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7.6-m Ice Pile-Up that Encroached 20 m on Narwhal Island in November 2011

ICE ENCROACHMENT
IN THE ALASKAN BEAUFORT SEA

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FINAL REPORT

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EXECUTIVE SUMMARY

This report describes an investigation of ice encroachment on man-made facilities and natural shorelines in the Alaskan Beaufort Sea. The study was performed as a joint-industry project on behalf of Shell Exploration and Production Company (Shell) and the Bureau of Safety and Environmental Enforcement (BSEE), U.S. Department of the Interior.

The primary objective was to assemble historical data on the characteristics and causes of encroachment events in a study area that extends from Point Barrow to Barter Island. Such data can be used to refine the prediction of encroachment distances using statistical methods, and to improve operational safety by identifying the environmental conditions most likely to trigger encroachment events.

The principal findings of the study are summarized below:

1. Ice encroachment can occur when moving ice impacts a fixed body such as a man-made structure or natural shoreline. If the ice remains intact or nearly intact as it is driven onshore, the phenomenon is referred to as “ride-up”. If the ice fails in buckling or bending and breaks into individual blocks as it moves ashore, the phenomenon is referred to as “pile-up”.

2. The ice motion that causes encroachment is governed primarily by wind stress on the ice surface. Although factors that include astronomical tide, storm surge, and waves can contribute to the initiation of pile-up and ride-up, the single most important factor is the loss of confinement of the sheet ice. This situation typically arises from a reversal in the wind direction.

3. Historical data from the Alaskan Beaufort Sea indicate that sustained wind speeds greater than or equal to 15 kt (8 m/s) are necessary to initiate pile-up and ride-up events. The events can result from both easterly and westerly storms, which usually are associated with changes in the wind direction.

4. Ice encroachment events tend to occur during two distinct seasons: freeze-up and break-up. Most pile-ups occur during freeze-up, when the ice is thin and brittle, while most ride-ups occur during break-up, when the ice is thick and ductile.

5. At sheltered locations where ice movement is limited by shallow water depths and/or partial protection from adjacent landforms, the typical periods of exposure to ice encroachment are as follows:

   Freeze-Up: early October through early December (2 months);

   Break-Up: late June through early July (2 to 3 weeks).

   At exposed locations, the period of exposure is considerably longer during freeze-up but comparable at break-up:

   Freeze-Up: early October through mid-January (3.5 months);

   Break-Up: late June through early July (2 to 3 weeks).

6. Natural shorelines are subject to encroachment from pile-up, ride-up, and combinations of the two. Historically, the largest encroachments have resulted from events that involve ride-up during freeze-up. The maximum recorded value is 76 m.

7. Man-made facilities are subject to encroachment from pile-up and combinations of pile-up and ride-up. Encroachment tends not to occur from pure ride-up, however, due the relatively steep, rough side slopes that typically are present. The maximum recorded value of 30 m occurred during freeze-up, but encroachments of comparable magnitude have been documented during break-up as well.

8. Ice encroachment represents a key design parameter for coastal and offshore facilities in the Alaskan Beaufort Sea. The encroachment that results from pile-up can be predicted using: (1) a statistical extrapolation of historical pile-up elevations that have occurred under similar circumstances; (2) the geometric characteristics of the pile-up; and (3) the geometric characteristics of the man-made side slope or natural beach on which the pile-up occurs.

9. Reliable methods that can be used to predict the encroachment that results from ice ride-up on a natural shoreline do not exist. However, historical ride-up events can be consulted to develop a first-order estimate of the encroachment that could result from this phenomenon (with particular emphasis on events that occurred on a similar type of shoreline and in the general vicinity of the proposed project). The result then can be compared with the encroachment predicted on the basis of ice pile-up, with the larger value adopted as the basis for design.

10. To facilitate the prediction of encroachment, one hundred and seventy three historical pile-ups, ride-ups, and combination events have been identified from freeze-up studies, break-up studies, and publicly-available documents pertaining to

the Alaskan Beaufort Sea. The events, which are tabulated in the appendices of this report, have been subdivided into six categories based on the type of event (pile-up vs. ride-up), the degree of exposure (sheltered vs. exposed), and the nature of the site (man-made vs. natural).

11. If a project site is susceptible to encroachment, a buffer zone or setback should be established to accommodate the design encroachment event. The buffer zone should remain free of all items of value during the windows of exposure that occur during freeze-up and break-up. It may be occupied during the remainder of the year, however.

12. Even if ice does not encroach onto the work surface of a man-made facility, it can damage the armor that protects the side slope. Such damage tends to be most severe during break-up, when the ice is thicker than during freeze-up. In the event of a significant encroachment event on a man-made facility with armored side slopes, the impacted area should be inspected immediately after break-up to ensure that the slope protection system has not been compromised.

13. On those occasions during freeze-up and break-up when coastal and offshore operations could be impacted by ice encroachment, particular vigilance should be maintained when a change in wind direction is accompanied by wind speeds greater than or equal to 15 kt (8 m/s).

