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Slush-Ice Berm Formation on the West Coast of Alaska

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ABSTRACT. Some coastal communities in western Alaska have observed the occurrence of “slush-ice berms.” These features typically form during freeze-up, when ice crystal–laden water accumulates in piles on the shore. Slush-ice berms can protect towns from storm surge, and they can limit access to the water. Local observations from the communities of Gambell, Shaktoolik, Shishmaref, and Wales were synthesized to develop a taxonomy of slush-ice berm types and a conceptual process model that describes how they form and decay. Results indicated two types of slush-ice berm formation processes: *in situ* (forming in place) and *advective* (pushed in by storm winds). Several formation mechanisms were noted for the crystals that compose in situ berms. Cold air temperatures cool the surface of the water, and winds that translate surface cooling through a greater depth aid crystal formation. Snow landing in the water cools via melting of the snow and by contributing crystals directly to the water. A negative surge can expose the wet beach to cold air, allowing crystals to form on the beach, which are then picked up by waves. Slush crystals for advective berm events form offshore. Winds move the slush towards shore, where it accumulates, and wind-induced waves move it up onto the beach.

Key words: slush-ice berm; community observations; local knowledge; synoptic; weather; coastal; Alaska; sea ice; Arctic

RÉSUMÉ. Certaines communautés côtières de l’ouest de l’Alaska observent la présence de « bermes de bouillie de glace ». Généralement parlant, ces bermes se forment au moment de l’engel, lorsque l’eau chargée de cristaux de glace s’empile sur la rive. Les bermes de bouillie de glace peuvent protéger les villages des ondes de tempêtes, tout comme ils peuvent restreindre l’accès à l’eau. Les observations locales à partir de Gambell, Shaktoolik, Shishmaref et Wales ont fait l’objet d’une synthèse afin d’aboutir à une taxonomie des types de bermes de bouillie de glace et à un modèle de processus conceptuel qui décrit comment ils se forment et comment ils se détériorent. Les résultats indiquent deux types de processus de formation des bermes de bouillie de glace : les bermes *in situ* (formation sur place) et les bermes d’*advection* (poussés par les vents de tempête). Plusieurs mécanismes de formation ont été notés dans le cas des cristaux qui composent les bermes in situ. Les températures de l’air froid refroidissent la surface de l’eau, et les vents qui transfèrent le refroidissement de la surface à une plus grande profondeur favorisent la formation de cristaux. La neige qui se dépose dans l’eau se refroidit en raison de la fonte de la neige et forme des cristaux directement dans l’eau. Une onde négative peut exposer la plage humide à l’air froid, permettant ainsi aux cristaux de se former sur la plage, et ceux-ci sont ensuite ramassés par les vagues. Dans le cas des bermes d’advection, les cristaux de la bouillie se forment au large. Les vents déplacent la bouillie vers la rive, où elle s’accumule, et les vagues créées par le vent la déposent sur la plage.

Mots clés : berme de bouillie de glace; observations des communautés; connaissances locales; synoptique; temps; côtier; Alaska; glace de mer; Arctique

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INTRODUCTION

Coastal western Alaska, defined for this study as the coast of the northern Bering and southern Chukchi Seas between the Yukon-Kuskokwim Delta and the area just north of the Bering Strait (Fig. 1), is home to numerous villages and several larger hub communities. Almost all of these communities are situated on the coast, and in some cases on sand or gravel bars—a necessity imposed by transport and subsistence needs, which include low, flat ground for airstrips and access to the water for hunting and fishing and to receive sea-lift barges. This region experiences annual

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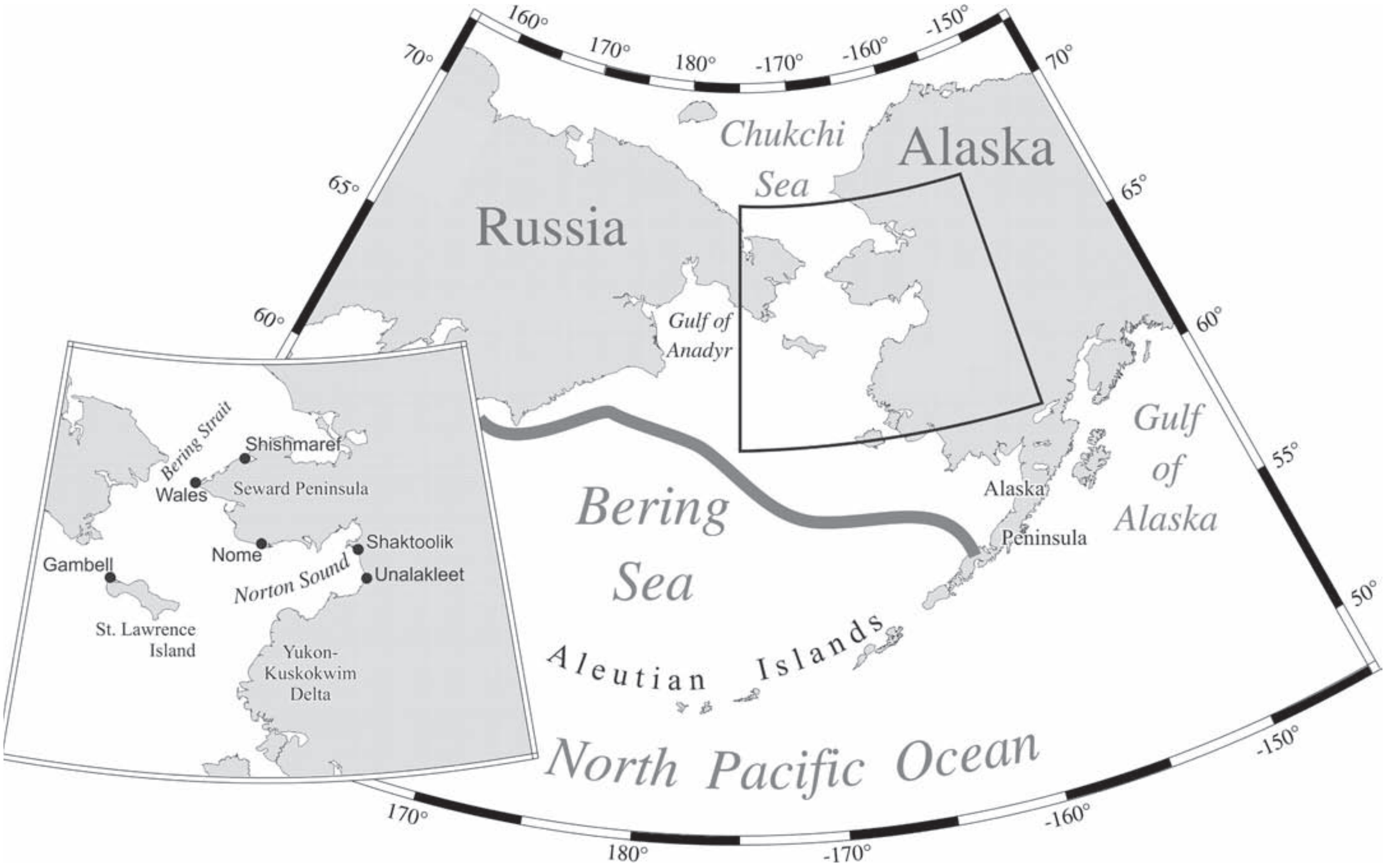

FIG. 1. Region of study. The broader image shows the Bering and Chukchi Seas and their coastal zones, while the inset map shows the specific area under consideration. The average maximum sea ice extent (2001–09) is plotted for reference.

sea ice cover formation, which, at its maximum extent, reaches well south into the Bering Sea (Fig. 1). In recent decades, the sea ice cover has been forming later in the fall. This delay has lengthened the ice-free season, resulted in a less stable ice cover, and exposed increasingly larger areas to storm impacts (Shaktoolik residents, pers. comm. 2013; Frey et al., 2014).

