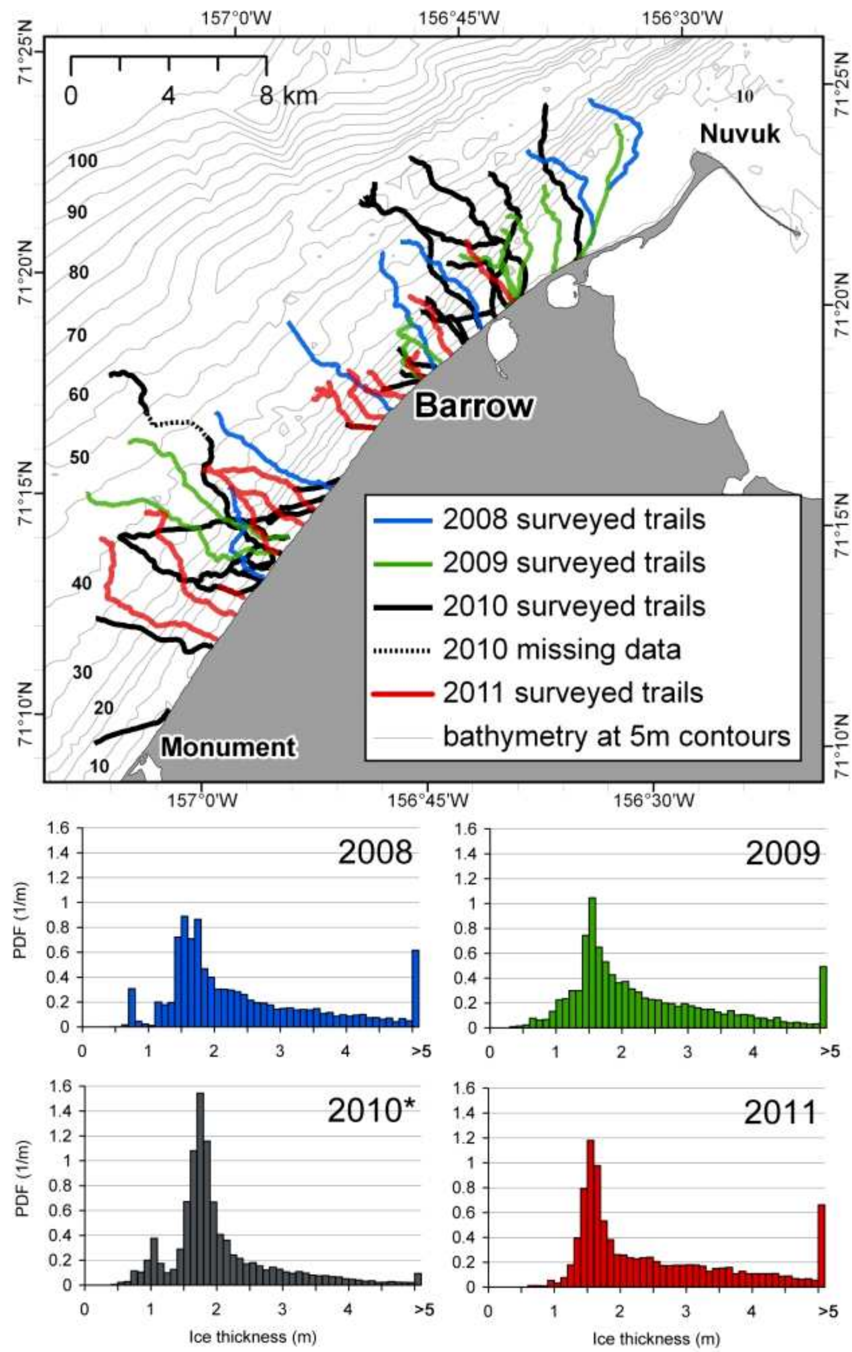


Figure 5.8 Summary of trail locations and ice thickness data (2008 to 2011). The locations of each year's trails are overlaid on bathymetric contours (top). A PDF of ice thickness is plotted for each year (bottom). The last bin in each PDF represents all thickness values greater than 5 m. *The 2010 data does not include the early season trails, which can be seen in Figure 5.4 as those not extending to the shorefast ice edge

Table 5.3 Ice trail and mass balance site thickness modes

Year	Ice trail surveys				Mass balance site[c]	
	"Thin ice" mode[a]		"Level first-year ice" mode[b]			
	ice thickness (m)	PDF value (1/m)	ice thickness (m)	PDF value (1/m)	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[d]	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 April 12, which is the average ice trail survey date. Measurements made by an acoustic pinger frozen into level ice (Druckenmiller et al. 2009, Chapter 2). See the 2010 site location in Figure 5.4. All other years were in roughly the same location.*
[d] *The 2010 data does not include the early season trails, which did not extend to the shorefast ice edge during active whaling.*

Table 5.3 shows a number of other noteworthy observations. The "level first-year ice" modes for the ice trail surveys are roughly the same for all years at between 1.5 and 1.6 m, with a slightly higher value in 2010 at between 1.7 and 1.8 m. (Here, the phrase "level first-year ice" refers to the thickness of level ice that specifically formed in place during fall freeze-up.) The same holds true for the measurements made at the mass balance site; years 2008 through 2010 show ice thickness at 1.3 m, while in 2011 it was 1.4 m. The fact that the thicker year in both datasets is not the same is not surprising given how different these datasets are in nature. The thicknesses of the "level first-year ice" modes are greater than the mass balance site measurements by approximately 30 cm on average. There are two reasons for this. First, as mentioned earlier, the trail surveys actually incorporate a compressed snow depth into the measurements. The average snow depth over this period at the mass balance site was approximately 25 cm. Second, the trails do not traverse only level ice that is within the expected thickness range of "level first-year ice", but also low-lying rubble fields.

The most important observation is that: (1) the mass balance site provides a similar value for level first-year ice thickness over the four year time period, and (2) the trail surveys also yield a fairly consistent value for ice thicknesses in the general range of expected level first-year ice thickness. However, important inter-annual differences are also prominent. Figure 5.9 displays the cumulative differences between the individual-year PDFs and average PDF for all four years to illustrate how the different years compare. For example, let us consider the uniqueness of 2010 relative to other years. The 2010 trails traversed proportionately more ice within the range of level first-year ice, but did not traverse much thick rumbled or ridged ice, which is the opposite of the 2011 trails.

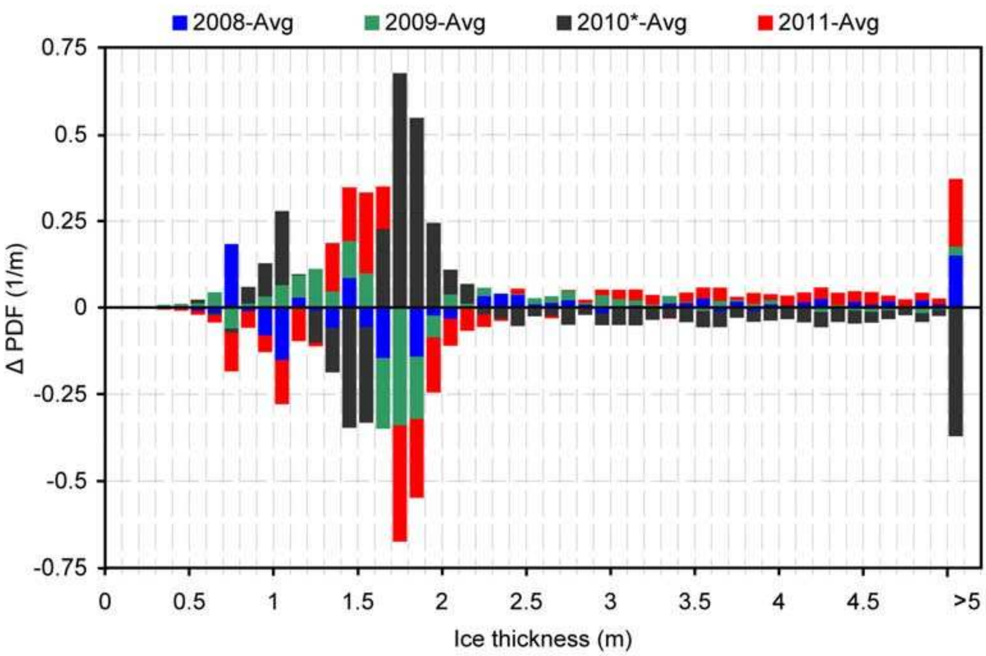


Figure 5.9 Yearly comparison of the ice trail thickness distributions. The last bin represents thickness values greater than 5m. *The 2010 data does not include the early season trails, which did not extend to the shorefast ice edge during active whaling.

From this, we can conclude that despite the nature of the sampling process, the trail surveys do provide a meaningful and consistent approach to monitoring modal ice thicknesses. Yet to fully understand what drives inter-annual differences in the ice thickness distributions, it is important to understand where the trails are built. One way to address this question is to consider the how the trails are distributed above different water depths.

Figure 5.10 presents a series of histogram contour plots that illustrate over what ice thicknesses and water depths the trails were placed for years 2008 to 2011. These reveal a number of interesting features. The modal ice thicknesses for different water depths can be compared, illustrating how the ice thickness of accreted ice farther offshore compares to ice near shore (at water depths similar to the mass balance site). In all years, the modal ice thickness in the expected range of level first-year ice was approximately the same between ice close to shore and ice further out near the ice edge, as summarized in Table 5.4. This indicates that when trails extend beyond the grounded zone (approximately the 20-m isobath) they typically are placed on ice of comparable thickness to that near shore. When this is not the case—when crews extend their trails out onto young ice (sikuliaq)—a separate mode appears (e.g., the mode in the upper left corner of the 2008 histogram contour plot).

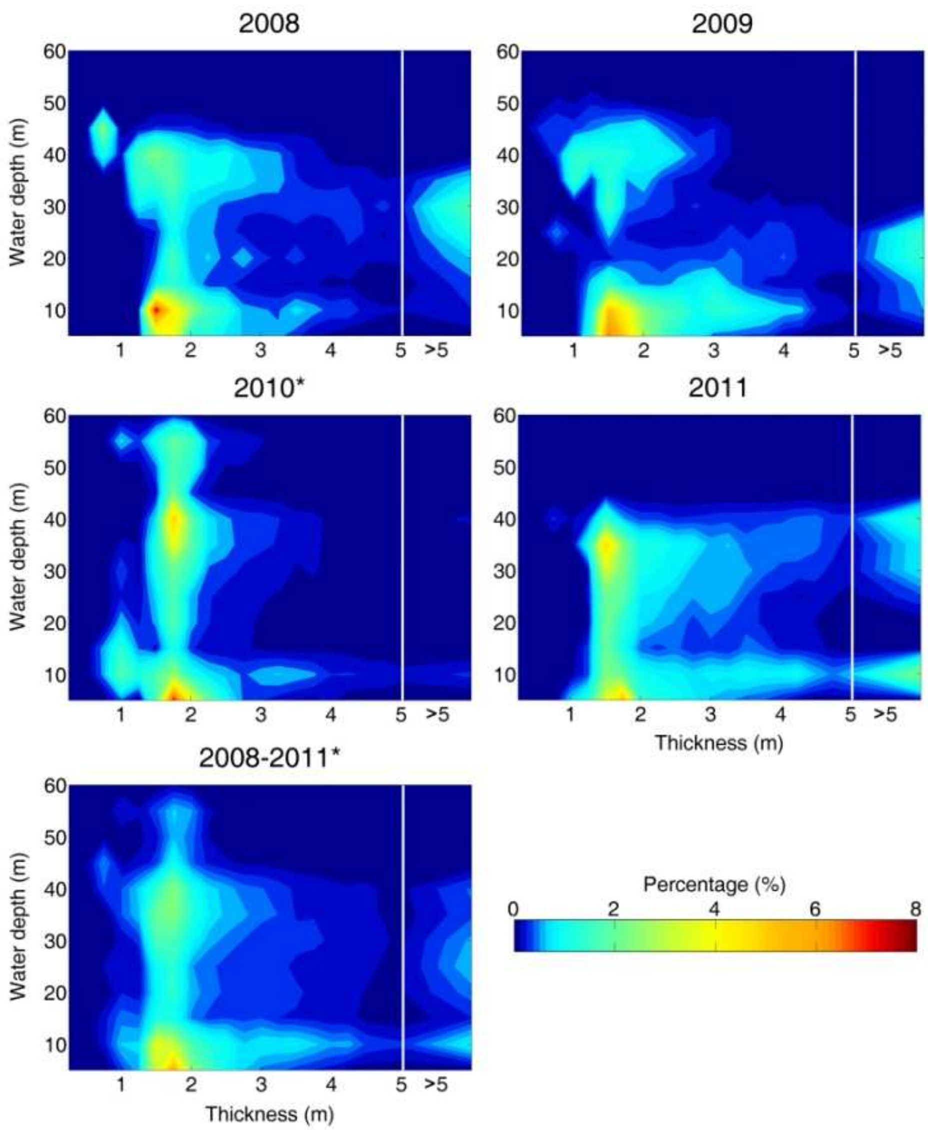


Figure 5.10 Histogram contours for ice thickness and water depth from the 2008 to 2011 trail surveys. The right end of each plot (separated by vertical white lines) represents one bin for all ice thickness values greater than 5 m. *The 2010 data does not include the early season trails, which did not extend to the shorefast ice edge during active whaling.

Table 5.4 Trail ice thickness and water depth modes.

Year	Near-shore mode[a]			Far-shore mode[a]		
	ice thickness [m]	water depth [m]	%	ice thickness [m]	water depth [m]	%
2008	1.25–1.50	10	7.5	1.25–1.50	40	2.4
2009	1.25–1.50	5	6.6	1.25–1.50	30	1.7
2010[b]	1.50 –1.75	5	7.4	1.50–1.75	40	5.2
2011	1.50–1.75	5	5.3	1.25–1.50	35	4.8
Average	1.50–1.75	5	5.7	1.50–1.75	40	2.5

[a] *Modes chosen at ice thicknesses nearest to expected level first-year ice thickness.*
[b] *The 2010 data does not include the early season trails, which did not extend to the shorefast ice edge during active whaling.*

Figure 5.10 also reveals the roughness of ice encountered in the near-shore. Ice thicknesses greater than level first-year values represent rubble fields, which indicate that the near-shore ice cover either (1) did not freeze in place under calm conditions, but rather established in a dynamic manner under the influence of winds, currents, or ice pressure, or (2) may have been level at one time but since experienced an ice ridging or shove event. Such an event took place in 2011. On February 17, 2011, a storm led to a localized ice shove event that resulted in large ridges (upwards of 11 m in height) forming very close to shore (see Chapter 3). Accordingly, Figure 5.10 shows that in 2011 there was thicker ice in the near-shore than in previous years. These ridges can be seen lining the beach in the photo of Figure 5.11.