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ICE ENCROACHMENT
IN THE ALASKAN BEAUFORT SEA

1. INTRODUCTION

Ice encroachment can occur when a sustained movement of the ice sheet causes the ice to ride up on, or pile up against, the side slope of a man-made facility or face of a natural beach. Such events typically occur in the fall, when the ice is thin, and in the spring, when the ice is weak.

This report describes an investigation of ice encroachment on man-made facilities and natural shorelines in the Alaskan Beaufort Sea. The study was performed as a joint-industry project on behalf of Shell Exploration and Production Company (Shell) and the Bureau of Safety and Environmental Enforcement (BSEE), U.S. Department of the Interior.

The primary objective was to assemble data on the characteristics and causes of historical encroachment events in a study area that extends from Point Barrow to Barter Island (Figure 1). Such data can be used to refine the prediction of encroachment distances using statistical methods, and to improve operational safety by identifying the environmental conditions most likely to trigger encroachment events. The data also can serve as a basis for developing and verifying predictive numerical models.

To provide context for the analysis of encroachment events, Section 2 presents an overview of the ice conditions that prevail in the Alaskan Beaufort Sea. Prominent ice features, ice growth, and ice movement are summarized for each season, with particular emphasis on freeze-up and break-up. Section 3 begins with a general discussion of ice encroachment, including definitions of key terms and a review of the causative factors. The nature of encroachment then is assessed separately for the freeze-up and break-up seasons.

Historical ice encroachment events on man-made facilities and natural shorelines (including barrier islands) were identified primarily from data acquired during a series of freeze-up and break-up studies conducted from 1980 through 1985. Additional events were derived from publicly-available sources and from proprietary reports describing the 2009-10 and 2010-11 freeze-up seasons (which are accessible to the present study by virtue of

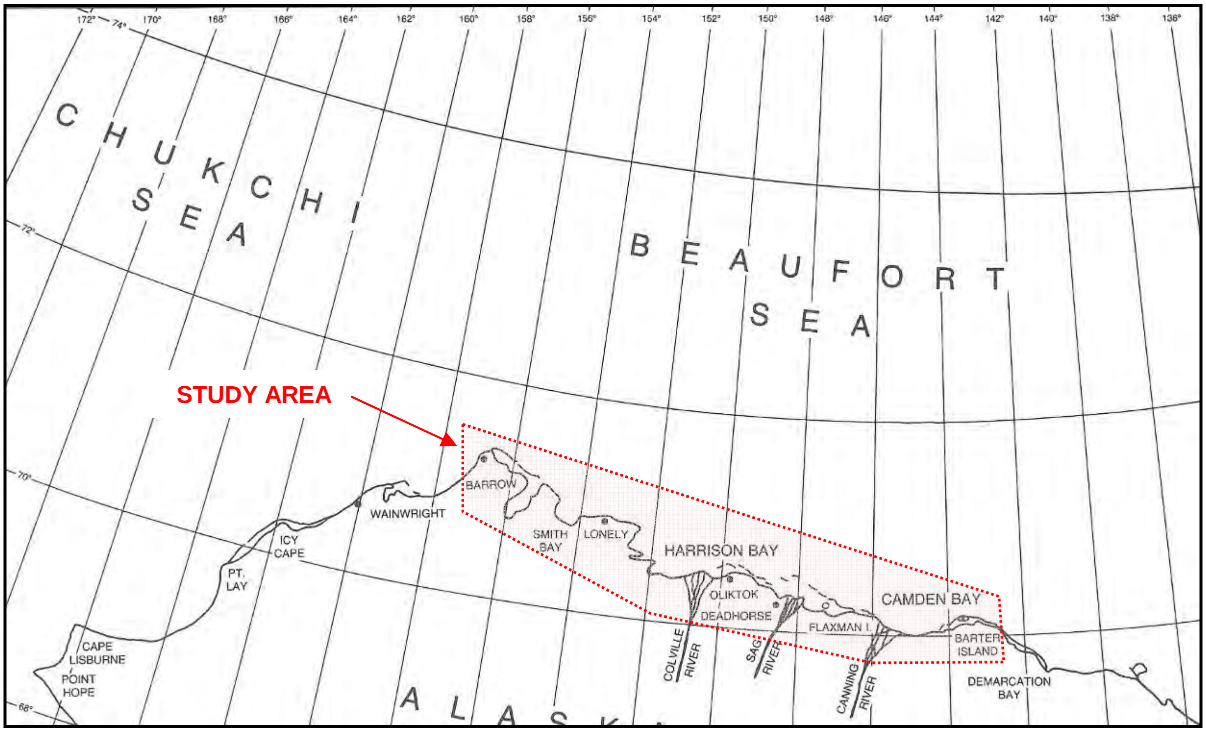


Figure 1. Study Area

identical joint-industry sponsorship). The combined data base was used to develop tabulations of significant pile-up and ride-up events that are introduced in Section 4. To facilitate access, the tabulations are provided at the end of the report in Appendices A through F.