Coastal western Alaska sees regular incursions of storms moving up from the western North Pacific, a spur off one of the most active storm tracks in the Northern Hemisphere, which stretches across the North Pacific Ocean from regions off eastern Asia to the northeast towards the Aleutian Islands and Gulf of Alaska (Mesquita et al., 2010). Often storms are in the mature phase of their life cycle when they reach this region, and their potential for peak impact is slowly weakening. Storms that move into the seas off western Alaska can stall, remaining stationary for days, resulting in moderate to strong winds blowing from the same direction for extended periods of time. In some cases, however, when upper air conditions are favorable, these storms can reenergize. The resultant strong winds from slow-moving, long-duration weather systems, when combined with long open-water fetches, can generate large waves that can reach up to 8 m and drive water-level surges of as much as 3 m into shallow coastal areas (Chapman et al., 2009; Terenzi et al., 2014; Erikson et al., 2015). Surges and wave action cause inundation and erosion that damage both infrastructure and subsistence forage areas (e.g., berry-picking areas) and can cut off communities.

Sea ice too can cause major damage. Atkinson et al. (2011) described severe damage to a local cannery in the Bristol Bay area that occurred as a result of a storm surge acting upon ice that had formed on the structure’s wharf facility. However, sea ice can also protect communities from surge and wave action in several ways. Large pieces of floating ice dampen wave energy and prevent the wind transfer of energy into the water, and land-fast ice armors the coast, increasing its resistance to erosion (Eicken et al., 2009; Atkinson et al., 2011). In the early stages of sea ice formation, storm winds can drive frazil or slush ice onto shore and pile it up in the nearshore area. If slush ice accumulating on the beach has an opportunity to consolidate through in situ freezing, it may form solid defensive structures and can greatly limit the adverse impact of surges, as has been witnessed by local ice experts and residents in communities such as Unalakleet, Shishmaref, and Wales (Eicken, 2010; Eicken et al., 2014). In 2009, a storm threatened Shaktoolik and other communities at the eastern end of Norton Sound with floods from an anticipated storm surge. However, slush ice was driven ashore, solidified, and formed a natural defensive barrier (a “berm”) that mitigated storm surge impact (observations from the community as reported in USACE, 2011). Similar findings have been reported for the Bering Strait region (Eicken et al., 2014). In Shishmaref, where coastal erosion threatens key infrastructure (GAO, 2009) and ice threatens the integrity of engineered revetments put in place to protect structures, ice berms may be at least as effective in mitigating storm impacts. Once solidified, slush-ice berms can also impede travel and access to the sea, and in an unfrozen state, they are hazardous to anyone trying to cross them. This potential to both protect and hamper creates a particular interest in understanding the occurrence of slush-ice berms.

While slush ice and berm formation are part of the traditional knowledge system of indigenous ice experts and residents of coastal communities in western Alaska, the topic has been addressed only a few times in scientific literature and reports. Slush ice in the coastal zone has been studied by Wiseman et al. (1973) and Reimnitz and Kempema (1987). More recently, a post-storm analysis of the November 2011 storm provided detailed descriptions of berm formation in the coastal zone, but the intent of the report was not to analyze causal mechanisms for the berms (Kinsman and DeRaps, 2012). These studies did not provide a detailed breakdown of the weather controls that need to be in place for berm formation. We therefore undertook a study that combines analysis of eight years of ice observations by Inupiaq and Yupik experts with field visits to gather traditional knowledge and local observations of slush and slush-ice berm formation in three communities: Shishmaref, Shaktoolik, and Gambell. Our goal for this paper was to develop a conceptual model of slush-ice berm formation based on observations and comments provided by local experts, as supported by an analysis of the synoptic weather conditions and the meteorological context that can lead to these types of events. Specific elements of the traditional knowledge on slush ice and slush-ice berm formation gathered for this project will be presented in a separate paper.

METHODS

Study Sites

Three communities—Gambell, Shaktoolik, and Shishmaref—were visited by some of the authors for this particular project. The community of Wales, although not visited, is also included because it has numerous entries in the community observation database called the Seasonal Ice Zone Observing Network (SIZONet), which provided additional useful observations and examples.

Gambell is a community of 681 people (U.S. Census Bureau, 2010) situated on the northwest cape of St. Lawrence Island, 200 miles southwest of Nome. The community is on a gravel spit that is constantly moved by waves and currents. Gambell's nearshore environment is categorized in this paper as "deep," which means it slopes rapidly down, reaching a depth of 30+ m at 6 km from shore. It has a small tidal range, approximately 0.5 m between high and low tide. The spit is periodically eroded along the north and west shorelines by storm-generated waves (USACE, 2008). The isolation of Gambell has helped residents to maintain their traditional St. Lawrence Yupik culture, their language, and their subsistence lifestyle, which is based on marine mammals. Gambell subsists largely on harvests from the sea: seals, walrus, fish, and bowhead and gray whales (Strickling, 2012a).

Shaktoolik is a community of 251 people (U.S. Census Bureau, 2010) situated near the north end of a sandspit in Alaska's Norton Sound. Shaktoolik has a "shallow" beachfront, reaching only ~6 m at 6 km distance from the coast, and a slightly larger tidal range than Gambell or Shishmaref, approximately 1.5 m. With the Tagoomenik River to the east and Norton Sound to the west, the community has water on two sides. The community has been relocated twice, once in 1933 and again in 1967, because these sites were prone to severe storms and winds. Its present location faces similar problems. The local economy is mixed: it is based on commercial fishing, traditional subsistence activities, and local jobs (Strickling, 2013).

Shishmaref, a community of 563 people (U.S. Census Bureau, 2010), is located on Sarichef Island along the northern coast of Seward Peninsula on the Chukchi Sea. It also has a shallow beachfront, reaching ~7 m at 6 km from shore, and a small tidal range of approximately 0.5 m. The island is exposed to severe fall storms. In this community, as in many others on the west coast of Alaska, state flood disaster declarations were issued in 1988, 1997, 2001, 2002, 2005, and 2011 (Parnell, 2011; Kinsman et al., 2013). According to Kawerak Inc. (2012), the bluff on the north shore of the island erodes at an average of 1 to 1.5 m a year. Several engineered structures have been built to lessen shoreline erosion (Mason et al., 1998). However, no engineered flood protection measures are in place (FEMA, 2009). It is a traditional Inupiat Eskimo village with a fishing and subsistence lifestyle (Strickling, 2012b).

Wales, a community of 145 people (U.S. Census Bureau, 2010) located near Cape Prince of Wales, defines the eastern boundary of the Bering Strait. The village is located in low-lying areas of unconsolidated sediments below Cape Mountain. Its nearshore zone may be categorized as deep: it reaches ~40 m at a distance of 6 km from shore. Wales also has a small tidal range of approximately 0.7 m. Strong winds and currents result in dynamic ice conditions beyond a narrow belt of shorefast ice that forms in December or January (W. Weyapuk, Jr., pers. obs). Wales is a traditional Inupiat Eskimo village with a fishing and subsistence lifestyle.

Observational data about slush-ice berm occurrence were obtained from two sources: site visits to the three communities (Shishmaref, Shaktoolik, and Gambell) and an existing database of community-based observations. We conducted two dedicated site visits in each community.