Figure 5.11 Large ridges along Barrow's coastline in 2011. Ridges up to 11 m in maximum sail height developed on or near the beach during a storm on February 17, 2010 (Chapter 3). Photo by M. Druckenmiller on April 16, 2011 from atop the Wells-Fargo Building, which also is the site of the BSIO's coastal radar.

Lastly, Figure 5.12 provides an alternative portrayal of the data by averaging the ice thickness from the trails into 5-m bathymetric bins. This more clearly shows the contrast in the distribution of the ridges encountered by the trails. Years 2008 and 2009 suggest that the majority of the most prominent ridges existed at the 20 and 25-m isobaths, respectively. These ice thickness distributions seem to align with the generic description of a typical shorefast ice cover off Barrow—ice along the coast near the expected range of level first-year ice thickness, a line of presumably grounded ridges near the 20-m isobath, and relatively thinner, less stable extension ice beyond (Shapiro and Barry 1978; George et al. 2004b). 2010 and 2011 offer contrasting distributions. The 2010 curve shows a relatively even distribution of ice thickness across the range of water depths. The 2011 curve reveals the previously mentioned ridges near the coast and even thicker ridged ice at the ice edge, which is indicative of a prominent and expansive shear ridge which the crews could not avoid (see Chapter 3).

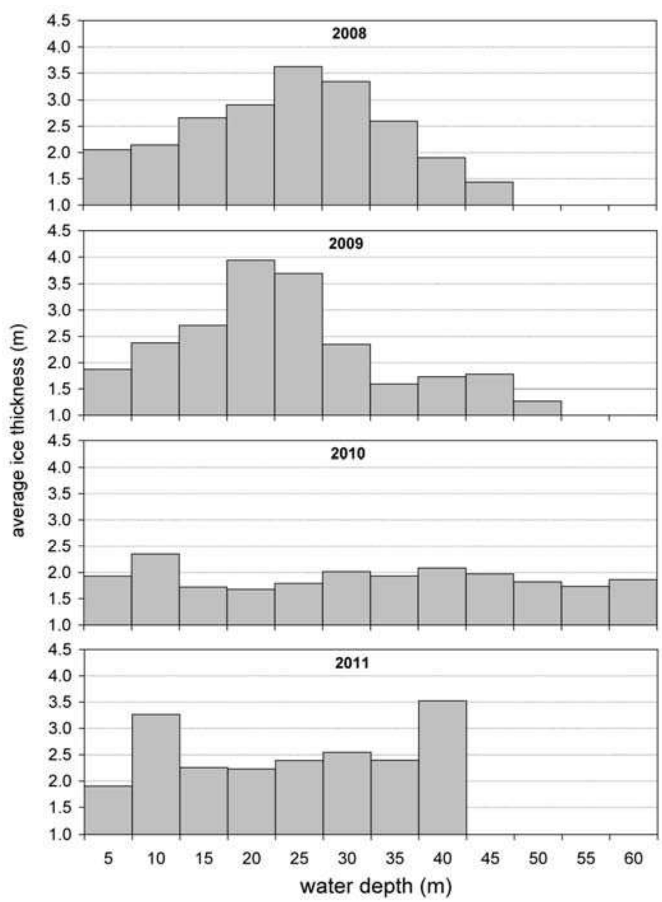


Figure 5.12 Average ice thickness along the trails for each water depth bin.

At this point, it is important to note that biases in the trail thickness data are inevitable as the trails are built in response to ice types encountered during route-finding. As will become evident in the coming section, the decisions of hunters may bias the surveys such that certain ice types are oversampled relative to others. For this reason, one may find that an ice thickness distribution for a set of random transects could be notably different than that of trail-based surveys for the same ice cover. While the diversity of strategies between different whaling crews (see Chapter 3) will tend to reduce overall bias when analyzing the full set of thickness data for all trails in a given year, it is expected that significant biases will be present within a very specific range of ice thickness. For example, a smooth refrozen lead within the shorefast ice will often provide a narrow yet highly traveled corridor of ice that parallels the coast. The resulting oversampling of thin ice in the trail thickness surveys may be accounted for with a data quality control strategy that looks for ice features that tend to attract a high number of trails. Such an effort would require a methodology for defining an acceptable spatial distribution of trails as related to an acceptable oversampling bias. This however is beyond the scope of this chapter.

5.4.3 Ice conditions, trafficability, and hunter decisions

Having examined the trail survey results in terms of what they reveal about the shorefast ice thickness distribution, it is important to reflect on the decisions that ultimately guided trail placement, and thus data collection. There are two ways this can be done. First, the specific ice conditions encountered each year can be considered alongside the general strategies described in Table 5.2. As mentioned, Druckenmiller et al. (2010, Chapter 3) provides this analysis in a descriptive, detailed summary of the on-ice whaling activities and associated challenges for each year. The second approach, which is the aim of this chapter, is to evaluate the data for quantifiable relationships that may indicate general hunter decision-making strategies.

Flat smooth ice can be found in shorefast ice as early as fall freeze-up if formed under calm conditions or it may develop in refrozen leads or cracks throughout winter and spring. As a resulting general rule, the thickness of flat smooth ice is either equal to or less than thicknesses observed at the mass-balance site (i.e., that of level first-year ice that formed during fall or early-winter freeze-up). Flat smooth ice is desirable since establishing a trail across it is essentially effortless. However, hunters also consider the anchoring strength and bearing capacity of the ice and must choose their trail's path with that in mind as well (Chapter 4). One of most common trail building strategies for navigating the highly variable shorefast ice is to connect various flat pans of ice, which are usually separated by rubble fields or ridges.

It costs a whaling captain considerable money to pay for his or her crew to travel back and forth to camp. During trail building or active hunting a typical crew will average about a half dozen people on the ice at a given time with close to that many snowmobiles. Although many hunters choose to camp on the ice for days at a time, regular daily trips between camp are made by many crew members. Hunters not only describe trail "distances" using the mileage recorded by their odometer or GPS, but also in terms of commute time or tanks of gas. For a whaling captain, fuel costs alone may easily extend beyond a thousand dollars in a single season. What influences a captain to decide on placing a whaling camp far from the village? They do so for reasons such as reaching localities that offer the most familiar conditions, have proven successful in recent years, promise remoteness from other crews and the village, or simply have favorable ice conditions (Druckenmiller et al. 2010, Chapter 3).

Figure 5.13, which plots the remoteness of the trail's terminus against the average ice thickness of a trail, also suggests that they will travel farther when the required effort to break trail is minimized by the presence of smoother (and consequently thinner) ice. In this figure, remoteness is defined as the distance between the trail's terminus and the center of the village[13]. A linear regression of the entire dataset (solid line) yields a correlation coefficient of -0.80. Linear regressions for the individual years (not shown) yield correlation coefficients for 2008, 2009, 2010, and 2011 as -0.78, -0.85, -0.84, and -0.42, respectively.

A main objective in trail building is to make the path as easy to drive along as possible while minimizing the amount of ice breaking and excavation required to route the trail. During trail building, ice picks are used to break-up ice blocks from the high-lying spots into smaller pieces, which are then redistribute as fill to the lower-lying spots. In other words, trail building does not remove significant volumes of ice but rather smoothes out the trail, reducing large-scale (>10 cm) roughness. Crews like to keep the trails straight, but since the ice cover is a mix of flat ice, rubble fields, and ridges, turns are inevitable as hunters look for the easiest route. Therefore, given the nature of the trail building process, how do ice conditions relate to the resulting trafficability of trails?

The trafficability of sea ice (i.e., the ability of a person or vehicle to travel across the ice) is not a new concept. In the 1970s, Hibler and Ackley (1975) developed a trafficability model that used satellite imagery to organize ridge height and spacing information to aid in the navigation of

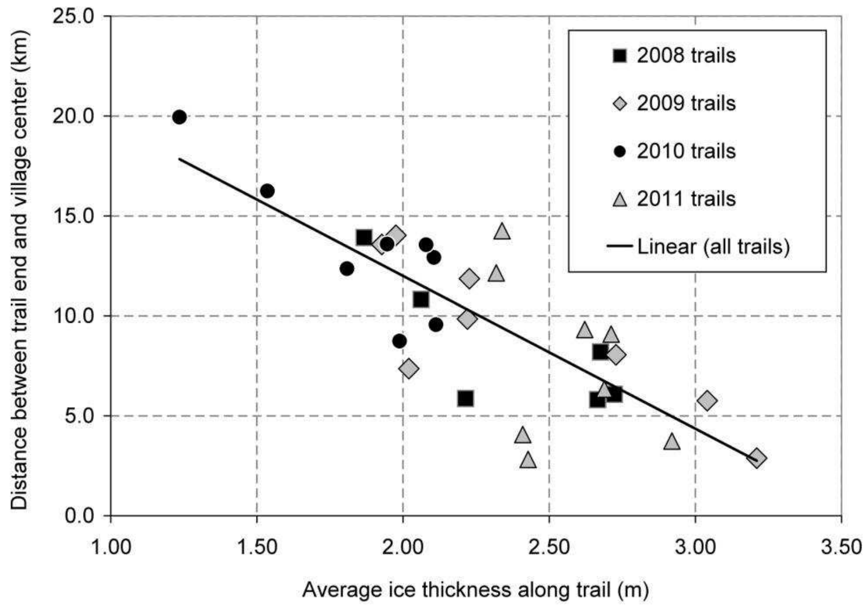


Figure 5.13 Average ice thickness along a trail relates to the remoteness of the terminus. The average ice thickness for trails that terminate at or very near the shorefast ice edge used during whaling is plotted against the distance between the trail's endpoint and the center of the village (71.2972° N, 156.77832° W)[13]. A linear regression of the entire dataset (solid line) yields a correlation coefficient of -0.80.

amphibious surface vehicles across arctic pack ice. Barker et al. (2006) conducted an empirical study of on-foot travel times across rubble fields of different block size for the purpose of better planning evacuation routes from man-made structures, such as those used in the oil and gas industry.

To explore the relationship between ice conditions and trafficability, I consider the trail's property of tortuosity, which describes how it twists and turns along its length. The underlying theory is that as tortuosity increases, the required travel time and driving effort increases, and thus the trafficability of a trail decreases.

Two separate definitions of tortuosity are considered. First, using the most widely used definition (Grisan et al. 2003), tortuosity t is given by:

$$t = \frac{L}{C}, \qquad [5.1]$$

where L is the total length of the trail (arc) and C is the straight line distance between endpoints (chord). Here, a unit-less tortuosity equals 1 for a straight line and infinite for a circle. Figure 5.14 plots the arc-chord ratio for each trail against its average ice thickness. At first glance there appears to be no apparent relationship between the two. Yet, with a closer look, a "y" shape to the data can be seen, which makes sense in the context of a hunter's practical approach to traveling across smooth ice. Large pans of relatively smooth and flat ice allow for easy turns of a large radius. Also such flat pans are often used to circumnavigate rougher ice, resulting in trails that have high arc-chord ratios. In this sense, twists and turns may not actually detract from a trail's trafficability since smooth ice can be traveled across at relatively great speeds and with little driving effort. Mächler (1993) makes the point that it is easy for a vehicle to travel along a curve with constant high curvature. This would logically hold true for a snowmobile traveling along a widely curved trail, providing the radius of the circle is greater than the turning radius of the snowmobile. With these ideas in mind, I conclude that this simple definition of tortuosity is not adequate to describe a property that more directly relates to trafficability.

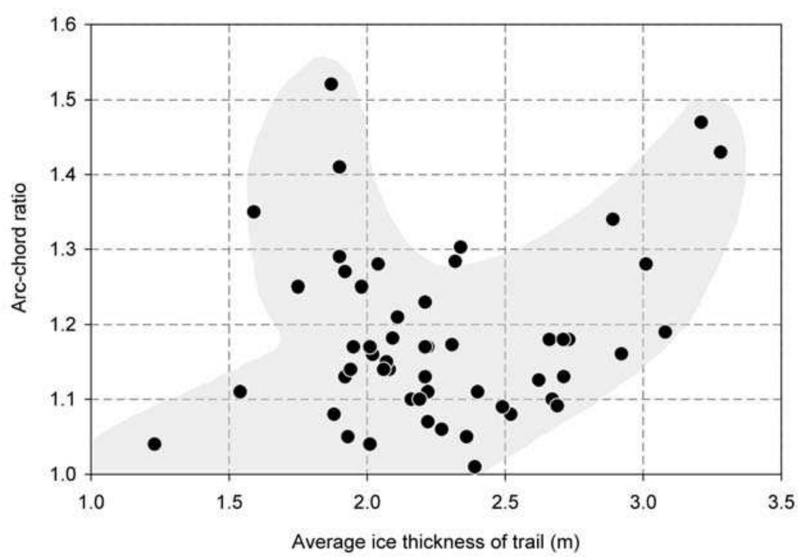


Figure 5.14 Average ice thickness along trail versus the trail's arc-chord ratio. The shaded region represents the author's visual interpretation of the "y" shape of the scatter plot.

A second and more useful definition of tortuosity, which considers changes in curvature, is borrowed from the field of ophthalmology where it has been used to evaluate the tortuosity of retinal vessels (Grisan et al. 2003). (It is interesting to note the resemblance of the trails in Figure 5.8 to blood vessels in the human eye.)