Additional insight into the factors that cause encroachment were acquired by monitoring the wind and ice conditions that prevailed during the 2011 break-up and freeze-up seasons while investigating pile-up and ride-up events on an opportunistic basis. The findings of the monitoring effort are presented in Section 5, while the ten pile-up events that were noted are included in the Appendix tabulations.

Section 6 outlines a method of statistical analysis that can be used in conjunction with historical ice pile-up observations to predict the pile-up elevations associated with various return periods. Representative calculations are presented for four cases: (1) man-made facilities in protected locations, (2) man-made facilities in exposed locations, (3) natural shorelines in protected locations, and (4) natural shorelines in exposed locations.

In Section 7, a procedure is presented for estimating the ice encroachment distance from the predicted pile-up height, the geometric characteristics of the pile-up, and the geometric characteristics of the man-made side slope or natural beach on which the pile-up occurs. Knowledge of the expected maximum encroachment can be used to establish an appropriate setback distance for topside facilities and pipeline shore crossings. Conclusions and recommendations are presented in Section 8, followed by references in Section 9.

Throughout this report, the locations of encroachment events are described relative to geographic features that include coastal villages, bays, points of land, and natural and man-made islands. For ease of reference, these features are shown in Figures 2 and 3 for the central and western portions of the Beaufort Sea. The horizontal datum for the geographic coordinates shown in these figures is the North American Datum of 1983 (NAD83).

The vertical datum for all elevations in this report is Mean Lower Low Water (MLLW). As MLLW lies only 10 cm below Mean Sea Level (MSL) at the Prudhoe Bay tide gauge (the only National Ocean Service tide gauge in the Beaufort Sea; National Ocean Service, 2012), the difference between MLLW and MSL is assumed to be negligible.

Units are provided in the SI system, with two exceptions: (1) distances are provided in nautical miles (nm) to maintain consistency with the use of geographic coordinates; and (2) wind speeds are provided in knots (kt), again to maintain consistency with the use of geographic coordinates. In both cases, however, the corresponding values in SI units are provided in parentheses.