Visits to Shishmaref took place in August and October 2013, and visits to Gambell and Shaktoolik, in November 2013 and August 2014. The November 2013 visit was particularly well timed because a strong storm was in progress, which afforded an opportunity to observe the process of berm formation firsthand. During the first visit, we held five semi-directed interviews with local observers to gather information about occurrence of slush-ice berm events and the environmental context of berm formation, including specific dates. Interview data consisted of raw written notes and audio recordings from the interviews. Discussions with community members also resulted in the acquisition of photographs. All raw interview data were reduced to an initial hand transcription, which was followed by a search through the transcribed notes and other sources for information relevant to berm occurrence. During the second visit to Shaktoolik and Gambell, we also asked the five interviewees to comment on photographs we had taken of the in situ slush-ice berm formed in November 2013 and photographs taken by residents of the advective slush-ice berm formed during the storm of 2009.

The second source was an existing database of community-based observations by indigenous sea ice experts established by SIZONet (Apangalook et al., 2013; Eicken et al., 2014). The database holds a large number of near-daily observations for several communities along the west coast of Alaska, including Gambell and Wales, beginning in fall of 2006. Observers are recognized indigenous sea ice and environmental experts from the respective communities who have recorded ice and weather conditions relevant to local uses of the ice cover and associated hazards.

Specific dates for berm occurrence came from both observations and interviews. These dates were important to guide the analysis of the synoptic (weather) patterns that prevailed for the periods preceding, during, and following berm occurrence. Data concerning weather patterns were obtained from an online portal and tool system maintained by Earth Systems Research Laboratory (ESRL), operated by the U.S. National Oceanic and Atmospheric Administration (NOAA). This site uses "reanalysis data"—grids of weather variables generated by weather forecast models run for past time periods using observational data available at those times—and a selection and display portal that makes it easy for users to plot variables of interest. We used two specific reanalysis datasets: the NCEP/NCAR global reanalysis (Kalnay et al., 1996) for rapid, general assessment and the higher-resolution North America Regional Reanalysis when more detail was required. Maps of pressure, wind, and temperature parameters were produced and then qualitatively analyzed to look for explanatory patterns. The NOAA/ESRL portal is found at http://www.esrl.noaa.gov/psd/data/composites/hour/. After initial analysis of community observations and weather information, we visited each community a second time and presented our findings in order to ensure veracity and obtain feedback from community members.

RESULTS AND DISCUSSION

Types of Berms

On the basis of their mode of formation, we identified three types of berms that can protect communities from storms and are relevant in the context of coastal dynamics. These are 1) *shoved ice*: non-slush berms consisting of slabs and boulders of ice piled up through an ice shove; 2) *in situ slush-ice*: berms consisting of slush ice formed in place or seawater that freezes in exposed parts of the beach, or both; and 3) *advective slush ice*: slush-ice berms composed of slush ice and aggregates of frazil or small ice (or both) moved in from somewhere else. The most essential condition for slush-ice berm formation (whether in situ or advective) is water temperature that is at or below the freezing point (−1.8˚C for ocean waters in the region). Note that we are distinguishing between ice berms by mode of formation, rather than by berm structure. This approach is in line with the goal of this study: relating specific environmental conditions to formation of ice berms. A classification based on structure would cut across the different formation modes and would need to differentiate berms in terms of the size of individual aggregates (e.g., frazil grain, aggregated slush flocs, ice gravel, ice block, ice raft).

Shoved-Ice Berms: Shoved ice is the most common type of berm mentioned by people in the communities. This type of berm forms when well-established sea ice is driven ashore by wind, currents, or both (Mahoney et al., 2004). A shoved-ice berm can form very rapidly, reaching a height of 10–13 m, and can form "anywhere" when the conditions are right during the fall season (Eddie Ungott, Gambell, pers. obs. November 2013; Roy Ashenfelter, pers. comm. April 2014). Shoved-ice berms are common throughout the area, but typically occur later in the season when the offshore ice pack is compact enough to transmit stress over longer distances (Mahoney et al., 2004). This type of berm is not the subject of this study, but is mentioned here to make the distinction clear.

In situ Slush-Ice Berms: These berms form primarily on the beach closest to the water under appropriate air and water temperature, wind, and wave conditions. A berm can form in a matter of hours in response to air and water temperatures below freezing. The height of in situ type berms is determined by wave splash height and is usually no more than 1 m. Berm width is determined by the distance between the high and low tidelines, in the following manner. After a drop in air temperature, at low tide the beach is exposed to cold air, which allows ice crystals to form in interstitial water and at the surface of beach sediments. As the tide moves in, the water picks up the crystals, which form an ice crystal–water slurry, termed slush, and builds successive berms culminating with a relatively large berm at the high tideline. As the tide goes out, it continues piling berms until it reaches the low tideline (Fig. 2). Community observations also indicate that the slush ice accompanying the berm can extend up to

FIG. 2. Two in situ slush-ice berms, one along the low-tide line and the other along the high-tide line. Slush has also accumulated between the two berms, joining them to form a single, large berm. Shaktoolik, November 2013 (Photo by L. Eerkes-Medrano).

roughly 1.5 km offshore, depending on weather conditions. This situation occurs under the persistent action of waves, which continues to push slush towards the shore. When the slush associated with the berm extends offshore to a distance of 0.5 km or more, wave action is attenuated, reducing wave energy at the shore. Snow falling on the water can also accelerate the in situ berm formation process: melting of the snow can cause the water to cool faster, and the introduction of ice crystals provides nuclei onto which larger sea ice crystals can grow, speeding the process of sea ice crystal formation (Osterkamp, 1978). Once the in situ berm has reached a certain height and width and is large enough to remain in place, if the winds intensify and waves spill onto and over the berm, the water will freeze when it comes in contact with the berm, creating a solid surface. However, the interior of the berm will still remain unfrozen until enough time has passed for it to solidify completely.

Community residents related their observations that slush-ice berms form faster in areas where the nearshore coastal environment is shallow, for example, at Nome. They noticed that as the waves break close to the shore (surf zone), the water continues moving up on the sloping beach and, if it is cold, when the water recedes (backwashes) it will start to form ice crystals (slush) on the beach. When exposed to cold air, the beach cools enough that it can rapidly freeze the water that washes over it during successive waves. In addition, slush will also begin to form in the shallow surf zone. When the waves come in, they lift the ice crystals from the beach and push them, along with the slush in the surf zone, onto the beach, where the ice will start to accumulate and form a berm. Each successive wave brings a new slush deposition, increasing the berm's height and thickness, and the berm continues to form as long as there is wave action. A drop in sea level (a negative surge) will enhance the slush-ice berm formation process by exposing more water-saturated beach to cold air.

Along deep coastal areas, such as those near Gambell, residents observed that slush takes longer to form and slush-ice berm formation starts only when the water is cold and a large number of crystals form in the nearshore zone, giving surface waters the consistency of "oatmeal" (a mixture of water and ice crystals). This ice in the water will rise to the surface, and if the slush layer is a few centimeters thick, it is able to dampen smaller waves and breakers, which reduces the movement of slush towards the shore. Therefore, waves of greater amplitude—often non-locally generated swell waves—are required to overcome the inertia conferred by the presence of the slush layer, lifting the slush up and pushing it to the shore, where it will start to pile up. As with the in situ berm, each subsequent swell will continue the process of piling the slush onto the shore.