For curve *s(l)* given in cartesian coordinates with respect to parameter *l*, the curvature $C_s(l)$ is:

$$C_s(l) = \frac{x'(l)y''(l) - x''(l)y'(l)}{\left[y'(l)^2 + x'(l)^2\right]^{3/2}}. \qquad [5.2]$$

By dividing curve *s(l)* into *n* turn segments, such that n–1 = the number of times the sign of curvature changes, tortuosity *τ(s)* is given by:

$$\tau(s) = \frac{n-1}{L_a} \sum_{i=1}^{n} \left[\frac{L_{a_i}}{L_{c_i}} - 1 \right]. \qquad [5.3]$$

where L_a is the total arc length, L_{a_i} is the arc length of each segment, and L_{c_i} is the chord length of each segment. A greater tortuosity measurement is associated with both greater arc-chord ratios for each segment and a greater number of twists along a trail. In order to evaluate the curvature and resulting tortuosity of the trails, a cubic spline interpolation was used to fit a curve to the trail data, which was sub-sampled to 5-m spacing (as mentioned previously). Here, tortuosity is in units of 1/length, which permits comparison of tortuosity from different length trails. I suggest the following definition for a unit-less measure of trafficability T:

$$T = \frac{1}{\tau(s)L_a}. \qquad [5.4]$$

Figure 5.15 presents a range of trail shapes and lists the resulting values for *τ* and *T*. A greater value for *T* indicates higher trafficability, and thus conceptually, less travel time and driving effort. In this regard, a lower trafficability score is associated with an increase in risk. The more tortuous and lengthy a trail, the more time and effort it will take to evacuate the ice in an emergency situation. It is important to note that *T* has not been calibrated in terms of travel time or driving effort, yet it is reasonable that this could be done in the future with a properly designed experiment

Trail	τ (m^{-1})	L_a (m)	$T \times 10^3$
1	0.01	3445	29.0
2	0.12	3720	2.2
3	0.26	5750	0.7
4	0.34	6065	0.5

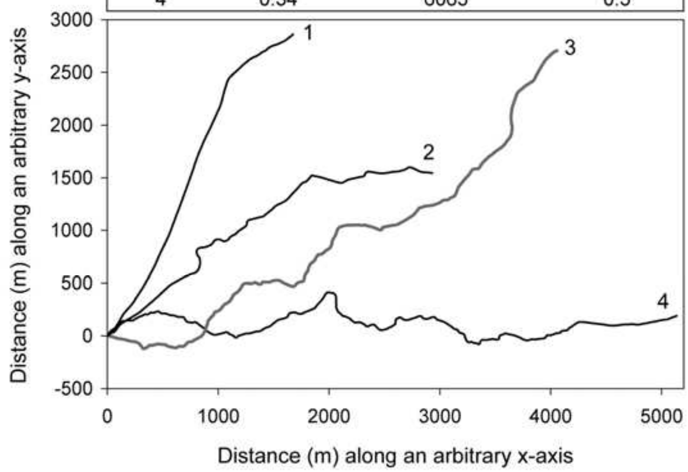


Figure 5.15 Tortuosity values for various select trails. The table at top lists a range in tortuosity values for the trails along with their arc lengths (L_a) and the resulting trafficability (T) scores. The bottom panel illustrates the shape of the indicated trails.

Surprisingly, this definition of tortuosity did not yield any noteworthy results that would suggest a clear relationship to ice thickness. Rather, it was found that tortuosity mostly relates to total trail length (arc length). Figure 5.16 plots the trail arc length versus tortuosity. A linear regression yields a correlation coefficient of 0.75. Equation 5.4 shows that trafficability is inversely related to both tortuosity and trail arc length. As Figure 5.16 suggests a direct correlation between tortuosity and trail arc length (and thus also ice extent), it is clear that the longest trails accept a greater risk not only because they extend into deeper water beyond the grounded zone, but also because they are highly tortuous and therefore have a low trafficability score. Furthermore, if we assume that a tortuous trail develops out of necessity to deal with difficult ice types during trail building, it is likely that more tortuous trail sections may have to be abandoned when unsafe spots (e.g., thin ice at the start of the melt season) develop because such spots cannot be avoided.

The finding that tortuosity is significantly related to trail arc length also suggests a relationship between tortuosity and trail building effort. A crew will often first build a “scouting

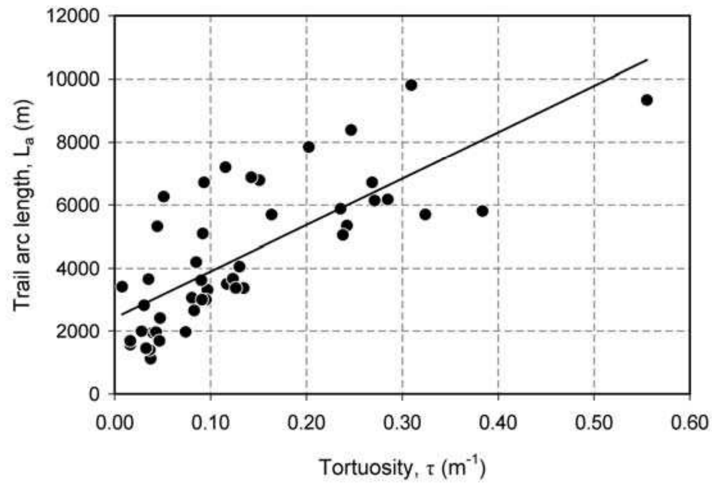


Figure 5.16 Tortuosity versus trail arc length. A linear regression yields a correlation coefficient of 0.75.

trail" to quickly find a place near the ice edge where they wish to hunt. Once the general ending location is reached, they will return to the middle sections of the trail to straighten them out and build shortcuts[14]. The time that hunters can afford for the physically demanding work of trail building is finite. Therefore, a longer trail means that the trail building effort must be proportioned over a greater distance, resulting in more twists and turns. In this context, trail tortuosity may also relate to the crew's perception of increased risk to their trail building investment. Building a straight trail in rough ice typically represents a significant investment of time. When making a long trail that extends into deep water, the hunters know that in general their risk of losing sections of trail to break-outs increases as they travel further beyond the grounded zone. Therefore, the result is that they save time by building more tortuous trails.

5.5 Resources for the community

Since 2005, the coastal radar of the BSIO (see Table 5.1) has provided the Barrow community with an internet-based near-real-time animation of coastal ice dynamics (Druckenmiller et al. 2009, Chapter 2). Since 2003, the Barrow Area Information Database (BAID)[7] has provided an online interactive mapping service that in recent years has hosted satellite imagery of sea ice for the Barrow region in springtime. 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 current ice conditions. However, such resources currently see little 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.

The introduction of ice trail maps to the community represents a new approach toward both gauging community interest in science-based resources and improving their understanding of the information's value and content. The trail monitoring project represents an ongoing open experiment to discover how research can better provide useful information to the community.

5.5.1 Trail maps: Benefits, concerns, and challenges

The ice trail maps produced and distributed to the community (see Figure 5.4) have been kept as simple as possible. Maps include GPS-tracked trail locations, recent satellite imagery (usually from 1-10 days before present), a coastline with traditional place names and commonly used location names, and a few points of interest, such as the locations of the BSIO's sea ice mass balance site and the recent whale census surveys[15]. Many maps have also included latitude and longitude for select points along trails, such as beginnings, ends, and junctures with other trails. In some years, whaling crew names were placed on the map in association with the trails that individual crews were using. The spatial coverage of the maps has been chosen to include all trails in the given year, as well as the nearby shorefast ice edge.

These maps have been largely considered by the community as useful for on-ice navigation, general ice-type discrimination (flat ice versus rough ice), and as a tool for communication between whaling crews. In 2008, Tom Brower, III mentioned that "*the maps can help people learn how to use a GPS, are good for search and rescue, and are good for directing people to harvest sites*".

As handheld GPS devices are increasingly used, elders and more experienced hunters have expressed mixed concerns over this trend. The technology both provides a great 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. However, reliance on this technology comes with a price (Aporta 2005)—traditional navigation skills and attention to local landmarks and place names are quickly fading and are already mostly non-existent amongst the youth. As a result, I must acknowledge that satellite imagery and trail maps are likely not always used to supplement local and traditional knowledge and may actually detract an inexperienced hunter from learning the ways of his elders. To a culture where learning traditionally takes place through hands-on experience, careful observation, and time spent on the land (or ice), it is conceivable that graphically mapping ice trails as a tool for navigation may be seen by some as a form of epistemological assimilation, just as Rundstrom (1995) has argued in regards to GIS technologies being used to document indigenous knowledge. However, today such trends are unstoppable as technology and innovation pervade all cultures at an unprecedented pace.

Over the past years, I have considered whether or not to provide ice thickness data to hunters and, accordingly, questioned the level of detail that would be appropriate to prevent miscommunication. In this context, data dissemination and the production of resources for the community face three primary challenges.

First, there is the challenge to avoid providing potentially misleading information. As stated earlier, EM-derived ice thickness measurements are not able to resolve the actual thickness of ridges (see Appendix A for a more thorough discussion on this topic). Given that the thickness of ridges relates directly to the keel depth of a ridge and therefore largely to the anchoring strength of grounded ridges (Chapter 4), EM-derived thickness measurements must be considered in light of all that contributes to errors upwards of 30% (Haas 2003).

Secondly, there is the challenge of providing information that is too specific. Regarding Inuit indigenous knowledge, Berkes and Berkes (2009) made the general claim that numerical precision is not highly valued or often used. Furthermore, they argue that local and traditional knowledge maintains real-word relevance because precise categorizations are avoided. If you were to survey whaling captains at their dining tables regarding how thick the ice has to be to haul up a whale, you would likely receive a wide range of answers. However, if together on the ice evaluating a potential whale haul-out site, these experts would likely come to consensus regarding whether the ice was suitable, and certainly their assessment would consider much more than ice thickness. Reasons for consensus are likely two fold. First, there is a hierarchy in their knowledge such that the elder's knowledge (i.e., that of those with more experience and empirical evidence) overrides that of the younger, more inexperienced hunters. Secondly, the hunters would evaluate the ice for cracks and consider other factors that could compromise the integrity of the ice other than the weight of the whale. For example, is the haul-out side sufficiently sheltered from potential direct impact from pack ice? Butchering a whale takes many hours; therefore the hunters must consider the duration of their specific activity when evaluating specific ice features. When on the ice the nuanced-nature of their knowledge is most evident when specific uses of ice are considered.

Thirdly, there is the challenge of providing too much information. In *The logic of failure*, Dörner (1996) writes that "*anyone who has a lot of information, thinks a lot, and by thinking increases his understanding of a situation, [but] will have not less but more trouble coming to a clear decision… As we gather more and more information, our conviction that we have formed an accurate picture of the world gradually gives way to doubt and uncertainty*." Dörner's primary thesis is that effective decision makers cannot be "*hobbled by excessive detail*". While most whaling captains will politely ignore available data well before they allow it to hobble them, I believe Dörner's argument is an important concern in our effort to provide usable sea ice information to the community. However, I am not categorically suggesting that hunting from sea ice is best done with little information. Clearly indigenous ice experts collect and "process" much information from the environment. The distinction between observations made in the context of local knowledge and the content of science-based information products is that the process of incorporating the former into decision making is already well encoded in the mind of the expert.

Figure 5.17 is the 2010 trail map shown in Figure 5.4 but with ice thickness values provided in color. More than once, stacks of similar maps have been delivered to Barrow's Search and Rescue Base, which is a widely-used meeting location for Barrow whalers (In these instances, the map's units for thickness were in feet, not meters). I observed that such products stimulated little feedback or interest amongst the hunters. The reason may be that too much and too specific information is provided and that it is not presented in a more meaningful manner. Ultimately hunters are not strictly concerned with ice thickness but rather the utility or hazards associated with different ice types, where ice thickness is only one defining characteristic, albeit an important one.

5.5.2 Toward an improved product

When Warren Matumeak traveled the trails in 2001 noting the types of ice he encountered (see Figure 5.3), he was essentially noting features and ice types that he deemed important. Based on what I have learned from the whalers, I assume he considered ice type a useful indication of ice anchoring strength ("pressure ridges"), trafficability ("smooth" versus "jumbled ice"), potentially dangerous ice edge conditions ("new ice"), and specific ice uses ("multi-year ice" as a solid platform for camp or as a source of fresh water).

In 2002, a year after Matumeak made the first detailed trail map with Craig George, Jana Harcharek of the NSB School District published *Aġviqsiuġnikun Whaling Standards* as an

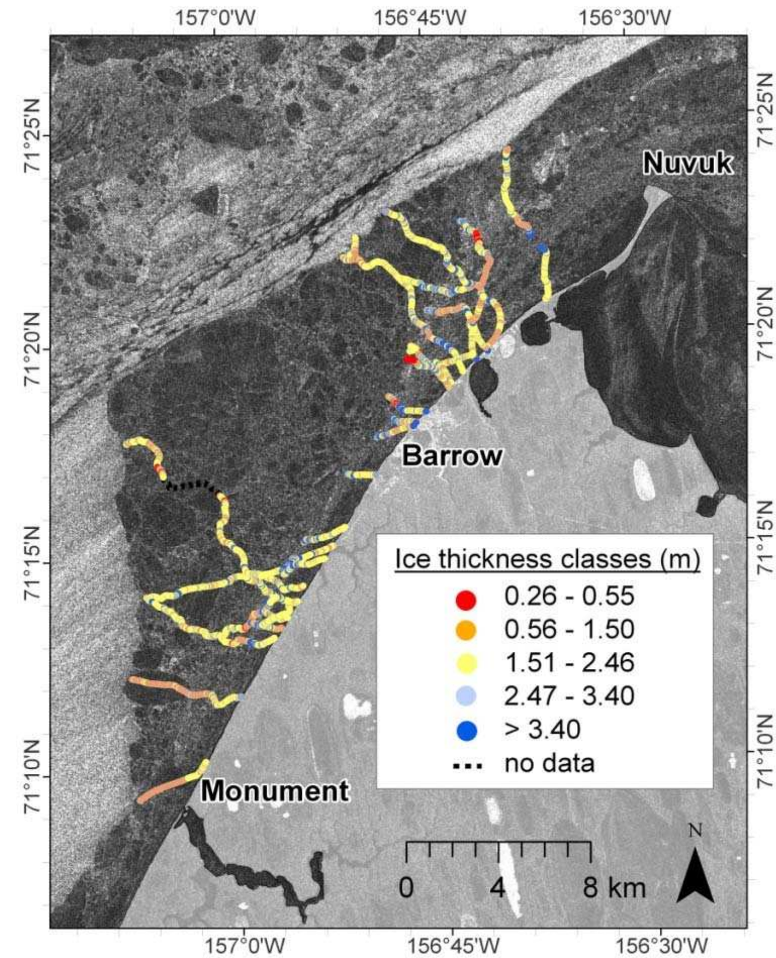


Figure 5.17 Barrow's 2010 ice trail map presented with ice thickness values. Colors represent different ranges in ice thickness values according to a classification scheme based on 1 standard deviation from the mean[16].

educational resource for the young hunters of Barrow and Wainwright. The handbook summarizes local and traditional knowledge of winds and ocean currents, bowhead whale morphological types, hunting equipment, and butchering methods. It includes a checklist for the things a whaling captain must pay close attention to when making decisions on the ice. Interestingly, it encourages the young whalers to travel their crews' trails in springtime and to sketch the different ice types they encounter.