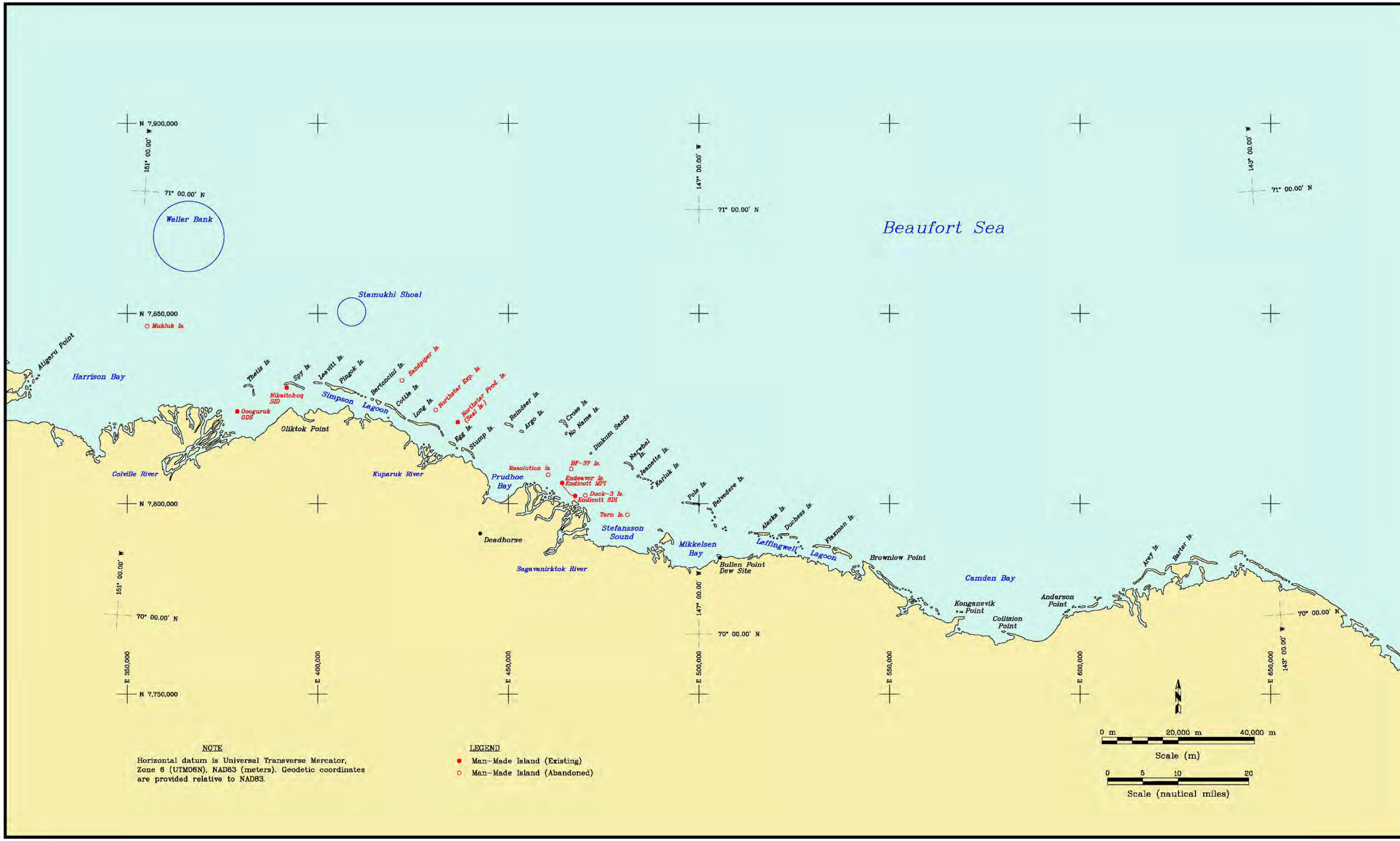


Figure 2. Geographic Features in Central Beaufort Sea

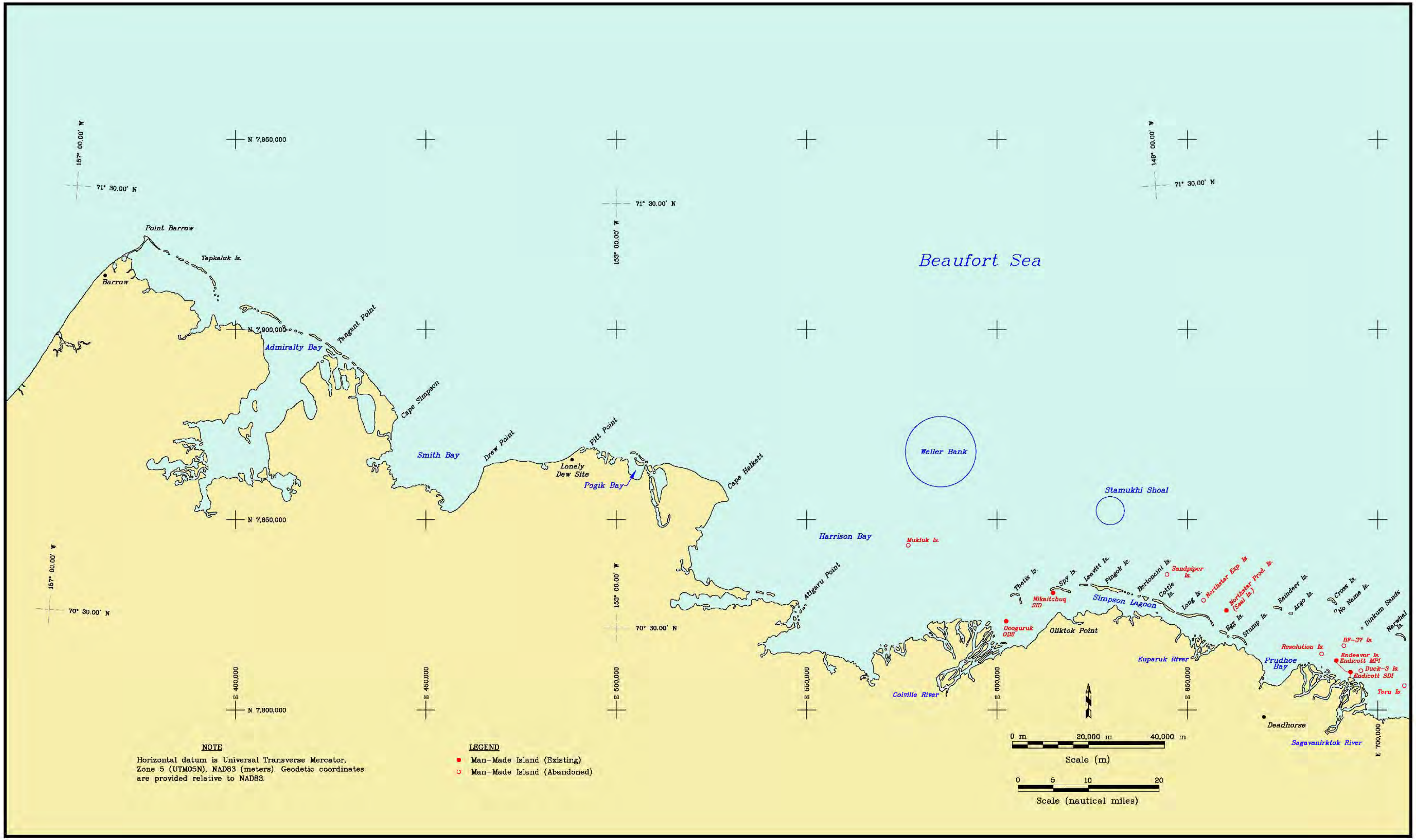


Figure 3. Geographic Features in Western Beaufort Sea

2. BEAUFORT SEA ICE CONDITIONS

Sea ice covers the nearshore region of the Beaufort Sea for approximately nine months of each year, with the ice season currently lasting about 260 days. Freeze-up tends to occur in mid-to late October, while break-up tends to occur in late June or early July. Based on a comparison with freeze-up and break-up data acquired in the 1980s and early 1990s (Vaudrey, 1981-86a; Vaudrey, 1988-92), the annual occurrence of freeze-up has slipped by two to three weeks since that period, while there has been little or no change in the timing of river overflooding and break-up (Vaudrey, 2007; Coastal Frontiers and Vaudrey, 2011).