We present three examples of in situ slush-ice berm formation and their associated weather contexts. Two of these events occurred in Wales, the first on 8 November 2007 and the second on 10 November 2012 (W. Weyapuk, Jr., pers. obs.). The third occurred in Shaktoolik on 15 November 2013 (L. Eerkes-Medrano, pers. obs.).

Observations of the ice berms formed at Wales are limited to indications of physical dimensions. Wind analysis for the first two events shows a general east/northeasterly direction and speeds of about 4 to 8 m/s (Fig. 3). Both events are associated with a low-pressure system over the Aleutian Islands (e.g., Fig. 4). The position of this low explains the air-flow direction. The low-pressure system was drawing relatively cold continental air from the Alaska mainland toward the west, which resulted in lower temperatures near Wales. In the day leading up to the slush-ice berm formation events, air temperatures of approximately −3˚C to −4˚C dropped to approximately −8˚C over a period of about 24 hours as the low-pressure systems moved in (Fig. 5). In both cases, Weyapuk reported an associated slush-ice zone extending for more than 0.4 km from shore.

In Shaktoolik, the in situ slush-ice berm started to form on the beach, along the low-tide line, on 15 November. The observed maximum temperature that day was −7˚C and the minimum −11˚C. Temperatures in this range continued during the week. Community members mentioned that 15 November was the first day of cold weather after a series of storms struck the town on 7, 9, and 13 November, bringing warm, humid air, and the first day of slush-ice berm formation. The berm disappeared in the afternoon when the temperature rose, and it formed again the next day. This diurnal cycle of formation and decay continued for the next three days. On the fourth day, two slush-ice berms had formed parallel to each other—one along the low-tide line and one along the high-tide line. Slush had also accumulated between these two berms and was starting to solidify (Fig. 2). Slush also extended offshore for about 200 m. Winds during this event were moderate out of the north/northwest. Unlike the first two events described, this event was not associated with a low-pressure system but rather with a general pressure pattern that favored a northerly flow. Despite different causes, these weather conditions are similar to those observed during the first two events discussed above: low to moderate wind speeds (< 8 m/s) brought weak wave conditions, and temperatures dropped to approximately −8˚C or −9˚C.

FIG. 3. Surface winds (10 m height) associated with the in situ slush-ice berm event of 10 November 2012 at Wales, Alaska. Small arrows indicate the direction of the wind. Contour lines indicate wind speed in meters per second (m/s). Only wind speeds of 8 m/s or greater are displayed. Contour interval is 2 m/s. Data from NOAA/ESRL.

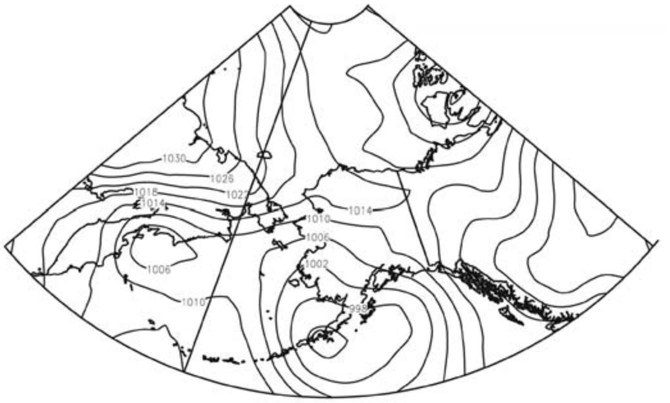

FIG. 4. Sea level pressure associated with the in situ slush-ice berm event of 10 November 2012 at Wales, Alaska. Contour lines indicate sea level pressure in millibars (mb). Contour interval is 4 mb. Winds rotate counter-clockwise around areas of low pressure. Data from NOAA/ESRL.

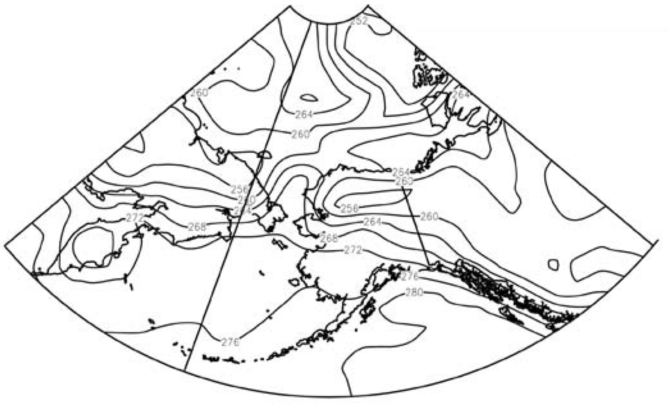

FIG. 5. Surface air temperature (2 m height) associated with the in situ slush-ice berm event of 10 November 2012 at Wales, Alaska. Contour lines indicate surface air temperature in Kelvin (K). Subtract 273 to arrive at the equivalent temperature in degrees Celsius (˚C). Contour interval is 4 K. Data from NOAA/ESRL.

Advective Slush-Ice Berm: The essential process distinguishing an advective slush-ice berm type from the in situ type is that the slush is moved in from elsewhere—advected—by strong winds or onshore currents.

Reimnitz and Kempema (1987) observed large volumes of slush ice forming during storms in the shallow areas of the Beaufort Sea. They theorized that during these storms, a large quantity of heat is removed from the surface water in a very short time, facilitating the formation of a large volume of slush ice, consisting of frazil ice crystals 1 – 5 mm in diameter (Martin, 1981), that rises to the surface. Reimnitz and Kempema (1987) refer to the sea turning into "applesauce" during these storm episodes. Because waves cause constant agitation of the slush ice, the formation of pancake ice, the first stage of a solid ice cover, is uncommon. This slush production was observed to occur only when the wind velocity was at least 10 m/s and the air temperature about −10˚C or lower. The water-saturated slush can range in thickness from a few centimeters to several meters, and when the storm subsides, the slush freezes from the surface down, slowing or stopping wave motion (Reimnitz and Kempema, 1987). Once the slush solidifies, tension or shearing usually causes it to break again, resulting in geometric ice shapes that are pushed by the waves and currents against the shore (Morecki, 1965; Reimnitz and Dunton, 1979). During the strong 2009 storm in Shaktoolik that resulted in a large berm, residents observed that the temperature was not cold at the time of the storm, that slush was not present in the water before the storm, and that they had no idea where the slush came from. It was snowing, and the sea conditions were very rough. After the storm, residents observed bands of crushed slush/frazil ice aligned obliquely to the beach, indicating compression by wave fronts (Fig. 6). These observations from Shaktoolik support the idea of rapid heat loss suggested by Reimnitz and Kempema (1987), as well as the solidification process suggested by Morecki (1965) and Reimnitz and Dunton (1979). In Gambell, residents also mentioned that when there is a fall storm, the slush-ice berm forms immediately, and that as long as the wind continues to blow, the accumulation continues to grow and solidify. If the wind-driven motion is directed offshore, the slush will be blown away from the beach.

Slush ice moves with the surface water, driven by winds and currents, until it is piled up against stationary ice or land (Reimnitz and Kempema, 1987). If pushed against sheets of solid ice, the slush ice will be driven downward and can accumulate to a thickness of more than 4 m (Bauer and Martin, 1983). Once the wind dies down, this accumulated slush ice, along with dislodged "boulders" of anchor-ice, rises to the surface, where it can mix with surface slush ice and snow and be pushed against the beach (Reimnitz and Kempema, 1987). Reimnitz and Maurer (1979) mention that ice "boulders," or wide, flat pans up to 5 m in diameter, were deposited along the Alaskan Beaufort Sea coast during a westerly storm in September 1970. Short and Wiseman (1974) noted that on Pingok Island, after a late fall storm, ice pans less than 10 m in diameter and 60 cm thick piled

FIG. 6. Advective slush-ice berm with ice boulders pushed against a deep beach in the old part of town. The slush/frazil broken into geometric pieces is aligned obliquely to the beach, Shaktoolik, 2009 (Photo by Simon Bekoalok of Shaktoolik).