Recognizing the importance of contributing to and complementing community led efforts, I decided that an improved product should resemble the ice type classification that Matumeak presented, while building from the type of ice thickness information shown in Figure 5.17.

Ice thickness is not the sole determinant of ice type. Age, floe size, roughness, and thermal state must all be considered. Therefore, ice thickness information alone is not adequate to inform hunters' decisions. With this thought in mind, I explored cluster analysis, which is a statistical data analysis approach available in most GIS software packages, as a way to manipulate the ice thickness dataset into something more useful. As opposed to a thickness classification where each class has a unique thickness range, cluster analysis allows for ice thickness values to exist in more than one class. ArcGIS provides a cluster tool, Hot Spot Analysis[17], which identifies and maps spatially significant clusters of high and low values. Each thickness data point is assigned a dimensionless z-score based on how many standard deviations an observation is from the mean within a moving window of specified length. A classification based on z-score, not ice thickness, allows thickness values to exist in more than one class providing that the z-scores are defined over a distance that is less than the spatial extent of the dataset.

Figure 5.18 presents an example of cluster analysis applied to ice thickness from a single trail in 2010. A trail classified based on thickness alone, using the same classification scheme shown in Figure 5.17, is contrasted with a classification that used clustered analysis over a moving window of 50 m. The relationship between ice thickness and the z-score is shown by the graph in Figure 5.18.

Assigning a z-score to each ice thickness data point, however, does not determine the classification. The most informative classification scheme will likely not be statistical in nature but rather based on expert knowledge and observations made along the trail. Figure 5.18 presents a manual classification of the z-scores into colored classes based on geo-located photos I took along the trail in mid-April, prior to the start of the active whaling season. In other words, I used knowledge of the observed ice types to adjust the classification such that the major ice types fell within mostly different classes. For example, light blue represents either rough ice or multi-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 the refrozen lead.

While the difference between the information presented by the two colored trails in Figure 5.18 is not dramatic, it presents an improved contrast between ice types along the trail compared to classifying by ice thickness alone. This approach for combing and organizing different types of information relies on both technical ability and expert knowledge. It will undoubtedly prove time-intensive when applying it to an entire year's trail surveys. However, as I will discuss further in Section 5.6.2, I believe this strategy may increase this project's level of collaboration with the community and lead to a usable resource that may also assists in the traditional learning of young hunters.

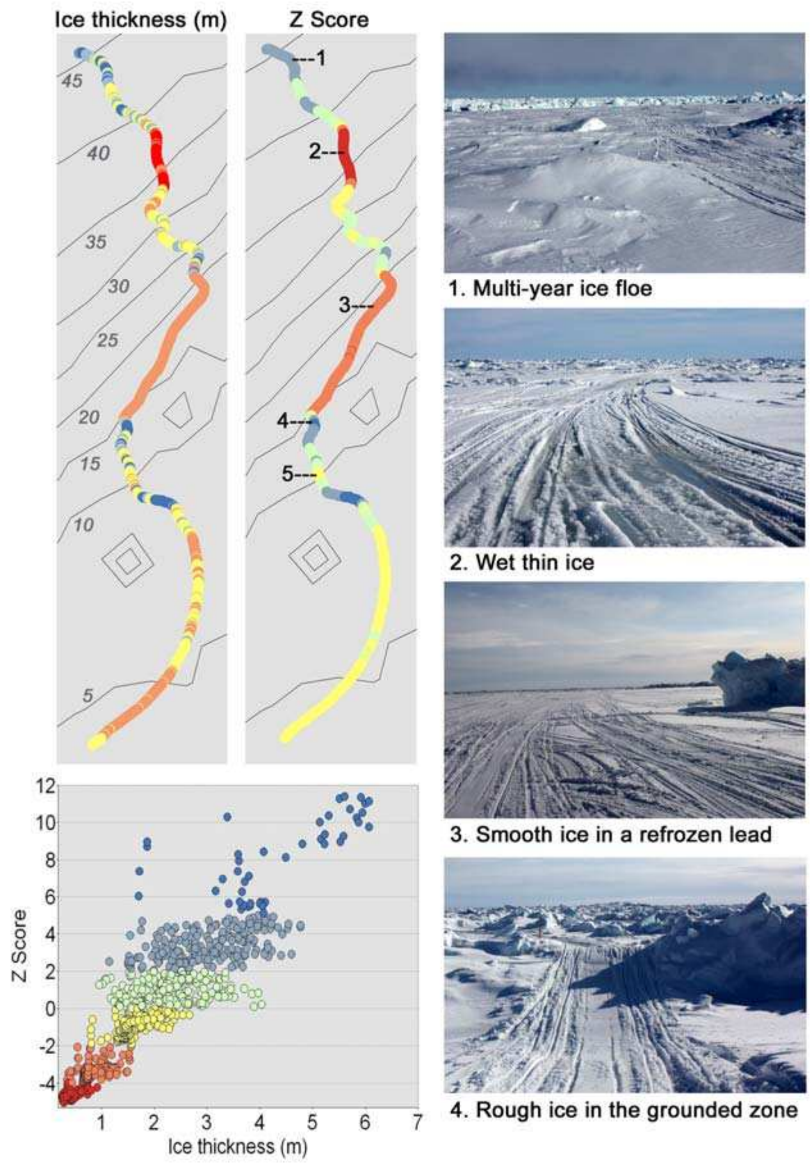


Figure 5.18 Ice trail morphology classification according to both thickness and type. *Top left*: Colors along the trail indicate ice thickness according to the classification scheme of Figure 5.17. Bathymetry is shown with 5-m contours. *Top middle*: Colors along the trail indicate z-score[17] according 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*. Number 5 represents the location of the safe camp shown in Fig. 5.2. The trail used in this figure is the second trail from the NE in Figures 5.4 and 5.17.

5.6 Conclusions

5.6.1 Summary of specific findings

Four years of trail monitoring between 2008 and 2011 and consideration of how the collected data relate to community use of shorefast ice have led to the following sets of specific findings:

(1) To understand how the general determinants of hunting location guide where ice trail surveys are performed, the following must be considered:

 i. Hunters decide on hunting location based on assessments of safety, access to whales, availability of preferred ice types, convenience, and tradition.
 ii. Whaling crews that begin their hunt earlier in the season typically hunt closer to town, most likely due to convenience and shorter travel times.
 iii. A significant range exists between different crews' inter-annual spatial extent of selected hunting sites, suggesting differences in tradition, personal preference, and general hunting strategy.

(2) A four year inter-annual comparison of the shorefast ice thickness distribution showed:

 i. Each year's trail surveys yielded a fairly consistent modal thickness for level first-year ice (as did the BSIO's mass-balance site), suggesting the surveys provide a meaningful and consistent approach to monitoring shorefast ice mass balance.
 ii. In all years, trail surveys revealed that the primary modal ice thickness close to shore was approximately the same as that near the ice edge, indicating that when trails extend beyond the grounded zone hunters typically seek ice of comparable thickness to that near shore.
 iii. Trail surveys revealed the roughness of encountered ice in the near-shore, which is indicative of either conditions during freeze-up or of significant ice compression events throughout winter and early spring.
 iv. Trail surveys revealed inter-annual differences in the water depth at which the primary grounded zone(s) developed.
 v. Biases in the trail-based ice thickness surveys due to oversampling of flat, smooth ice, which is typically ice equal to or thinner than expected level first-year ice thickness, should be considered.

(3) Relationships between trail building and ice conditions:

i. Whaling crews will travel a greater distance from the village when the required effort to break trail is minimized by the presence of smoother (and consequently thinner) ice.

ii. In the context of assessing trail trafficability, tortuosity is a highly informative property. Tortuosity, which is likely linked to the time and effort crews invest in trail building, directly correlates to trail length, and thus to ice extent.

(4) Improving science based resources for the community:

i. Resources must be developed such that they are compatible with the type of information hunters are already using to evaluate the ice cover. Consideration for the proper level of detail and precision in the type of information provided is essential. Success is likely to be achieved through multiple iterations of a product and continued community feedback.

ii. The trail monitoring project may improve on the usefulness of the trail maps by discriminating ice types based not only on ice thickness, but also on the spatial clustering of ice thickness observations and visual-based expert knowledge of the specific ice types encountered along the trails.

5.6.2 Sustaining the program

Effective communication and clear intentions are fundamental to any long-term partnership. Therefore, I am left to concisely answer the question: "*Why do you want to map our trails?*" This paper has demonstrated that the trail monitoring project is important along three themes.

First, we as scientists are learning from indigenous ice experts in a way that is unique to the experiential nature of this work. Making measurements along the same ice trails that the hunters use throughout the season provides for an immeasurable context for discussion with local ice experts about current ice conditions, observed changes, and the details of their local and traditional knowledge.

Second, the project tracks inter-annual local ice conditions in the Chukchi Sea coastal zone while documenting the intricate relationship to community ice-use and subsistence activities. Illuminating these relationships may support adaptation if the current strategies employed by the whaling community are not solely adequate to cope with future change. Unfortunately, it is often not until the benefits people derive from their environments are disrupted or lost that they begin to fully comprehend their functionality and value (Daily 1997). Accordingly, the "baseline" for assessing change will not be characterized by a single variable, such as ice thickness, but rather by how that variable manifests in impacts to human activities.

Thirdly, the project is improving our ability to provide resources for the community as a way of reciprocating for what we in the science community have gained from this partnership. This project recognizes that the information needs of the community are not static as each year brings unique ice conditions (Druckenmiller et al. 2010, Chapter 3). Community information needs fall within two categories: (1) they are interested in tools to inform them of current ice condition, and (2) they are interested in improving their overall understanding of the changes taking place in their environment. Just as scientists, local ice experts also look to understand larger scale causal relationships that explain how current conditions fit within long-term patterns.

These three reasons are justification for continuing this project into the future; however, I admit that many of the challenges faced by the community have little to do with climate-related stresses. Similar to other arctic indigenous communities (Ford et al. 2010), Barrow struggles with barriers to locally-relevant education and loss of local and traditional knowledge. Just as the NSB School District realized when they produced a handbook of whaling standards for young hunters (Harcharek 2002), revitalization of a culture in today's Arctic requires collaboration between the school system and traditional activities (Roué 2006).

Through the involvement of young hunters, this project may develop improved products for the community (starting with the approach outlined in Section 5.5.2) while at the same time providing a unique traditional learning experience alongside exposure to science and technology.

I am reminded of a lesson I learned in 2008. I had led a two-day workshop in Barrow[18] to instruct local leaders, professionals, and hunters on how to access and interpret online sea ice information (see Figure 5.19). One session was devoted to instruction on how to interpret the type of radar-based satellite imagery that provides the background for the ice trail maps. While the goal was to contribute to the practical skill of local people, we paid close attention and documented the feedback we received. Participants overwhelmingly agreed that the workshop would have been more effective in engaging the elder participants, who lacked the necessary basic computer skills, by partnering an elder with a younger person from the community (preferably a younger family member). The youth of today are almost always more technologically savvy.

Elsewhere in the Arctic, many programs have developed that match elders with youth—some have originated from entirely within the community, but most have involved "outsiders" (Roué

Figure 5.19 Participants at the 2008 ACCAP Sea Ice Workshop[18] in Barrow, Luther Komonaseak of Wales, AK (left) and George Noongwook of Savoonga, AK (right) assist each other as they followed along to a guided tutorial. Photo by Sarah Trainor.

2006). While my familiarity with such programs is limited, I presume that those with a strong influence from outsiders, such as University academics, are typically seen as an import to the community such that it detracts from the community's willingness to assume ownership of the program. The trail mapping project initiated within the community, but admittedly became "mine" as most PhD research projects do. Developing this effort further to incorporate young people will be a step toward returning the project to the community. I hope that we may soon 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 Harcharek (2002) proposed. This acquired data and knowledge will inform their later conversations with elders regarding how to interpret ice observations, their own personal understanding of the environment, and the process of classifying the ice trail thickness surveys.

I end this paper without knowing the fate of this project. Certainly, funding represents a concern for any long-term monitoring effort. However, by maintaining direct relevance to environmental change with a consistent monitoring approach, this project may be relevant to various funding opportunities as climate change and adaptation research remains a key priority amongst local, state, and national institutions. As a sea ice scientist, I am thankful for the opportunity to have been involved in an effort that enabled me to learn in an experiential and hands-on manner from the local indigenous ice experts in Barrow. The key for sustaining such an effort, which has undoubtedly developed a foundation in the community through its inherent partnerships with local institutions (the BWCA, the NSB Department of Wildlife Management, and the Barrow Arctic Science Consortium), is to focus on promoting inter-generational learning within Barrow's whaling community. Ultimately, this is a choice the community must make.

Notes

1. Barrow receives approximately 22 strike permits per year from the total five year block quota of 255 for Alaska Eskimos set for 2008-2012.
2. Trail data from 2007 is not included in this analysis as it was not systematically collected as it was in 2008 through 2011. A map of the 2007 trail locations can be found in Druckenmiller et al. (2010, Chapter 3).
3. Shorefast ice break-out events, which may separate people from the stable/stationary ice attached to the coast, were heavily discussed at the meeting. These events have been the focus of other recent papers (George et al. 2004b; Druckenmiller et al. 2009, Chapter 2), and are specifically addressed in detail in Chapter 4.
4. There are various reasons crews may not be actively hunting, such as because few or no whales are passing by Barrow, ice conditions are unsafe, the lead is closed, or a cease-fire is called as the community simultaneously retrieves and harvests multiple struck whales (a self-imposed limit exists based on the number of functioning block and tackle in the community).
5. A DGPS base station at the Barrow Arctic Science Consortium (BASC) allowed for post-processing of the data.
6. While it is reasonable to assume that my presence on the ice while mapping trails was occasionally unwanted, the gracious nature of the hunters always prevented this feeling from being openly expressed.
7. The Barrow Area Information Database, located at http://www.baidims.org/, is operated out of the University of Texas at El Paso and funded by the National Science Foundation.
8. Browerville is a section of the greater Barrow village which sits north of the main village, across a lagoon.