2.1 Ice Seasons

Freeze-Up and Winter: Freeze-up is defined as the first time in the fall when nilas or young ice (10 to 15 cm thick) covers 100 percent of the sea surface at a specific site or over a particular region. As indicated above, it tends to occur in the nearshore region between mid-and late October, with an approximate average of date of October 20. The freezing process usually begins in the calm, shallow waters of protected bays and lagoons and then spreads rapidly offshore into deeper water (Plate 1). The young first-year ice is only 10 to 20 cm thick and susceptible to movement and deformation by storm winds in late October and early November, even in protected locations.

Plate 1. First Stages of Freeze-Up at BF-37 Exploration Island (October 1981)

Once the sheet ice thickness reaches 30 to 45 cm, the ice cover along most of the shoreline in the central Beaufort Sea (from Cape Halkett to Barter Island) becomes relatively stable. The nearshore region around Prudhoe Bay, from Thetis Island on the west to Flaxman Island on the east, is sheltered by the coastline on the south and barrier islands to the north. During seven freeze-up studies conducted from 1979 through 1985 (Oceanographic Services Inc., 1979; Vaudrey, 1981-86), no freeze-up ice movement was observed or measured after November 1 in protected areas such as Simpson Lagoon and Stefansson Sound. The sheet ice in these locations can be considered a part of the landfast ice zone after mid- to late November; however, there have been exceptions. For example, a significant ice movement event occurred at the Bullen Point DEW station during a westerly storm on November 11-13, 1973 (Kovacs, 1983).

Significant ice movements continue to occur in late November and throughout December in more exposed locations, such as on the seaward side of the barrier islands and off the open coastline in Camden Bay. Although significant ice movements are rare after December, they nevertheless can occur. In mid-January 1984, for example, northwesterly winds drove the ice ashore at Collinson Point in Camden Bay. Similarly, in mid-January 2008, westerly winds caused a 14-m high ice pile-up on Northstar Production Island (Coastal Frontiers, 2009). These unusually late ice movement events indicate that the transition from freeze-up to winter is somewhat arbitrary, in regard to both date and ice thickness, and can vary considerably from site to site and year to year.

The easterly winds that prevail in the Beaufort Sea produce ice motion that is roughly parallel to the coast, creating a stable landfast ice zone out to water depths of 15 to 20 meters. In the western Beaufort, between Point Barrow and Prudhoe Bay, numerous shoals are present at distances as large as 10 to 20 nm (19 to 37 km) offshore. These shoals significantly widen the landfast ice zone in the adjacent region. The most prominent shoal is Weller Bank in northeastern Harrison Bay. Large rubble piles of first-year ice typically ground on this feature (Plate 2), stabilizing the ice to the south and establishing a seaward perimeter for the landfast ice zone that lies well offshore. By contrast, water depths to the east of Prudhoe Bay increase more rapidly offshore of the barrier islands from Cross to Flaxman and north of the coast in the vicinity of Barter Island. Along this stretch of the Beaufort Sea coast, the width of the landfast ice zone can vary from a few hundred meters to 10 nm (19 km; except in Camden Bay, where the landfast ice zone can extend up to 15 nm or 28 km offshore). This large variation in the width of the landfast ice stems from the occurrence or non-occurrence of southwesterly storm winds, which prevent the ice from developing grounded anchor points and make it susceptible to break out and movement away from the shoreline.