FIG. 7. Advective slush-ice berm. The slush ice is piled up against a shallow beach in front of Shaktoolik in November 2009. There it formed an advective slush-ice berm more than 4 m high and deposited large, thick ice pans on the beach, forming a wall (Photo by Agnes Takak of Shaktoolik).

up on the shore along with the slush ice, but these formation episodes varied in time and place and from year to year. In years without fall storms, such as 1971 and 1985, Reimnitz and Kempema (1987) did not notice the production of large amounts of slush or frazil ice, but during the fall storm of 1978, the slush-ice berm was 4 m thick.

Shaktoolik residents made similar observations during the fall storms of 2009, 2011, and 2013. During the advective slush-ice berm formation episode of 2009, residents mentioned that two berms formed in town. During the first part of the storm episode, the storm surge, accompanied by strong wave action, pushed the slush ice farther back from shore onto the shallow part of the beach in front of the town, where it accumulated to a height of more than 3 m (Fig. 6). When the winds subsided, the swells continued to pack the slush against the beach. A few hours later, the wind picked up and the storm surge pushed more slush ice onto the shallow beach and in front of the old town, where the beach is only slightly deeper than in front of the new town. There it formed an advective slush-ice berm higher than 4 m and deposited large, thick ice pans on the beach, forming a wall (Fig. 7). Residents noted that fall temperatures had been relatively warm before the 2009 storm episode, that the advective slush-ice berm formation was a result of the storm, and that it was snowing heavily at the time the berm formed. In 2011, it was also snowing, and the berm formed during the storm and protected the town from storm impacts. In contrast to 2009, however, no large pieces of ice were deposited on the beach. During the 2013 storm no slush-ice berm was formed.

Residents of Gambell and Shaktoolik mentioned that snow and blizzards accelerate the process of advective slush-ice berm formation. Osterkamp (1978) noted that if it starts to snow heavily, the introduction of snow into the water will aid ice crystal growth, as mentioned previously. Under the right conditions, the ice nuclei grow rapidly but are broken up by flow turbulence and collisions (Martin, 1981). The broken pieces act as secondary nuclei for the formation of more ice crystals, and large amounts of slush ice are produced very quickly (Kempema et al., 1990).

Synoptic Weather Patterns

The NCEP/NCAR reanalysis data for these events reveal the relationship between berm formation and large-scale patterns of temperature and air pressure. For example, during the 2009 and 2011 episodes, an advective slush-ice berm formed during periods of intense storm activity that resulted from a low-pressure system located in the Bering Sea, just to the west of Norton Sound (Figs. 8 and 9). In both cases, the location of the low-pressure system resulted in west and southwest winds at Shaktoolik, which drove waves and slush directly onto the beach. The wind speeds were about 14 m/s with gusts of up to 22 m/s during the 2009 storm event and reached 18 m/s with gusts of up to 39 m/s during the 2011 event (Figs. 10 and 11). In both years, during the 10 days prior to the storms, temperatures ranged between −5˚C and −10˚C. On 11 November 2009 and 9 November 2011—the days when the storms hit—the temperatures were about −8˚C and −9˚C, respectively (Figs. 12 and 13). These two storms may be contrasted with another storm that occurred on 9 November 2013, which did not produce a berm. In the 10 days preceding that storm, the air temperatures were above 0˚C, and during the storm episode the air temperatures were 2˚C (Fig. 14), not cold enough to cool the water to produce slush. Although the low-pressure system was west of Norton Sound, it covered a much larger area than the low-pressure systems of 2009 and 2011, extending from Bristol Bay to the Chukchi Sea (Fig. 15). The greater width of the storm meant that the wind direction was from the south and southwest (instead of from the west) and was not facing Shaktoolik so directly.

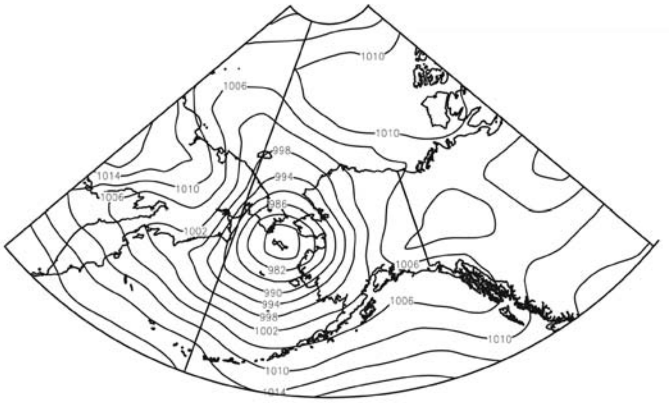

FIG. 8. Sea level pressure associated with the advective slush-ice berm event of 11 November 2009 at Shaktoolik, Alaska. Contour lines indicate sea level pressure in millibars (mb). Contour interval is 4 mb. Winds rotate counterclockwise around areas of low pressure. Data from NOAA/ESRL.

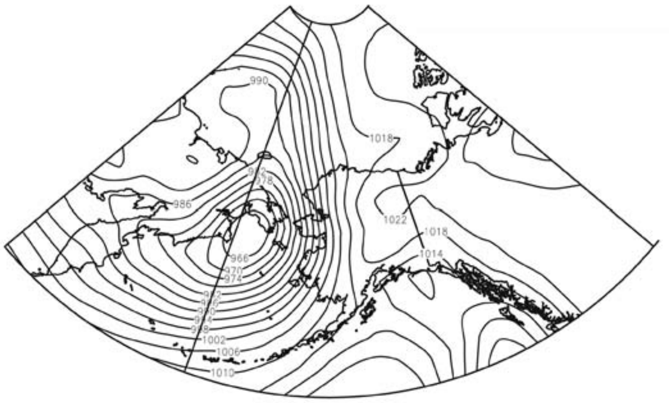

FIG. 9. Sea level pressure associated with the advective slush-ice berm event of 9 November 2011 at Shaktoolik, Alaska. Details as in Figure 8.

FIG. 10. Surface winds (10 m height) associated with the advective slush-ice berm event of 11 November 2009 at Shaktoolik, Alaska. Small arrows indicate the direction of the wind. Contour lines indicate wind speed in meters per second (m/s). Only wind speeds of 8 m/s or greater are displayed. Contour interval is 2 m/s. Data from NOAA/ESRL.

FIG. 11. Surface winds (10 m height) associated with the advective slush-ice berm event of 9 November 2011 at Shaktoolik, Alaska. Details as in Figure 10.

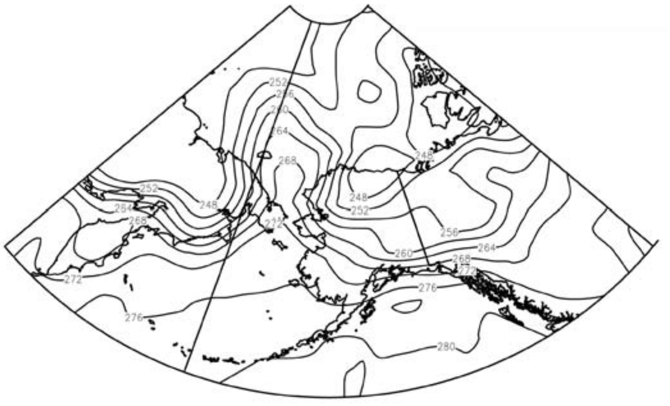

FIG. 12. Surface air temperature (2 m height) associated with the advective slush-ice berm event of 11 November 2009 at Shaktoolik, Alaska. Contour lines indicate surface air temperature in Kelvin (K). Subtract 273 to arrive at the equivalent temperature in degrees Celsius (°C). Contour interval is 4 K. Data from NOAA/ESRL.