9. Monument is the locally used term for the Will Rogers-Wiley Post Memorial at Walakpa Bay.
10. A standard deviation ellipse (SDE) is a measure of directional distribution and represents a measure of dispersion around a mean center of a group of points along two orthogonal axes. The major axis represents the primary geographical orientation of the data. I use two standard deviations to define the ellipse. If the data is normally distributed about the mean center, a two standard deviation ellipse will include approximately 95 percent of the data.
11. Given the length and number of trails surveyed, the high variability in snow cover, and the absence of an instrument that can continuously make measurements from a sled, it is extremely difficult to account for snow depth.
12. The bathymetry used was created from GEODAS (GEOphysical DAta System) depth soundings for the Chukchi Sea acquired from the National Geophysical Data Center (NGDC).
13. I selected the center of the village to be a point on the coast between downtown Barrow and Browerville (N71.2972°, W 156.77832°) at approximately Brower's Café, Charles Brower's old whaling station.
14. The tortuosity of a mapped trail is to some extent determined by when in the trail building process the trail survey was performed.
15. In 2009, 2010, and 2011, the North Slope Borough's Department of Wildlife Management conducted a "whale census" of the Bering-Chukchi-Beaufort stock of bowhead whales. They use a visual count from the shorefast ice edge and acoustic recordings to statistically estimate an overall population.
16. The ArcGIS standard deviation classification creates classes that represent dispersion about the mean of the distribution. Here, the classes have an interval that is one whole standard deviation, except for the lowest and highest classes that are cut-off at the endpoints of the data range. The center class straddles the mean value.
17. Hot Spot analysis in ArcGIS calculates a z-score for each data point based on a threshold distance, or the size of a moving window over which the data is analyzed. In this analysis, I used a fixed Euclidian threshold distance of 50 m. The z-scores are measures of standard deviation. For example, a z-score of -2.0 for the specific data point at the center

of the moving window means that the data value is 2.0 standard deviations below the mean of the values within the moving window.

18. On November 19-20, 2008, a tutorial-style workshop organized by the Alaska Center for Climate Assessment and Policy (ACCAP) was held in Barrow, Alaska to introduce online sea ice information resources to local residents and community leaders from six different native coastal whaling communities.

References

Albert, T.F., 1988. The role of the North Slope Borough in arctic environmental research. Arctic Research of the United States, 2 (spring): 17-23.

Aporta, C., 2004. Routes, trails and tracks: Trail-breaking among the Inuit of Igloolik. Etud. Inuit 28(2): 9-38.

Aporta, C., 2005. From map to horizons; from trail to journey: The challenges of documenting Inuit geographic knowledge. Études Inuit Studies 29(1-2): 221-231.

Aporta, C., 2009. The trail as home: Inuit and their pan-arctic network of routes. Human Ecology 37: 131-146.

AWMP, Aboriginal Whaling Management Procedure, 2006. First Intersessional AWMP Workshop for the 2007 Bowhead Implementation Review. Report of the AWMP Intersessional Workshop, National Marine Mammal Laboratory, Seattle, 24-27 April, 2006.

Barker, A., Timco, G., Wright, B., 2006. Traversing grounded rubble fields by foot – implications for evacuation. Cold Regions Science and Technology 46(2): 79-99.

Barry, R.G, Moritz, R.E., Rogers, J.C., 1979. The fast ice regimes of the Beaufort and Chukchi Sea coasts, Alaska. Cold Regions Science and Technology 1, pp. 129-152.

Berkes, F., Berkes, M.K., 2009. Ecological complexity, fuzzy logic, and holism in indigenous knowledge. Futures 41: 6-12.

Brewster, K., 1997. Native contributions to arctic sciences at Barrow, Alaska. Arctic 50(3): 277-288.

Daily, G.C., 1997. *Nature's services: Societal dependence on natural ecosystems.* Washington, Island Press, 412 pp.

Dörner, D., 1996. *The logic of failure: Recognizing and avoiding error in complex situations* Metropolitan Books, New York, 240 pp.

Druckenmiller, M.L., Eicken, H., Johnson, M., Pringle, D., Williams, C.C., 2009. Toward an integrated coastal sea ice observatory: System components and a case study at Barrow, Alaska. Cold Reg. Sci. Technol. 56: 61-72.

Druckenmiller, M.L., Eicken, H., George, J.C., Brower, L., 2010. Assessing the shorefast ice: Iñupiat whaling trails off Barrow, Alaska. In: Krupnik, I., Aporta, C., Gearheard, S., Kielsen Holm, L., Laidler, G. (Eds), *SIKU: Knowing our ice*. Springer-Verlag, New York, pp. 202-228.

Eicken, H., Shapiro, L.H., Gaylord, A.G., Mahoney, A., Cotter, P.W., 2006. Mapping and characterization of recurring spring leads and landfast ice in the Beaufort and Chukchi Seas. U.S. Dept. of the Interior, Anchorage, Alaska, OCS Study MMS 2005-068.

Ford, J.D., Pearce, T., Duerdan, F., Furgal, C., Smit, B., 2010. Climate change policy responses for Canada's Inuit population: The importance of and opportunities for adaptation. Global Environmental Change 20: 177-191.

Gearheard, S., Aipellee, G., O'Keefe, K., 2010. The Igliniit Project: Combining Inuit knowledge and geomatics engineering to develop a new observation tool for hunters. In: Krupnik, I., Aporta, C., Gearheard, S., Kielsen Holm, L., Laidler, G. (Eds.), *SIKU: Knowing Our Ice*. Springer-Verlag, New York, pp. 181-203.

George, J.C., Zeh, J., Suydam, R., Clark, C., 2004a. Abundance and population trend (1978-2001) of western arctic bowhead whales surveyed near Barrow, Alaska. Marine Mammal Science 20(4): 755-773.

George, J.C., Huntington, H.P., Brewster, K., Eicken, H., Norton, D.W., Glenn, R., 2004b. Observations on shorefast ice dynamics in arctic Alaska and the responses of the Iñupiat hunting community. Arctic 57(4): 363–374.

Grisan, E., Foracchia, M., Ruggeri, A., 2003. A novel method for the automatic evaluation of retinal vessel tortuosity. Proceedings of the 25th Annual International Conference of the IEEE EMBS, Cancun, Mexico, Sept. 17-21: 866-869.

Haas, C., Gerland, S., Eicken, H., Miller, H., 1997. Comparison of sea ice thickness measurements under summer and winter conditions in the Arctic using a small electromagnetic induction device. Geophys. 62(3): 749-757.

Haas, C., 2003. Dynamics versus thermodynamics: The sea ice thickness distribution. In: Thomas, D.N., Dieckmann, G.S. (Eds.), *Sea ice—An introduction to its physics, chemistry, biology and geology*. Blackwell Science, Oxford, pp. 82-111.

Harcharek, J.P., 2002. Aġviqsiuġnikun whaling standards: Barrow and Wainwright. North Slope Borough School District, Barrow, Alaska.

Hibler, W.D., Ackley, S.F., 1975. A sea ice terrain model and its application to surface vehicle trafficability. Journal of Terramechanics 12(3-4): 171-190.

Huntington, H.P., Brower Jr., H., Norton, D.W., 2001. The Barrow Symposium on Sea Ice, 2000: Evaluation of one means of exchanging information between subsistence whalers and scientists. Arctic 54(2): 201-206.

Huntington, H.P., Gearheard, S., Druckenmiller, M.L., Mahoney, A., 2009. Community-based observation programs and indigenous and local sea ice knowledge. In: Eicken, H., Gradinger, R., Salganek, M., Shirasawa, K., Perovich, D., Leppäranta, M. (Eds.), *Field techniques for sea ice research.* University of Alaska Press, Fairbanks, AK, pp. 345-364.

Kovacs, A., 1976. Grounded ice in the fast ice zone along the Beaufort Sea coast of Alaska. CRREL Report 76-32, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Mächler, M., 1993. Very smooth nonparametric curve estimation by penalizing change of curvature. Report No. 71, Eidgenössiche Technische Hochschule, Zürich.

Mahoney, A., Eicken, H., Shapiro, L., Graves, A., 2005. Defining and locating the seaward landfast ice edge in northern Alaska. Proceedings of the 18th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC '05, Volume 3, Potsdam, N.Y., June 26-30, 2005.

Mahoney, A., Eicken, H., Gaylord, A.G., Shapiro, L., 2007. Alaska landfast sea ice: Links with bathymetry and atmospheric circulation. Journal of Geophysical Research, 112, C02001, doi:10.1029/2006JC003559.

Norton, D.W., 2002. Coastal sea ice watch: Private confessions of a convert to indigenous knowledge. In: Krupnik, I., Jolly, D. (Eds.), *The earth is faster now: Indigenous observations of arctic environmental change*. Arctic Research Consortium of the United States, Fairbanks, Alaska, pp. 127-155.

Nuttall, M., 1991. Memoryscape: A sense of locality in northwest Greenland. North Atlantic Studies 1(2): 39-50.

Pelletier, B.R., Shearer, J.M., 1972. Sea bottom scouring in the Beaufort Sea of the Arctic Ocean. *In*: Marine Geology and Geophysics, Proceedings of the 24th International Geological Congress, Sect. 8, pp. 251-61.

Reimnitz, E., Barnes, P.W., 1974. Sea ice as a geologic agent on the Beaufort Sea Shelf of Alaska. *In*: Reed, J.C., Slater, J.E. (Eds.), The coast and shelf of the Beaufort Sea. Arctic Institute of North America, Arlington, VA, pp. 301-353.

Roué, M., 2006. Healing the wounds of school by returning to the land: Cree elders come to the rescue of a lost generation. Intl' Soc. Sci. J., Cultural Diversity and Biodiversity, 187: 15-24.

Rundstrom, R.A., 1995. GIS, indigenous peoples, epistemological diversity. Cartography and Geographic Information Systems 22(1): 45–57.

Sejersen, F., 2004. Horizons of sustainability in Greenland: Inuit landscapes of memory and vision. Arctic Anthropology 41(1): 71-89.

Shapiro, L.H., Barry, R.G. (Eds.), 1978. The sea ice environment. In: Weller, G., Norton, D., Johnson, T. (Eds.), Interim Synthesis Report: Beaufort/Chukchi. Outer Continental Shelf Environmental Assessment Program, National Oceanic and Atmospheric Administration, Boulder, CO, 54 pp.

Tremblay, M., Furgal, C., Lafortune, V., Larrivée, C., Savard, J., Barrett, M., Annanack, T., Enish, N., Tookalook, P., Etidloie, B., 2006. Communities and Ice: Bringing Together Traditional and Scientific Knowledge. In: Riewe, R., Oakes, J. (Eds.), *Climate Change: Linking Traditional and Scientific Knowledge*. Aboriginal Issues Press, University of Manitoba, pp. 123-138.

Wilkinson, J.P., Hanson, S., Hughes, N.E., James, A., Jones, B., MacKinnon, R., Rysgaard, S., Toudal, L., 2011. Tradition and technology: Sea ice science on Inuit sleds. Eos Trans. AGU, 92(1), 1, doi:10.1029/2011EO010002.

Chapter 6. Conclusions and recommendations

This dissertation represents the first major work to interface science and modern geophysical techniques with the local and traditional knowledge (LTK) of indigenous ice experts. The ultimate goal has been to better understand coastal sea ice processes and how they impact the use of ice by the community of Barrow, Alaska. Consulting LTK alongside a thorough documentation of where, when, and how the community of Barrow uses shorefast sea ice and assesses risk during traditional spring whaling has been the essence of this work. My experience working alongside both highly trained sea ice scientists and local indigenous ice experts has proven highly rewarding, especially in terms of understanding the potential benefits of blending scientific research into arctic community activities. In this final chapter, I offer conclusions regarding the advantages of interfacing geophysics with LTK, some of which may be specific to Barrow. Next, I make specific recommendations as to how to continue the research I have presented in this thesis. Lastly, I offer some final thoughts on the future of Barrow's whaling community and the potential role science might play in supporting adaptation strategies that they might adopt in the face of future environmental change.

6.1 Conclusions

(1) Shorefast ice break-out events offer an excellent focus for geophysical-based monitoring of coastal sea ice in the Chukchi Sea. Such monitoring can help address an important and persistent threat to Iñupiat ice hunters while providing a clear context within which local experts can share their knowledge. This work has demonstrated the nuanced nature of how local experts observe ice features, atmospheric and oceanic forces, and local to regional processes when deciding whether it is safe to be on the ice. Fault tree analysis, a diagrammatic means for conceptualizing the interaction of variables that contribute to a defined failure event, offers an approach for combining geophysical and local knowledge in a framework for assessing shorefast ice stability. However, one drawback to this approach is its inability to explicitly deal with the temporal aspects of natural systems. This is especially evident when considering that local experts largely base their assessments of ice stability on how different ice types and features, such as anchored ridges, evolve throughout winter and spring.

(2) It follows from Conclusion 1 that the greatest lesson that sea ice geophysicists stand to learn from indigenous ice experts is the importance of observing the entire ice-year in order to assess stability and risk. Hunters track and memorize the mechanical and thermal history of the local ice cover in a given year so that they may interpret conditions alongside their recollection of what they observed in past years. As air temperatures warm in mid-Spring, hunters closely monitor for changes in the ice, either through direct observation or use of indicators.

(3) Given that much of LTK is of a practical, applied nature, studying it may reveal important lessons for those looking to operate on sea ice, such as the oil and gas industry (see Eicken et al. 2011). As the arctic ice environment continues to become milder and encounters with new, young, and first-year ice dominate, as opposed to encounters with more solid multi-year ice, industry may benefit from the experience of indigenous ice experts. As whalers in springtime route-find, build snowmobile trails, establish hunting camps, and haul whales onto the ice for butchering, they regularly deal with ice that is highly mobile and susceptible to rapid changes in morphology and structural properties.