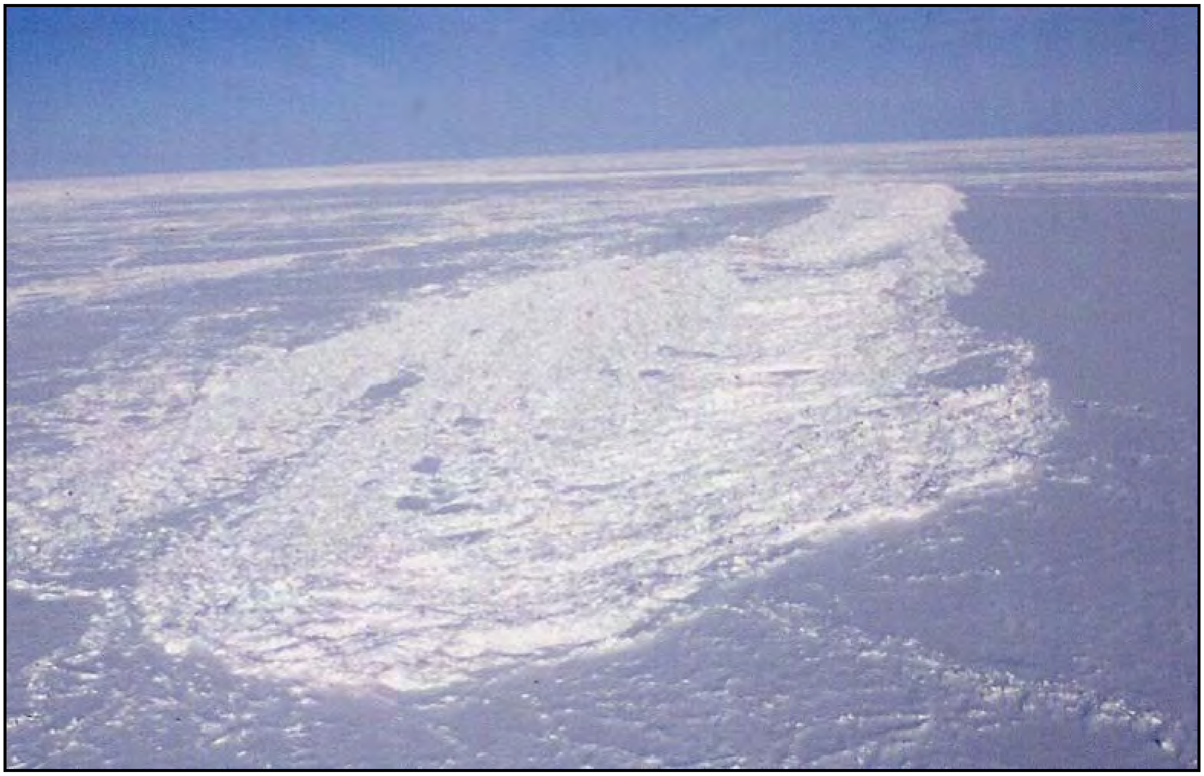


Plate 2. Typical Rubble Formation on Weller Bank (May 1989)

Offshore of the landfast ice zone, the pack ice continues to move throughout the winter, driven by the steady-state east-to-west motion of the Beaufort Gyre (typically 5-7 nm/day or 9-13 km/day) and by the transient, short-term movement events generated by prevailing easterly winds (typically 10-20 nm/day or 19-37 nm/per day). Westerly storms can halt the ice motion produced by the Gyre and even reverse its direction, depending on the strength and duration of the winds.

The transition or shear zone that separates the landfast ice from the pack ice usually is well-defined by a series of grounded ridges and rubble fields (Plate 3) where the offshore perimeter of the relatively stationary landfast ice interacts with the moving pack.

Break-Up and Summer: The transition from winter to break-up begins in late April or early May, when the daylight hours are lengthening and air temperatures are on the rise. By early to mid-May, the ice sheet has lost bearing capacity to such an extent that ice roads become incapable of supporting large loads.

In early May, before the sea ice shows signs of significant deterioration, melting snow begins to swell the upland river channels. Bottomfast ice in the shallow water offshore of

Plate 3. Shear Zone Formation in Outer Camden Bay (March 1987)

the river deltas forms a dam that causes the river water to discharge on the top of the sea ice for one to two weeks in late May or early June.

By mid- to late June, about two to three weeks after the flooding has ceased, most of the ice within the overflood zone has melted in place from a combination of the fresh, relatively warm, river water and the increased heat absorption by the ice surface, which is covered with a thin layer of silt deposited by the flood water. This decay, along with the ensuing loss of confinement, promotes break-up of the nearshore landfast ice (Plate 4) about three to four weeks after the conclusion of the overflood period.

Break-up of the landfast ice in the Beaufort Sea sometimes is preceded by significant "breakout" ice movement events in the temporary fast ice located just offshore of the grounded shear zone and weakened by warm air temperatures and solar radiation. Such events were observed in early June in both 1986 and 1987, with similar events occurring in late May 2002 and early June 2007.

Warm air temperatures initiate melt pond formation on top of the landfast ice sheet, especially where the surface has been contaminated with dirt. The increased absorption of solar radiation by the melt water and incorporated sediment (relative to the highly reflective,

Plate 4. Break-Up of Landfast Ice in Stefansson Sound (early July 1983)

clean snow and ice in winter) accelerates this process. Historically, in late May or early June at the time of river overflood, melt ponds tended to cover less than 10% of the landfast ice area beyond the overflood limits, but that percentage increased to roughly 30% in the late 1990s and early 2000s, based on personal observations. Just before break-up in late June or early July, the number and size of the melt ponds increase dramatically to the extent that the ponds cover almost 50% of the ice surface.

Break-up is defined as a reduction in the ice canopy from complete (10 tenths) coverage to 9 tenths or less coverage. At the time of break-up, a 20-kt wind is capable of breaking up the deteriorated sheet ice, which is roughly 1-m thick between melt ponds.