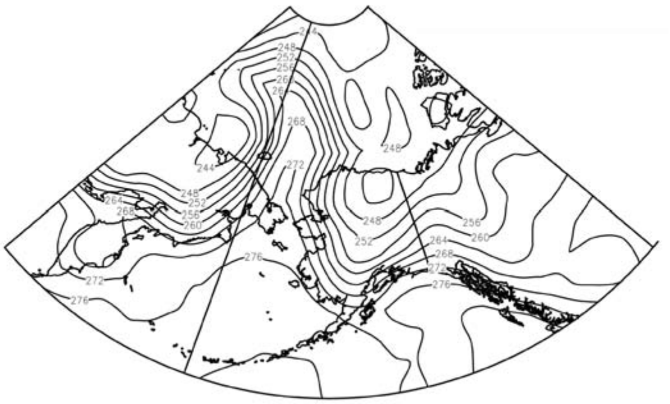

FIG. 13. Surface air temperature (2 m height) associated with the advective slush-ice berm event of 9 November 2011 at Shaktoolik, Alaska. Details as in Figure 12.

Advective slush-ice berms form in the presence of onshore winds. The particular form they take is determined by two additional environmental conditions—air temperature and the presence of a storm surge—that can combine to result in four possible advective slush-ice berm forms.

FIG. 14. Surface air temperature (2 m height) associated with the storm event that did not result in a berm on 9 November 2013 at Shaktoolik, Alaska. Details as in Figure 12.

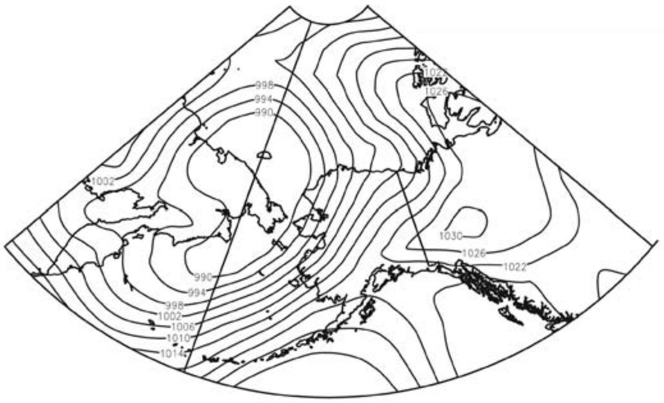

FIG. 15. Sea level pressure associated with the storm event that did not result in a berm on 9 November 2013 at Shaktoolik, Alaska. Contour lines indicate sea level pressure in millibars (mb). Contour interval is 4 mb. Winds rotate counter-clockwise around areas of low pressure. Data from NOAA/ESRL.

The first condition, *storm surge and cold air*, can result in the formation of large advective slush-ice berms farther inland from the shoreline (Fig. 16). This type of berm usually forms above the normal high-water mark, is mostly solid, and is higher than about 3 m. It can protect a village from storm action. Once it forms, it solidifies and may remain in place for the duration of the winter.

The second condition, *no storm surge and cold air*, results in an advective slush-ice berm of moderate height, about 3 m or less, forming near the shore. Because it forms in cold air and with wave action, the resulting berm is quite strong, durable, and larger than an in situ berm. Note that in the Bering Strait region, berms of moderate height are typically less than 1 m high because of significantly smaller fetch and different nearshore bathymetry, which affect advective slush-ice berm formation.

The third condition, *storm surge but no cold air*, results in a large, wide advective slush-ice berm that is dangerous to walk on because the air is not cold enough for the berm to be frozen thoroughly. A person can fall through when attempting to walk on it. Residents of Gambell mentioned that with this type of berm, the more a person moves, the deeper and deeper he or she sinks into it, because the slush ice is like quicksand.

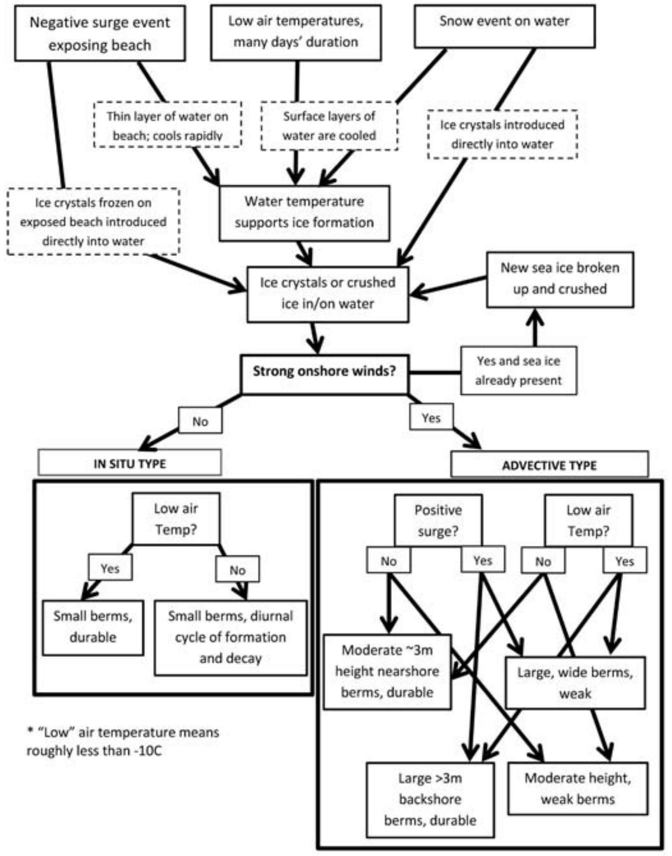

FIG. 16. General taxonomy of slush-ice berm features. A feature not listed here is a situation that occurs when there is so much slush ice piled against the shore that wave activity is damped out. In this case, without wave action, the slush does not get up onto the beach to form berms. These near-shore slush ice mats can extend many meters out from shore. Large waves can break through and carry slush up onto the beach, and the action of storm surge can lift and then deposit slush directly onto the beach.

The fourth condition, *no storm surge and no cold air*, results in an advective slush-ice berm of moderate height, not frozen solid and therefore also not strong enough to walk on safely. As with the previous type, a person can sink while attempting to walk on such a berm.

Both in situ and advective slush-ice berms, if they form under conditions of warm air (above 0˚C), will remain in a slushy state: solid enough to remain in place, but not strong enough to support the weight of a human. If no subsequent wave or surge event acts to melt them, these berms eventually solidify as air temperatures decrease.

In situ Berm Conditions: An issue that came up during this study is the role of beach characteristics in the formation of in situ slush-ice berms. In the shallow coastal areas, the in situ slush-ice berm will form as long as there is slush in the surf zone. The slush will be washed onto the beach and deposited along the low or high tideline, where it can develop further. Along beaches with a steeper profile, community residents mentioned that swell must be occurring in order to push the slush onto the beach. The role of temperature is also identified: if the temperature is too low and there is no wave action, the beach surface may freeze, forming a solid crust, and no slush-ice berm formation will occur. These observations point to the importance of two factors, the slope of the beach and nearshore zone and the size of sediment grains, but detailed consideration of these factors is beyond the scope of this study. The steeper gravel beaches of St. Lawrence Island and parts of the North Slope of Alaska exhibit different wave run-up characteristics, and because of higher permeability of beach sediments and larger grain size, they are less likely to form surface ice crusts.