(4) Mapping and surveying Barrow's ice trails reveals how the community uses the ice during spring whaling, which may serve as a baseline for understanding how future environmental change may impact subsistence hunting from sea ice. Trail characteristics expose the inter-annual variability of the shorefast ice's thickness distribution and extent. The placement of the whaling trails reflects the hunters' knowledge, decisions, and strategies to deal with not only the inter-annual variability, but also significant intra-seasonal changes in conditions (ice extent, accretion of desirable or undesirable ice types, thermal deterioration of the ice cover, etc.). The project has proven useful in its ability to characterize the range of hazards hunters avoid, as well as the types of ice they prefer.

(5) Engaging local experts in the research process while documenting community ice-use has shown that there is an interest within the community to use science-based information in their traditional activities. Their interest in information is largely because they hunt amongst very dynamic and potentially dangerous conditions (and always have), and because ice conditions are becoming increasingly unfamiliar. The community's information needs are not static; therefore it is important to maintain mechanisms for continued feedback on the usefulness of science-based information to the types of decisions they make. Additionally, it is important for scientists to devote time to instructing local people on how to actually use the information. There are significant technological, cultural, and epistemological barriers to learning how to interpret the type of information that scientists often produce. It is important to realize that local experts are better able to share their knowledge when they understand the type of information that scientists use. In this context, the greater the symmetry in the two-way sharing and use of knowledge between scientists and local experts the more successful the collaboration will be in the long-term.

(6) Collaborating with local ice experts and arctic coastal communities is a process that requires a lot of time and should be incorporated into research only when the appropriate capacity exists within a project. (The five years I spent working with local hunters in Barrow resulted in the outcomes presented in this thesis largely because my efforts built upon the many previous years' work by others.) It is also necessary to engage local experts and community members early and directly in the research process. For LTK to be most meaningful to a scientist it is often necessary for topics to be discussed several times over the course of years. Text devoted to sea ice LTK, such as this dissertation, are no substitute for face-to-face discussions over a cup of coffee or on the ice. LTK is largely in reference to specific conditions experienced in the local environment; therefore being able to observe something together and to have the local expert describe what is being seen is the best way to learn what LTK is truly about.

6.2 Recommendations

At the heart of my research work in Barrow was the ice trail mapping and surveying project (see Chapters 3 and 5), which was largely initiated from within the community. Recognizing the project's value to long-term monitoring, I offer the overarching recommendation that this effort continue. Here, I provide three specific recommendations for how this may done effectively. In addition, I offer two recommendations that build upon other efforts presented in this thesis.

(1) Relate ice thickness data from the trail surveys to the accretion history of the shorefast ice cover. The width of shorefast ice incrementally extends shoreward from late-fall through May as various ice types attach, all of which carry different implications for stability and safe use of the ice by the community. An important research question follows: How is the timing of the advancement of the shorefast ice edge and the co-occurring condition of the regional pack-ice environment linked to the types of ice that get accreted? Addressing this question may shed light on how the local-availability of specific ice types is linked to long-term regional and pan-arctic processes.

(2) Involve young hunters in the trail project, possibly through collaboration with the North Slope Borough School District. This may offer opportunities for Barrow's youth to take part in data collection while observing and photographing the various ice types encountered along the trails. Their observations could assist in the classification of ice thickness data, while providing an opportunity to develop the GIS (geographic information systems) skills needed to produce trail maps for the community. This experience may provide a basis for their interaction with elders and more experienced hunters, therefore contributing to traditional learning.

(3) Overlay trail locations on the coastal radar as a tool for hunters. The coastal radar of the Barrow Sea Ice Observatory provides detailed near-real-time information on local-scale sea ice dynamics in a very accessible format (daily animations available via the internet), yet is not widely used by hunters. Overlying the mapped trail locations on radar imagery and animations, as shown in Figure 6.1, will provide greater spatial context to the data. A computer monitor placed at the Barrow Search and Rescue Base would allow access to the information for hunters without computers. It is very likely that such a product would strengthen the project's partnership with the community.

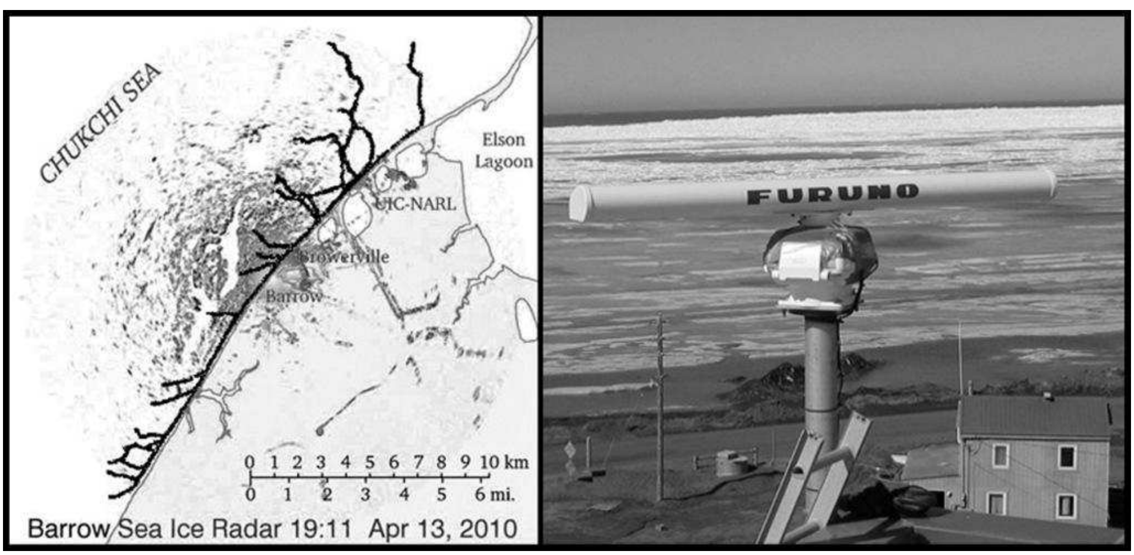


Figure 6.1 Barrow's whaling trails in early April 2010 overlaid on a radar image (left) from the 10 kW X-band marine radar overlooking the sea ice off Barrow (right).

(4) The Fault Tree Analysis (FTA) approach for evaluating shorefast ice stability (see Chapter 4) may incorporate LTK in a quantitative manner through the use of "fuzzy logic". Zadeh (1965) recognized that physical things observed in the real world usually do not fall within precise classes. Accordingly, he developed the statistics-based field of fuzzy logic to be able to incorporate this idea into quantitative modeling. Berkes and Berkes (2009) similarly make the claim that Inuit LTK maintains real-world relevance because numerically precise categorizations are avoided. At least one study (Mackinson and Nøttestad 1998) has already explored fuzzy logic as a tool to combine science and local knowledge. The combination of FTA with fuzzy logic, which was first introduced by Tanaka et al. (1983), may allow for a greater integration of hunter assessments of safety with geophysical based monitoring.

(5) Pair elders and youth in tutorial-style training for how to access and use science-based information products, such as satellite imagery. This would allow the more technologically skilled younger generation to assist their elders with computers while creating an environment for the elders to discuss their local and traditional knowledge. This was a direct recommendation from elder participants at the 2008 ACCAP Sea Ice Information Workshop that I organized in Barrow to introduce online sea ice information resources to local residents, hunters, and community leaders.

6.3 Final thoughts

The final chapter of Richard Nelson's (1969) *Hunters of the northern ice* is titled "The death of hunting". This comes after one of the more detailed accounts ever written about the extensive sea ice knowledge and hunting skill of the Iñupiat, or of any arctic people. In Wainwright, Alaska (135 km to the southwest of Barrow), Nelson had seen that the elder's knowledge was only being partially passed down to the younger generations—an ongoing trend that began nearly a century before when commercial whaling ships and fur traders introduced the concept of the cash economy. Nelson observed the impact missionaries and teachers had left on traditional education. He noted that self-sufficiency was no longer encouraged as government welfare swayed active hunters from the ice. Prospects for the future were bleak in eyes of an anthropologist that understood the practical value of their traditional knowledge and the risks it faced. However, Nelson also recognized that the Iñupiat are a proud people and that the acculturization process is complicated.

At the time Nelson's book was being published, oil was discovered at Prudhoe Bay. In the decade that followed, the Alaska Native Claims Settlement Act was signed, the Trans-Alaska Pipeline was built, and dollars began to flow into communities on the North Slope. Perhaps unexpected by many, native whaling experienced a resurgence in the years that followed. The communities made the choice to remain a whaling people.

Interestingly, it was around this same time in the mid-1970's that elders and experienced hunters began to see unfamiliar conditions in their local sea ice (Norton 2002). Through recent years, the coastal waters of northern Alaska have experienced notable changes, including later freeze-up in fall (Mahoney 2007), less stable ice in springtime (George et al. 2004), and decreases in multi-year ice (Drobot and Maslanik 2003). Despite these differences and the persistent decline in local and traditional knowledge, hunters have continued to safely and successfully hunt the bowhead whale.

One of the most important outcomes of my research is that I have shown the variability in ice conditions that hunters face within a single hunting season and from year-to-year. I have always been amazed at the persistence, mobility, and ingenuity of Barrow whalers to deal with this variability. Although at the same time their humble recognition of unacceptable risk and inability to control nature was always evident. While local and traditional knowledge of the environment is reliant upon empirical observation and trial and error learning, and accordingly takes a long time to develop, resourcefulness and the ability to work together is more inherent to a people. For this reason, the Iñupiat of recent decades have proven highly adaptive to change in spite of losses to their local and traditional knowledge.

An important question to consider is 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 environments. Certainly, in comparing the shorefast sea ice environment at Barrow to elsewhere in the Arctic, such as near the coastal communities in northern Canada and Greenland, conditions are more dynamic. This is largely related to its location at a regional scale promontory of land and its steep coastal bathymetry. 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.

One potential counterargument relating to Barrow's proven adaptability to future environmental change relates to the delicate timing of spring whaling. In recent years, the arrival of above freezing air temperatures has been around 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, this has not significantly impacted the harvest of whales since the majority of the migrating whales have already passed by this time. Furthermore, the last whales to pass Barrow are mostly comprised of large old whales, which are much less preferred by hunters than the younger smaller whales. Though, as coastal temperatures on Alaska's North Slope show an increasing trend over recent decades (Wendler et al. 2010), 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.

This leads to an important question: how can science support adaptation at the community level? First, in the context of traditional activities, I propose it is more likely that science stands to benefit local people in their efforts to cope and adapt to present-day variability than to plan for future change. Yet currently the broader science community places more emphasis on monitoring long-term change in comparison to understanding changes that take place on intra-annual and intra-seasonal timescales. An increased emphasis on the latter may actually allow researchers to better relate their work to the activities of local people. I have found through speaking with hunters in Barrow that while they are certainly concerned with long-term change, the overwhelming majority of their planning is based on the conditions of the current year. They want to know what the ice was doing earlier in the winter to predict current or near future conditions in spring. Their understanding of local processes is nearly always confined to the annual scale, which may be linked to the fact that ice in the region completely disappears from the coastal waters each summer (with some uncommon exceptions).

With more closely aligned interests in how local processes operate on these scales, scientists and local people may more effectively identify where targeted research may begin to inform local decisions. The crucial step that follows is to ensure that the resulting information provided to local people is interpretable. Without this, local people are unable to make up their minds whether a resource is truly useful and may contribute to their ingenuity in coping with variable and unfamiliar sea ice conditions.

References

Berkes, F., Berkes, M.K., 2009. Ecological complexity, fuzzy logic, and holism in indigenous knowledge. Futures, 41: 6-12.

Drobot, S.D., Maslanik, J.A., 2003. Interannual variability in summer Beaufort Sea ice conditions: Relationship to winter and summer surface and atmospheric variability. J. Geophys. Res., 108(C7): 3233, doi:10.1029/2002JC001537.

Eicken, H., Jones, J., MV, Rohith, Kambhamettu, C., Meyer, F., Mahoney, A., Druckenmiller, M.L., 2011. Environmental security in arctic ice-covered seas: From strategy to tactics of hazard identification and emergency response. Marine Technol. Soc. J., 45(3): 37-48.

George, J.C., Huntington, H.P., Brewster, K., Eicken, H., Norton, D.W., Glenn, R., 2004. Observations on shorefast ice dynamics in arctic Alaska and the responses of the Iñupiat hunting community. Arctic 57(4): 363-374.

Mackinson, S., Nøttestad, L., 1998. Combining local and scientific knowledge. Reviews in Fish Biology and Fisheries 8: 481-490.

Mahoney, A., Eicken, H., Gaylord, A.G., Shapiro, L., 2007. Alaska shorefast sea ice: Links with bathymetry and atmospheric circulation. Journal of Geophysical Research, 112, C02001, doi:10.1029/2006JC003559.

Nelson, R., 1969. *Hunters of the northern ice.* University of Chicago Press, Chicago, 429 pp.

Norton, D.W., 2002. Coastal sea ice watch: Private confessions of a convert to indigenous knowledge. In: Krupnik, I., Jolly, D. (Eds.), *The earth is faster now: Indigenous observations of arctic environmental change*. Arctic Research Consortium of the United States, Fairbanks, Alaska, pp 127-155.

Tanaka, H., Fan, L.T., Taguchi, K., 1983. Fault tree analysis by fuzzy probability. IEEE Trans. on Reliability, 32: 453-457.

Wendler, G., Shulski, M., Moore, B., 2010. Changes in the climate of the Alaskan North Slope and the ice concentration of the adjacent Beaufort Sea. Theor. Appl. Climatol., 99: 67-74.

Zadeh, L.A., 1965. Fuzzy sets. Information and Control, 8: 338-353.

Appendix A. Electromagnetic induction-derived ice thickness surveys

A.1 Background

Indirect ice thickness surveys using electromagnetic (EM) induction sounding were performed using a Geonics EM-31 conductivity meter, which operates at a frequency of 9.8 kHz. The instrument consists of horizontally coplanar transmitter and receiver coils, which are separated by 3.66 m spacing. As an oscillating current is passed through the transmitter coil, a primary EM field is produced. When the instrument is placed above a conductive surface, this primary EM field induces eddy currents in the material below. These eddy currents in-turn generate a secondary magnetic field, whose strength and phase are detected by the receiver coil, providing that the signal received from the stronger primary EM field is properly accounted for within the instrument's internal calibration. The instrument measures apparent conductivity of the underlying half-space in units of millisiemens per meter (mS/m) (Haas and Druckenmiller 2009). The EM-31 may be used in either one of two orientations: horizontal dipole mode (HDM) or vertical dipole mode (VDM). The difference between the two relates to: (1) the geometry of how the primary and secondary fields intersect with the underlying half-space, and (2) the resulting strength of these fields (Haas and Druckenmiller 2009).