Ice concentrations immediately after break-up tend to vary considerably, depending on the wind direction and intensity. If the winds that cause break-up are intense or sustained, rafting may occur as thinner melt pond ice breaks loose and overrides the surrounding sheet ice. The rafting increases the amount of open water between ice floes, causing accelerated melting by waves and currents. As the wind direction changes, the broken ice floes and pans move back and forth in belts and patches of varying concentrations while melting rapidly. Open water, defined as one tenth or less ice coverage, typically occurs within two to three weeks after break-up.

Outside the landfast ice zone, the primary mechanisms for ice deterioration and retreat in the Alaskan Beaufort Sea are: (1) the Chukchi Current, (2) discharge from the Mackenzie River, and (3) the prevailing easterly winds. The coastal branch of the warm Chukchi Current rounds Point Barrow and enters the western Beaufort Sea. Simultaneously, a substantial quantity of relatively warm, fresh water enters the Canadian Beaufort from the Mackenzie River. Easterly winds drive the Mackenzie discharge westward along the coast, creating a vast open-water polynya in the eastern Beaufort Sea. The combined effect of the two warm-water currents is to isolate a "tongue" of ice in the western Beaufort (Plate 5).

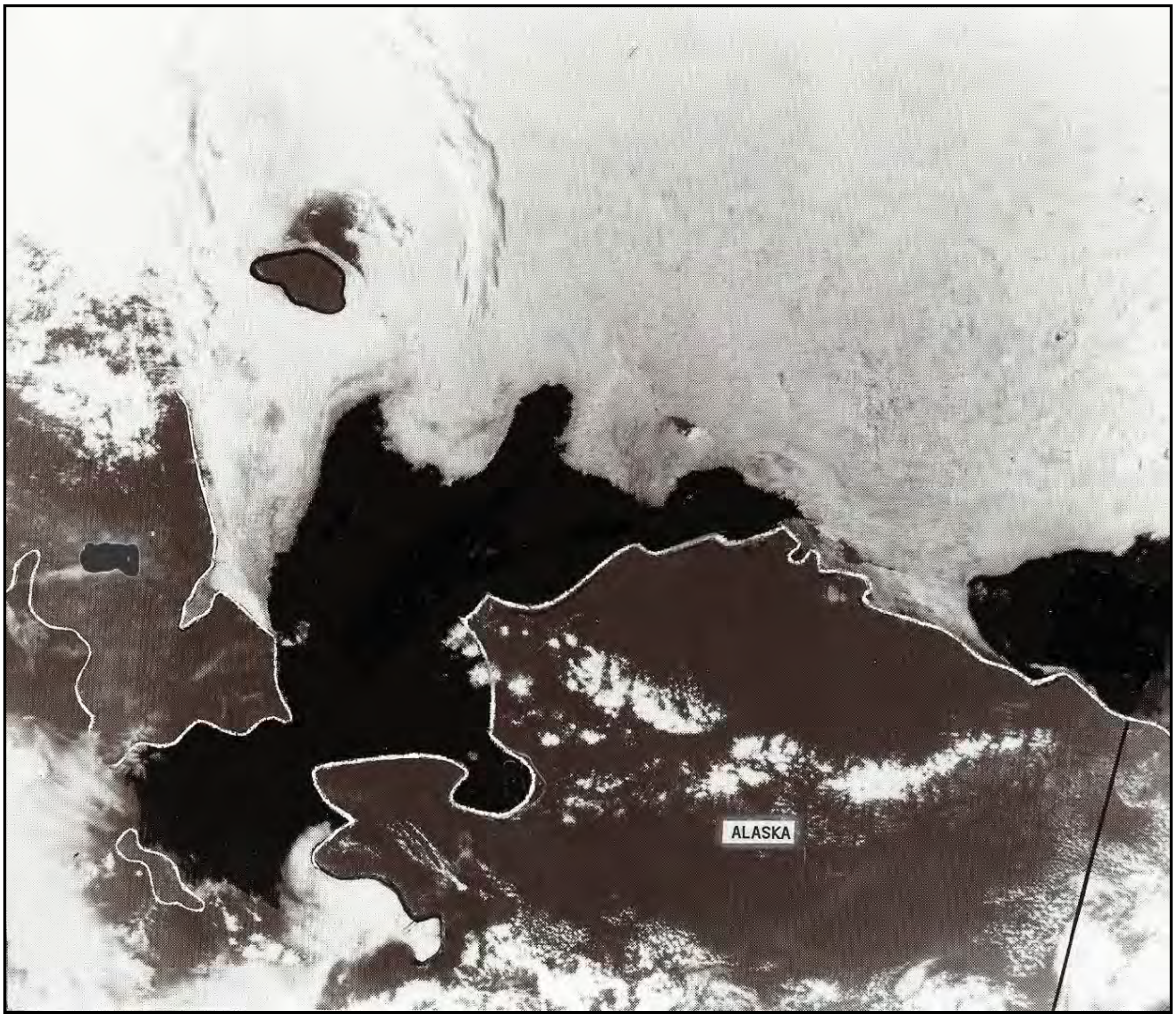


Plate 5. AVHRR Image Showing "Tongue" of Ice Remaining near Shore in Western Beaufort Sea (8 July 1987; Vaudrey, 1988)