Synoptic weather analysis of in situ slush-ice berms corroborates the community observations that they can form "very rapidly" if there is a rapid drop in temperature. During the days prior to the in situ slush-ice berm formation in Wales (on 8 November 2007 and 10 November 2012) and Shaktoolik (on 15 November 2013), the temperatures had been above 0˚C, and as soon as temperatures dropped below 0˚C, the berms formed. The SIZONet database shows that several other episodes of small in situ slush-ice berm formation and disappearance took place in Wales, Barrow, and Gambell during the fall every year between 2006 and 2014. A total of 53 daily observations out of more than 5000 refer to slush-ice berm formation in these communities during the specified time period. Most of these episodes were observed in Wales, but they were not considered in more detail here because the berms were too small to protect the town from a storm. However, a cursory synoptic weather analysis suggests that these smaller events have no particular relation to low-pressure systems, but rather are related to a general cooling of temperatures associated with the fall season. Also, the beach in Wales is wider than in Gambell or Barrow, which corroborates observations from residents of Shishmaref that the in situ slush-ice berms formed when the town had a sizable beach. Now that the beach has been eroded, a slush-ice berm does not form in Shishmaref. In Gambell, it was mentioned that slush-ice berms form faster on shallow coastal zones and are safer to walk on than those that form on deeper coastal zones. The berms in shallow water solidify more rapidly and as a result are stronger.

Advective Slush-Ice Berm Conditions: An analysis of the synoptic weather conditions that produced an advective slush-ice berm in Shaktoolik during the storms of 2009 and 2011 reinforces the observations of Reimnitz and Kempema (1987) as follows. First, the occurrence of strong winds (> 10 m/s) from an onshore direction allows large wind-driven waves and causes the slush in the nearshore to offshore zone to be pushed directly onto the beach. Second, conditions of low air temperature are important insofar as durable slush-ice berms were observed only at temperatures below −10˚C. Third, the occurrence of snow provides crystals for nucleation and aids in cooling of the surface water layer (Osterkamp, 1978). It was snowing during both of the advective slush-ice berm formation episodes in Shaktoolik, and in both cases the wind speed was well above 10 m/s (14 m/s in 2009 and 18 m/s in 2011), and the air temperatures were about −10˚C. The observation by Osterkamp (1978) that snow contributed by seeding the water and accelerating the slush formation process was corroborated by residents in all three communities. One additional community observation is that the weather patterns conducive to the formation of an advective slush-ice berm are very limited and site-specific. Short and Wiseman (1974) and community observers have mentioned that this process takes place in a very short period of time when the conditions are adequate.

Effects of Slush-Ice Berms on Communities

Slush-ice berms offer both advantages and disadvantages to coastal communities. The most common advantage of slush-ice berms mentioned by interviewees was the protection the berms offer from storm-induced surge or severe marine state, an advantage noted in the following news report:

> The storm could generate waves of up to 12 feet [3.5 m] and cause localized erosion along the northern coast of the Seward Peninsula as winds gusting up to 40 mph [17.5 m/s] pummel the area, according to the National Weather Service … Shelton Kokeok, whose home is about 30 feet [9 m] from the sea, said he watched throughout the day as the north wind blew in slush, which turned out to protect Shishmaref.
>
> (Anon., 2007)

The often-mentioned disadvantages of slush-ice berms include the following:

- They make hunting for seals difficult, because they block the shore, and the presence of slush prevents the seals from being washed all the way to shore after they have been shot.
- They limit onshore access to the beach, with the result that hunters must cut a pass through the berm to haul their boats out to the beach.
- They are not safe to walk on if they have not solidified.

An interesting observation by residents in Shaktoolik was that slush-ice berms used to form in October, when the weather became colder, but just before freeze-up occurred. Now slush-ice berm formation is happening later in the year, in either November or December, depending on local conditions.

CONCLUSION

This project has characterized the two major types of slush-ice berm that can help protect coastal communities in Alaska from storm impacts, as well as the synoptic weather patterns associated with these phenomena. It shows that both types of berms—in situ and advective slush-ice berms—form in the fall, just before sea ice forms, under specific weather conditions. Observations and descriptions from community residents, ice observations by indigenous experts in the SIZONet database, and personal observations were critical in identifying the role that beach characteristics play in the development of in situ slush-ice berms, and previous research results have been reinforced by community observations.

These findings illustrate the benefits derived from collaborative approaches that involve local and indigenous knowledge holders in the scientific collaboration. Their knowledge, combined with observations during community visits, the literature review, and synoptic weather analysis, sheds light not only on the types of berm formation but also on the relationships between weather conditions and slush ice that result in the two types of berms. This information will be valuable in developing future process-models of slush-ice berm formation that could be incorporated into predictive models. It may also serve as a basis for refining weather parameters and for understanding the dynamic interplay of the weather variables conducive to slush-ice berm formation during storms.

Additional fieldwork is required to identify more accurately the specific thresholds and ranges of air temperature, storm surge, and wind speed necessary to support the formation of various types of slush-ice berms. Characterization of beach and nearshore morphology and sediment grain size, as well as detailed observations of the entire freeze-up season of approximately one month's duration, will also be required. However, as Short and Wiseman (1974) point out, berm formation varies from place to place and from year to year. Once these parameters are identified, the opportunity exists to incorporate these results into routines used by computer modelers to improve slush-ice berm forecasting. The work conducted for this project may also have potential benefit for engineering applications, considering that slush-ice berms appear earlier and form faster in shallow near-shore waters.

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REFERENCES

Anon. 2007. Coastal village escapes ire of Chukchi Sea storm. *SanDiegoSource*, November 15.
http://www.sddt.com/News/article.cfm?SourceCode=200711151f#.V_k-YOArLy0

Apangalook, L., Apangalook, P., John, S., Leavitt, J., Weyapuk, W., Jr., and other observers. 2013. The Seasonal Ice Zone Observing Network (SIZONet) local observations interface, Version 1. Edited by H. Eicken and M. Kaufman. Boulder, Colorado: National Snow and Ice Data Center.
https://doi.org/10.7265/N5TB14VT

Atkinson, D.E., Schweitzer, P., Smith, O., and Norris, L. 2011. The Arctic Coastal System: An interplay of components human, industrial, and natural. Chapter 4.9. In: Lovecraft, A.L., and Eicken, H., eds. North by 2020: Perspectives on Alaska's changing social-ecological systems. Fairbanks: University of Alaska Press. 277–298.

Bauer, J., and Martin, S. 1983. A model of grease ice growth in small leads. Journal of Geophysical Research: Oceans 88(C5):2917–2925.
https://doi.org/10.1029/JC088iC05p02917

Chapman, R.S., Kim, S.-C., and Mark, D.J. 2009. Storm damage and flooding evaluation, storm induced water level prediction study for the western coast of Alaska. ERDC/CHL Letter Report. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. 92 p.