Because sea ice has a negligible conductivity (approx. 20 mS/m) in comparison to that of seawater (approx. 2500 mS/m), the EM induction technique may be used to indirectly measure ice thickness. By placing the EM-31 on the surface of the ice (or a known distance above since air or snow also have a negligible conductivity), the distance to the ice-water interface below can be inverted from the measured apparent conductivity of the half-space using an empirically derived relationship between the two. This distance minus the height of the instrument above the surface is assumed to be the ice thickness. When snow is present on the ice, the depth of the snow must also be accounted for to arrive at a more accurate measurement of ice thickness.

When using the EM-31 on sea ice, it is typically operated in the HDM orientation. This provides unique solutions when inverting between apparent conductivity and ice thickness over the entire range of thicknesses. In contrast, the VDM orientation allows for two solutions over the range of most typical ice thicknesses (Haas and Druckenmiller 2009). Also, the HDM orientation provides a smaller instrument footprint (Kovacs and Morey 1991), which allows for a derived ice thickness that is representative over a smaller area, and accordingly more comparable to ice thickness measurements obtained by drilling.

A.2 Calibration methodology

In this study, the empirical relationship between apparent conductivity and ice thickness (or distance between the instrument and the ice-water interface) was derived by lifting the EM-31 above level ice in moderate water depths while measuring apparent conductivity at approximately 10-cm increments above the ice surface. Ice within the footprint was drilled to determine thickness, which was necessary to compute the distance between the instrument and the ice-water interface. Calibrations were performed in both HDM and VDM orientations; however, only data from the HDM orientation is reported here since that was the orientation used for the ice thickness surveys presented in this thesis. Figure A.1 shows the field set-up for these calibrations. A wooden boom constructed with 2x4s extended out from the top rungs of an 8-ft aluminum ladder. A nylon rope was used to hoist the EM-31 above the ice. Additional guy-ropes were used to keep the horizontal orientation of the instrument constant, despite the wind.

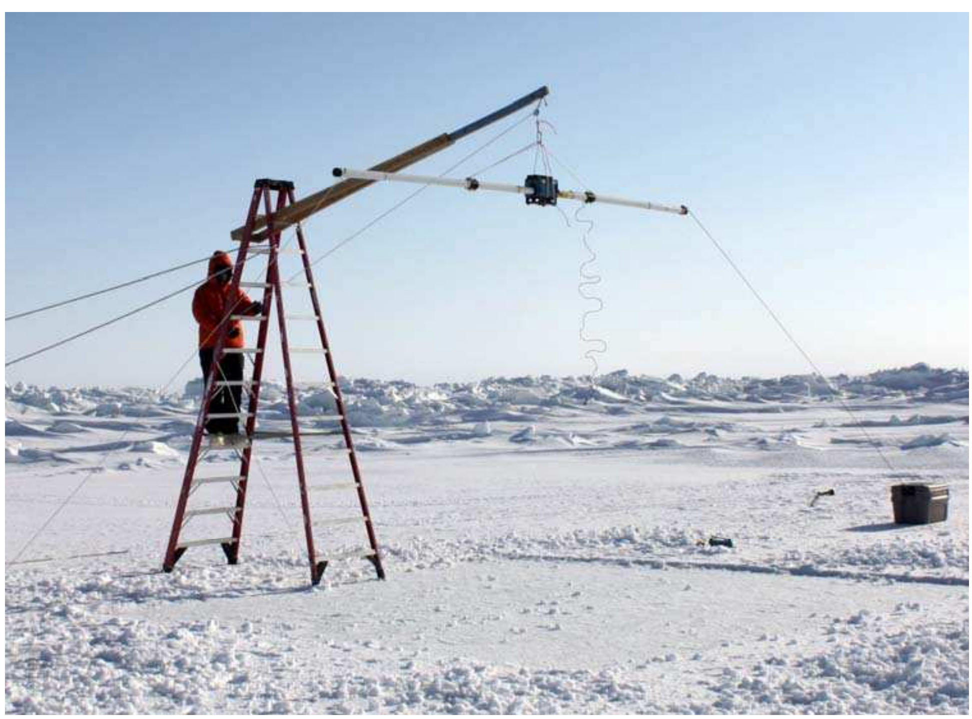


Figure A.1 Field set-up for EM-31 calibrations. Marie Kapsch did the heavy lifting.

Four separate calibrations were performed on the following dates: 5 April 2008, 30 March 2009, 16 May 2009, and 6 April 2011. In 2008, 2009, and 2011, the water depths at the calibrations sites were 10, 13, and 22 m, respectively. Figure A.2 presents the obtained data to which curves of form $y = a\exp(-bx) + c$ were fit. Variable y represents the apparent conductivity, σ_a, and x represents the instrument's distance above the ice-water interface. Differences between the fitted curves may be due to a number of factors, including electronic drift that may have taken place within the instrument between calibrations, the influence of water depth, or differences in the salinity of the water beneath the ice. For the work presented in this thesis, the environmental factors that contribute to errors in EM induction-derived ice thickness measurements were largely ignored since maximized accuracy was not necessary for the analysis I have presented.

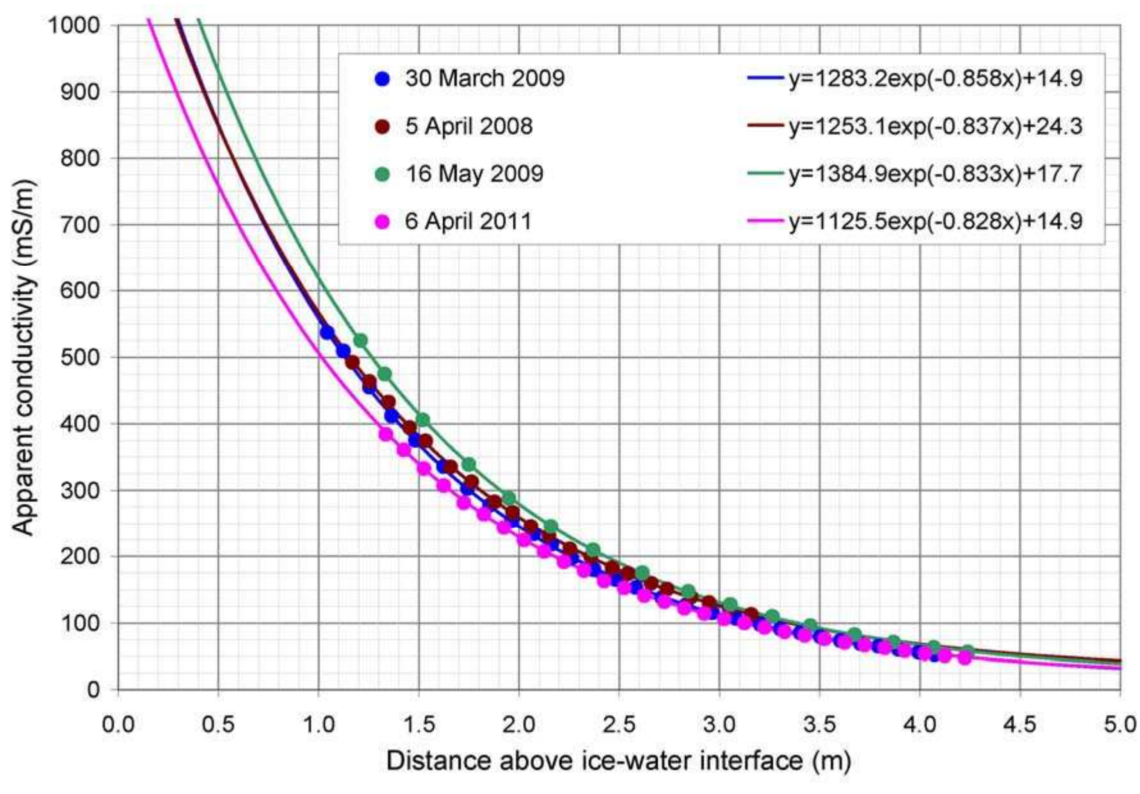


Figure A.2 Apparent conductivity versus the distance between the instrument and the ice-water interface during EM-31 calibrations. Curves of the form $y = a\exp(-bx) + c$ were fit to each data series.

For the EM-31 ice thickness surveys performed in years 2008 through 2010, the inversion used was derived from the total data from the first three calibrations (i.e., those in years 2008 and 2009), which were combined to produce the following inversion equation: $y = 1271.2\exp(-0.820x) + 12.4$. Alternatively, this equation may be rewritten as $Z_t = 8.72 - 1.22\ln(\sigma_a - 12.4)$, where Z_t represents the total layer thickness of ice and snow. This was done both because of the close agreement between the April 2008 and March 2009 calibrations and because it allowed for the straightforward use of a single equation to invert the EM data for all surveys in these years, which were performed on dates spread fairly evenly throughout the seasonal time period that these calibrations spanned (late March through mid-May). In hindsight, it would have been appropriate to treat surveys in mid-May separately given that the inversion for the May calibration suggests that thinner ice thicknesses are slightly overestimated. This is possibly due to fresh, less conductive melt water beneath the ice that arrived with warmer air temperatures and increased solar heating in May.

For the EM-31 ice thickness surveys performed in 2011, which were confined to a single week in mid-April, I used the inversion derived from the calibration performed on 6 April 2011. Here, the equation $y = 1125.5\exp(-0.828x) + 14.9$ may be rewritten as $Z_t = 8.49 - 1.21\ln(\sigma_a - 14.9)$. This was deemed appropriate because of the close agreement in time between the calibration and all 2011 surveys and because the fitted curve varied significantly from the calibrations performed on similar dates in April 2008 and March 2009, especially for ice thicknesses less than approximately 1.5 m.

During the ice thickness surveys performed along ice trails, the EM-31 instrument was placed on a sled (see Sections 3.4 and 5.2 and Figures 3.9 and 5.4) and the vertical distance between the center of the coils and the bottom of the sled was measured in order to calculate ice and snow thickness. As discussed in Section 5.4.2, I neglected snow depth and treated total layer thickness measurements as measurements of ice thickness unless otherwise noted.

A.3 What is measured during ice thickness surveys along trails?

An important factor to consider with performing sled-based EM-31 surveys along trails that pass through rubble fields and ridges is that trails are typically disrupted ice surfaces. During trail building, ice picks are used to break-up ice blocks from the high-lying spots into smaller pieces, which are then redistributed as fill to the lower-lying spots. As a result, trail building does not remove volumes of ice but rather smoothes out the trail, reducing large-scale (>10 cm) roughness.

In spring 2010, an experiment was conducted to assess how well trail surveys through rubble compare to off-trail transects. As shown in Figure A.3, four trail segments through rubble fields of different block sizes were identified and trail surveys were performed according to the methodology discussed in Section 5.4.2 (1 second sampling rate, driving at approximately 2.5 m/s). Next, roughly parallel to each trail segment and passing through what visually appeared to be similar ice conditions, four off-trail transects of approximately 200 m were marked (see Figure A.3 for exact locations). It was difficult to make transects exactly parallel due to low-light conditions and the challenge of simply walking upright across the rubble. The EM-31 was carried by hand and placed on the snow surface at 2-m increments for measurements of total layer thickness. Coincident snow measurements were made with a probe in order to calculate ice thickness. A differential global positioning system (DGPS) instrument was used to measure the surface height. Verification of ice thickness using direct drilling was not feasible due to time and man-power constraints.

Table A.1 summarizes the data from this field experiment. For each of the four off-trail transects, values are provided for average total layer thickness (snow depth plus ice thickness) $\overline{Z}_T$, average ice thickness $\overline{Z}_i$, the standard deviation in ice thickness $stdev(\overline{Z}_i)$, and the average block thickness within the rubble. For the trails surveys, values are provided for average ice thickness $\overline{Z}'_T$ and the standard deviation in ice thickness $stdev(\overline{Z}'_T)$. The observed standard deviations are similar for all transects if the anomalous 8-m deep keel in off-trail transect D is ignored. However, the differences between the average total layer thicknesses for these four sets of paired off-trail transects and trail surveys ($\overline{Z}_T - \overline{Z}'_T$) are significant, ranging between -0.21 m and 0.90 m. Despite observing similar variability in ice thickness, ice trail surveys reveal significant differences in ice thickness in comparison to those performed on unaltered ice surfaces. The different sampling rates (every 1 and approx. 2.5 m for the off-trail transects and trail surveys, respectively) may relate to discrepancies between the measured average ice thickness and standard deviation values. A more thorough study over greater distances is recommended to more conclusively compare these two different methods of measuring ice thickness. Also, it is important to recognize that significant differences that may exist are not necessarily indicative that conducting ice thickness surveys along trails are of any lesser value than those performed along unaltered surfaces. As long as we understand how certain ice features are under- or overestimated by performing surveys along trails and maintain a consistent inter-annual methodology, trails surveys may effectively reveal inter-annual trends in the ice thickness distribution as is discussed in Section 5.4.2.