Eicken, H. 2010. Indigenous knowledge and sea ice science: What can we learn from indigenous ice users. In: Krupnik, I., Aporta, C., Gearheard, S., Laidler, G.J., and Kielsen Holm, L., eds. SIKU: Knowing our ice – Documenting Inuit sea–ice knowledge and use. New York: Springer-Verlag. 357–376.
https://doi.org/10.1007/978-90-481-8587-0_15

Eicken, H., Lovecraft, A.L., and 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.
https://doi.org/10.14430/arctic126

Eicken, H., Kaufman, M., Krupnik, I., Pulsifer, P., Apangalook, L., Apangalook, P., Weyapuk, W., Jr., and Leavitt, J. 2014. A framework and database for community sea ice observations in a changing Arctic: An Alaskan prototype for multiple users. Polar Geography 37(1):5–27.
https://doi.org/10.1080/1088937X.2013.873090

Erikson, L.H., McCall, R.T., van Rooijen, A., and Norris, B. 2015. Hindcast storm events in the Bering Sea for the St. Lawrence Island and Unalakleet regions, Alaska. Open-File Report 2015–1193. Washington, D.C.: U.S. Geological Survey. 47 p.
https://doi.org/10.3133/ofr20151193

FEMA (Federal Emergency Management Agency). 2009. Digital flood insurance rate map database, City of Shishmaref, AK, USA [electronic resource]: Washington, D.C.: U.S. Federal Emergency Management Agency.

GAO (Government Accountability Office). 2009. Alaska Native villages: Limited progress has been made on relocating villages threatened by flooding and erosion. GAO-09-551. Washington, D.C.: U.S. GAO. 53 p.
http://www.gao.gov/new.items/d09551.pdf

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L. Iredell, M., et al. 1996. The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society 77(3):437–471.
https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2

Kawerak Inc. 2012. Communities of the Bering Strait: Shishmaref. Nome, Alaska: Kawerak, Inc.
http://www.kawerak.org/communities/shishmaref.html

Kempema, E.W., Reimnitz, E., and Hunter, R.E. 1990. Flume studies and field observations of the interaction of frazil ice and anchor ice with sediment. Outer Continental Shelf Environmental Assessment Program, Final Reports of Principal Investigators 72:283–330. Anchorage: U.S. Department of Commerce and U.S. Department of the Interior.

Kinsman, N.E.M., and DeRaps, M.R. 2012. Coastal hazard field investigations in response to the November 2011 Bering Sea storm, Norton Sound, Alaska. Report of Investigations 2012-2 v. 1.1. Fairbanks: Alaska Division of Geological & Geophysical Surveys, Department of Natural Resources. 51 p.
https://doi.org/10.14509/24484

Kinsman, N.E.M., DeRaps, M.R., and Smith, J.R. 2013. Preliminary evaluation of coastal geomorphology and geohazards on 'Kigiqtam Iglua,' an island northeast of Shishmaref, Alaska. Fairbanks: Alaska Department of Natural Resources, Division of Geological & Geophysical Surveys.
http://pubs.dggsalaskagov.us/webpubs/dggs/pir/text/pir2013_003.pdf

Mahoney, A., Eicken, H., Shapiro, L.H., and Grenfell, T.C. 2004. Ice motion and driving forces during a spring ice shove on the Alaskan Chukchi coast. Journal of Glaciology 50(169):195–207.

Martin, S. 1981. Frazil ice in rivers and oceans. Annual Reviews of Fluid Mechanics 13:379–397.
https://doi.org/10.1146/annurev.fl.13.010181.002115

Mason, O., Neal, W.J., Pilkey, O.H., Jr., Bullock, J., Fathauer, T., Pilkey, D., and Swanston, D. 1998. Living with the coast of Alaska. Durham, North Carolina: Duke University Press. 348 p.

Mesquita, M.S., Atkinson, D.E., and Hodges, K.I. 2010. Characteristics and variability of storm tracks in the North Pacific, Bering Sea, and Alaska. Journal of Climate 23:294–311.
https://doi.org/10.1175/2009JCLI3019.1

Morecki, V.N. 1965. Underwater sea ice: Problemy Arktiki i Antarktiki 19:32–38. Translated by E.R. Hope, Directorate of Scientific Information Services, Defence Research Board Canada, April 1968. Paper T 497 R. Available from National Technical Reports Library, U.S. Department of Commerce, Accession # AD668841.

Osterkamp, T.E. 1978. Frazil ice formation: A review. Journal of the Hydraulics Division, American Society of Civil Engineers 104(HY9):1239–1255.

Parnell, S. 2011. State of Alaska declaration of disaster emergency. Juneau, Alaska: Office of the Governor of the State of Alaska, December 5, 2011.
http://fc.ak-prepared.com/dailysitrep/I021925EC.1/2011_West_Coast_Storm_Declaration120511.pdf

Reimnitz, E., and Dunton, K.H. 1979. Diving observations of the soft ice layer under the fast ice at DS-11 in the Stefansson Sound Boulder Patch. In: Environmental Assessment of the Alaskan Continental Shelf: Principal Investigators' Annual Reports, March 1979. National Oceanic and Atmospheric Administration 9:210–230.

Reimnitz, E., and Kempema, E.W. 1987. Field observations of slush ice generated during freeze-up in Arctic coastal waters. Marine Geology 77(3-4):219–231.
https://doi.org/10.1016/0025-3227(87)90113-7

Reimnitz, E., and Maurer, D.K. 1979. Effects of storm surges on the Beaufort Sea coast, northern Alaska. Arctic 32(4):329–344.
https://doi.org/10.14430/arctic2631

Short, A.D., and Wiseman, W.J., Jr. 1974. Freezeup processes on Arctic beaches. Arctic 27(3):215–224.
https://doi.org/10.14430/arctic2875

Strickling, S.E. 2012a. Gambell local economic development plan 2012–2017. Prepared for the Community of Gambell and the Bering Strait Development Council. Nome, Alaska: Kawerak Inc.
http://www.kawerak.org/ledps/gambell.pdf

———. 2012b. Shishmaref local economic development plan 2013–2018. Prepared for the Community of Shishmaref and the Bering Strait Development Council. Nome, Alaska: Kawerak Inc.
http://www.kawerak.org/ledps/shishmaref.pdf

———. 2013. Shaktoolik local economic development plan 2013–2018. Prepared for the Community of Shaktoolik and the Bering Strait Development Council. Nome, Alaska: Kawerak Inc.
http://www.kawerak.org/ledps/shaktoolik.pdf

Terenzi, J., Jorgenson, M.T., and Ely, C.R. 2014. Storm-surge flooding on the Yukon-Kuskokwim Delta, Alaska. Arctic 67(3):360–374.
https://doi.org/10.14430/arctic4403

USACE (U.S. Army Corps of Engineers). 2008. Erosion Information Paper – Gambell, Alaska.
http://www.poa.usace.army.mil/Portals/34/docs/civilworks/BEA/Gambell_Final%20Report.pdf

———. 2011. Shaktoolik coastal flooding analysis. U.S. Army Corps of Engineers, Alaska District.
https://www.commerce.alaska.gov/web/Portals/4/pub/2011_USACE-Coastal_Flooding_Analysis_Oct_2011.pdf

U.S. Census Bureau. 2010. Table DP-1: Profile of general demographic characteristics: 2000. United States Census Bureau.
https://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t

Wiseman, W.J., Jr., Coleman, J.M., Gregory, A., Hsu, S.-A., Short, A.D., Suhayda, J.N., Waters, C.D., Jr., and Wright, L.D. 1973. Alaskan Arctic coastal processes and morphology. Technical Report No. 149. Baton Rouge: Coastal Studies Institute, Louisiana State University. 171 p.
http://www.dtic.mil/get-tr-doc/pdf?AD=AD0766475