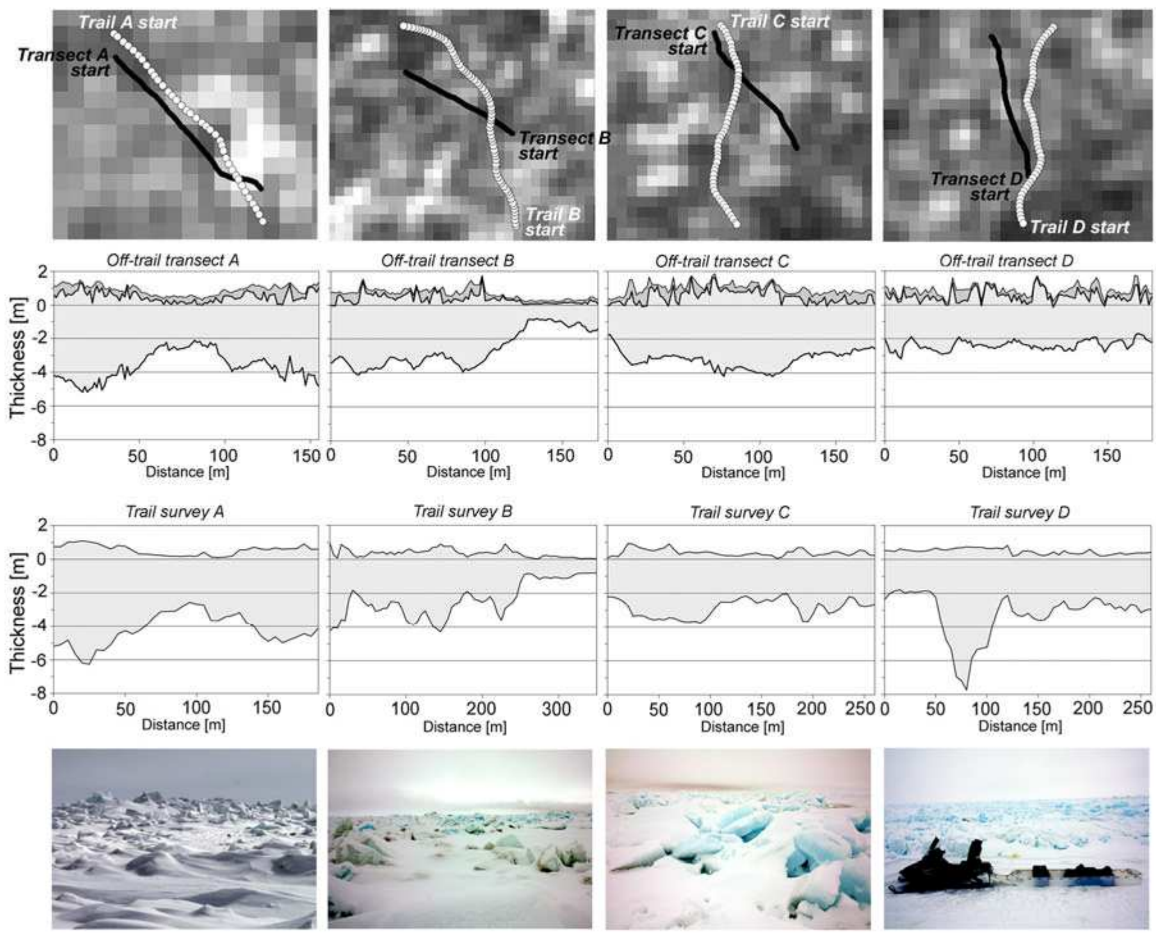


Figure A.3 Comparison of trail surveys to off-trail transects. *Top*: Relative locations are shown for the off-trail transects and trail surveys. The grey-scale colored pixels correspond to backscatter coefficients from a synthetic aperture radar satellite image of 12.5-m resolution. *Top middle*: Stacked snow and ice thicknesses profiles from the off-trail transects are plotted versus distance along the transect. 0 m on the y-axis represents sea level. *Bottom middle*: Total layer thickness (compressed snow and ice) profiles from the trail surveys are plotted versus distance along the trail. 0 m on the y-axis represents sea level. *Bottom panel*: Photos of the respective rubble fields.

However, it is important to note that biases in the trail data are inevitable. As discussed in Chapters 3 and 5, the trails are built according to a wide range of strategies. One of the primary considerations in building a trail is trail construction effort. Trails are routed across areas of flat, smooth ice with virtually no effort at all. These areas represent ice thicknesses mostly equal to or less than that of typical first-year ice thickness (e.g., refrozen leads within the shorefast ice). Therefore, the decisions of hunters may bias the surveys such that these areas of flat smooth ice are oversampled. For this reason, one may find that an ice thickness distribution for a set of random transects could be notably different than that of trail-based surveys over the same ice cover.

Table A.1 Comparison of off-trail transects to trail surveys. Transects and trail surveys A through D are those shown in Figure A.4. Trail D' represents trail D with removal of data representing the section with the anomalous 8-m deep keel. *All values are in meters*.

Off-trail transect	**A**	**B**	**C**	**D**	
Average total layer thickness, $\overline{Z}_T$	4.57	3.30	4.17	3.26	
Average ice thickness, $\overline{Z}_i$	4.18	3.01	3.71	2.93	
$stdev(\overline{Z}_i)$	1.09	1.27	0.85	0.44	
Average block thickness in rubble	0.70	0.45	0.50	brash mixture of all sizes	
Trail Survey	**A**	**B**	**C**	**D**	**D'**
Average total layer thickness, $\overline{Z}'_T$	4.78	2.73	3.27	3.73	3.07
$stdev(\overline{Z}'_T)$	1.23	1.27	0.67	1.47	0.47
Differences between individual off-trail transects & trail surveys	**A**	**B**	**C**	**D**	**D'**
$\overline{Z}_T - \overline{Z}'_T$	-0.21	0.57	0.90	-0.47	0.20
$\overline{Z}_i - \overline{Z}'_T$	-0.60	0.28	0.44	-0.81	-0.14

In order to better understand how ice trail thickness surveys through ridges may underestimate the original (pre-trail) ridge sail heights, I have developed a general correction. Figure A.4 presents trail measurements of surface elevation (adjusted to reflect freeboard) versus measurements of total layer thickness from all trail surveys performed in 2008. For arctic first-year ridges, Timco and Burden (1997) estimate the ratio of keel thickness to sail height for floating ridges to be 4.4. Assuming that measurements of thickness over 5 m are close to being measured from the top of ridges, applying this ratio to the measurements of freeboard results in the top line in the curve. The bottom line in Figure A.4 represents where the linear-fitted trend line for the "observed" data should be for observations of thickness over 5 m when accounting for the likelihood that measurements of ridge thickness typically are underestimated by 30% (Haas 2003). This underestimation is mostly due the averaging effect due to the large (approx. 4 m) footprint of the instrument and the presence of saline water within the unconsolidated portion of the ridge keels. In order to "move" the top line (the typical keel-to-sail ratio of 4.4) down to overlay with the bottom line (the 30% error correction), the keel-to-sail ratio of a ridge profile that has been altered to accommodate a trail would have to be 8.3. This implies that the pre-trail sail heights are typically reduced by 50% through the construction of the trail, which roughly agrees with visual and directly measured estimates from the field.

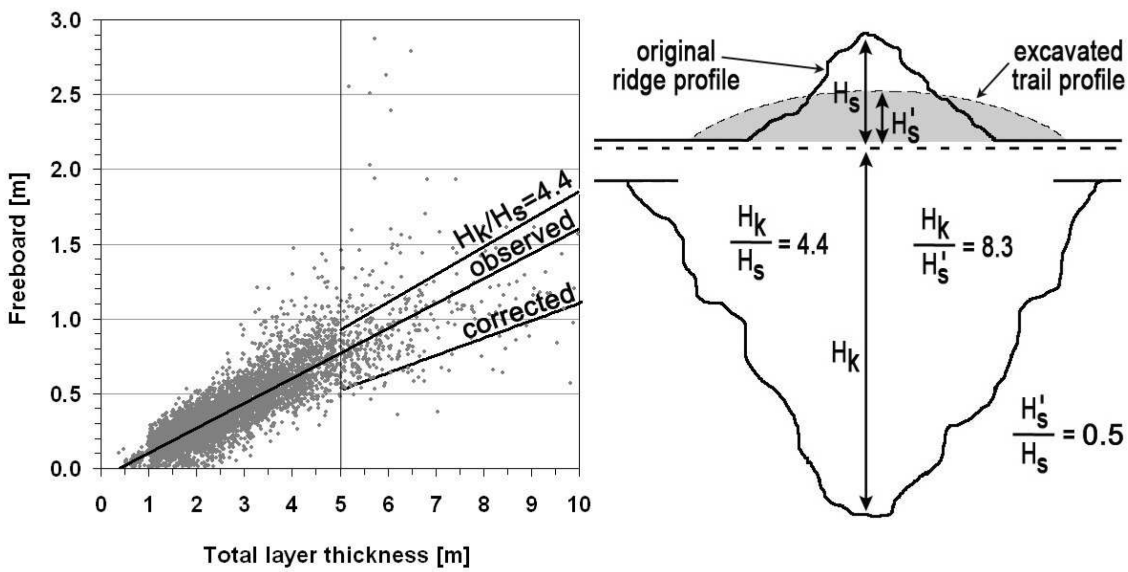


Figure A.4 DGPS-derived freeboard versus EM-31 measurements of total layer thickness (left) and ridge profile characteristics along trails (right). In the plot, the middle line represents a linear regression with a correlation coefficient of 0.87. Assuming thicknesses above 5 m are from atop ridge sails, the top line represents applying a keel height H_k to sail height H_s ratio of 4.4 (Timco and Burden 1997) to the freeboard measurements and the bottom line represents observed thickness measurements corrected for an underestimation of ice thickness of 30% (Haas 2003).

References

Haas, C., 2003. Dynamics versus thermodynamics: The sea ice thickness distribution. In: Thomas, D.N., Dieckmann, G.S. (Eds.), *Sea ice—An introduction to its physics, chemistry, biology and geology*. Blackwell Science, Oxford, pp. 82-111.

Haas, C., Druckenmiller, M.L., 2009. Ice thickness and roughness measurements. In: Eicken, H., Gradinger, R., Salganek, M., Shirasawa, K., Perovich, D., Leppäranta, M. (Eds.), *Field techniques for sea ice research.* University of Alaska Press, Fairbanks, AK, pp. 49-116.

Kovacs, A., Morey, R.M., 1991. Sounding sea ice thickness using a portable electromagnetic induction instrument. Geophysics, 56: 1992-1998.

Timco, G.W., Burden, R.P., 1997. An analysis of the shapes of sea ice ridges. Cold Reg. Sci. Tech. 25: 65-77.

Appendix B. List of Iñupiaq sea ice terminology from Barrow

The sources for the Iñupiaq sea ice terminology used throughout this thesis were the many interviews and informal discussions I had with Barrow whalers between 2007 and 2011. Accordingly, these terms are specific to Barrow and may vary considerably when compared to similar terminology lists that originated from other Iñupiaq speaking coastal communities, such as the lists complied for Wainwright (Nelson 1969) and Wales (Weyapuk and Krupnik, in press). The following alphabetical listing offers explanations according to how the terms were used throughout the individual chapters. Ronald Brower, Sr., an Iñupiat language teacher at the University of Alaska Fairbanks and Barrow native, assisted to determining the most appropriate spelling for this list. Exceptions are indicated in the footnotes.

Agiuppak	Ridge formed through shear motion of the ice
Akilinaaq	Ocean current from east of Nuvuk
Amuaq	Ramp cut at the ice edge to launch a boat or pull a whale from the water
Atchaġnaq	Offshore ocean current that pushes the ice open
Igniġnaq	Zone of flat ice
Iiawwaqtuk [1]	When rough water acts to chip away the ice edge
Iiguaq	Ice that weakly attaches to the outer edge of the shorefast ice
Ikalgusak	Shoal north of Nuvuk where ice ridges typically ground
Iluliaq	A location at the ice edge where you generally have only a view of whales traveling away
Ivuniq	Pressure ridge
Kanaŋaiññaq	Current from Northwest that pushes ice toward shore
Kaŋikḷuk	Embayment along ice edge
Kisitchat	Anchored (grounded) ridge; means “anchor”
Kasruq	When a whaling crew is finished whaling and pulls their skin boat off the ice
Katak	A sudden drop in sea level; means “to fall”; may cause floating ice near grounded ridges to crack

Manilinaaq	A good place along the ice edge to watch whales coming toward you; camping on the north side an embayment in the ice edge and facing south
Muġaala	When pieces of submerged ice detach or become free and emerge in the open water of the lead; means "to throw-up"
Muġaliq	Piled up slush ice or brash ice that forms through shear and the incorporation of snow
Naŋiaqtuġvik	Safe place on shorefast ice where hunters store their whaling equipment and camp when waiting for the lead to open or for other favorable conditions to develop
Nipaaq	To be along the edge of the ice observing the environment, watching the water, and looking for whales
Nutaqqutaq	Cracks which are kept from freezing by repeatedly being opened by either currents or tides; often get covered with snow and can't be seen
Nuvuġaq	Promontory of ice extending out from the ice edge
Nuvuġaqpuk	Large promontory of ice extending out from the ice edge
Palusaqniq [2]	Weather system that begins with winds out of the Southeast that continue to swing around to the Southwest where the wind direction leads to dangerous increases in sea level and tends to bring pack ice in toward the coast
Pamiuqtak	To launch a boat from the ice edge and travel toward a whale's path
Piqaluyuk	Old ice that is fresh enough to drink
Piruġaġnaq	Current from Northeast
Qaiġsuaq [3]	Flat pan of ice
Qaisagnaq	Current from the Southwest; current that brings the animals in spring
Qinu [1]	Slush ice that piles up during the early stages of freeze-up in late fall or early winter, and, due to cold temperatures, develops into ice that is considered stable
Sagrat [4]	Moving ice floes
Sikuliaq	Young ice
Tuuq	When pack ice impacts shorefast ice and acts as a chisel; means "to chisel"
Tuvaġruaq	Stable ice; ice that will not break-up or shatter when impacted by pack ice

Tuvaq	Shorefast sea ice
Tuvaqtaq	Bottom-fast ice along the coast; ice frozen to seafloor
Uiñiq	Open lead
Uisauniq	A shorefast ice separation or break-out event resulting in people adrift amongst the pack ice
Yuayuk [2]	A place where currents meet (for example, north of Point Barrow)

Notes

1. Term, definition, and spelling provided by Lewis Brower.
2. Term, definition, and spelling provided by Joe Leavitt.
3. Term and definition provided by Lewis Brower. The correct spelling was unknown.
4. This spelling was provided by Ronald Brower, Sr., however it differs significantly from that provided by George et al. 2004, who published the term as Sarri.

References

George, J.C., Huntington, H.P., Brewster, K., Eicken, H., Norton, D.W., Glenn, R., 2004. Observations on shorefast ice dynamics in arctic Alaska and the responses of the Iñupiat hunting community. Arctic 57(4): 363–374.

Nelson, R., 1969. *Hunters of the northern ice.* University of Chicago Press, Chicago, 429 pp.

Weyapuk Jr., W., Krupnik, I., (Compilers), Sereadlook, P., Ongtowasruk, F. (Advisors), Anungazuk, H., Krupnik, I., Druckenmiller, M.L. (Eds.), In press. Kiŋikmi Sigum Qanuq Ilitaavut – Wales Sea ice Dictionary. Smithsonian Institution, Arctic Studies Center.