As the remaining ice cover continues to melt, it drifts offshore due to the Coriolis effect associated with the prevailing easterly winds. In addition, occasional southeasterly winds not only drive the ice offshore, but also transport warmer air from the land over the ice. In mild summers, the ice edge lies at least 50 nm offshore by mid- to late August. The retreat of the ice edge typically continues until mid- to late September, at which the time the sea ice attains its minimum annual extent.

2.2 Ice Features, Growth, and Movement

First-Year Ice Features and Growth: The predominant ice feature in the Alaskan Beaufort Sea is first-year sea ice, which remains relatively flat in sheltered areas near the coast that include bays and lagoons. Occasionally, light ridging (about 1 m high) and rafting occur during early freeze-up ice movement events. If left undisturbed throughout the winter, the sea ice grows about 26 cm per month from October through March and attains an average thickness of 1.7 meters by early May, based on accumulated freezing-degree days over the last 20 years. This thickness is 10 to 12 cm less than that computed for the 1970s and 1980s.

In more exposed areas, frequent early-season storms produce numerous deformed first-year ice features that include rafted ice, ridges, and rubble piles, especially when the ice is thin and highly mobile. As the ice grows thicker and many of the ridges and rubble features become grounded in 10 to 20 m of water, the nearshore ice becomes more stable and less susceptible to movement. However, ridge-building continues throughout the winter in the moving pack ice as the floes impact one another.

Rafted ice forms when one ice sheet overrides another. Very thin ice may stitch together, under light pressure, and form a pattern of “finger” rafting to produce ice floes composed of as many as 10 layers, each 5 to 10 cm thick. Late winter ice movement can produce rafted ice made up of two or three sheets that are 1.0 to 1.5 m thick.

A ridge, which is a linear feature, forms as a result of buckling when ice floes collide or shearing when one floe grinds past another. The thickness of the ice blocks in the ridge sail (the portion of the ridge above sea level) may be used to estimate when the ridge was formed.

Rubble piles, which are grounded ice features of areal, rather than linear, extent, are composed of ice broken into blocks of different shapes (Plate 6). Rubble piles rarely occur in the protected bays and lagoons inside the barrier island chain unless they form as part of an ice pile-up event on a natural shoreline or manmade structure. Both ridges and rubble

Plate 6. 700-m Long by 18-m High Rubble Pile on Shoal 8 nm NW of Seal Island (Rubble formed in December 1983 and survived for two open-water seasons.)

piles frequently form in the shear zone, at the boundary between the stationary landfast ice and the mobile pack ice.

Multi-Year Ice: Multi-year ice is sea ice that has survived at least one melt season. During freeze-up, multi-year ice floes (Plate 7) can invade the nearshore region of the Beaufort Sea north of the barrier island chain and typically seaward of the 12-m isobath. However, small multi-year fragments (up to 30 m across) can enter the shallow waters adjacent to the coast. During the 2010-11 freeze-up season, for example, such fragments were observed on the seaward shorelines of many of the barrier islands between Harrison and Camden Bays (Coastal Frontiers and Vaudrey & Associates, 2011). Most multi-year ice invasions occur during freeze-up, because pack ice confinement and the landfast ice zone tend to preclude such events in mid-winter.

During the 16-year period from 1977 through 1992, multi-year ice invaded the nearshore portion of the Alaskan Beaufort Sea just over 50% of the time. By comparison, there have been three such invasions in the last 12 years (2000-2011), for an occurrence frequency of 25%. These findings suggest that a multi-year ice invasion of the nearshore Beaufort Sea is about 50% less likely to occur now than it was several decades ago.

Plate 7. 1000-m Diameter Multi-Year Ice Floe in Camden Bay (October 1985)

An additional change in the nature of multi-year ice invasions relates to the source of the ice itself. In the 1980s, the invading ice typically consisted of about 50% perennial polar pack floes advected from the Arctic Ocean, and 50% second-year ice floes representing fragments of vast first-year ridges and rubble fields that had survived relatively cold, calm summers. Such locally-developed "multi-year" floes differ from the perennial pack floes by virtue of greater surface relief, including many embedded ridges, and greater thickness. During the past decade, however, little or no second-year ice has been created in the nearshore Beaufort Sea. As a result, the multi-year ice invasions have consisted solely of pack floes.

Ice Movement: Ice motion is dominated by the wind. During break-up and early freeze-up, when the ice is partially confined, ice movement rates tend to average 2 to 3% of the sustained wind speed. When ice floes travel in open water, the "wind factor" can exceed 5%. Extreme values for ice movement rates are on the order of 1.3 to 1.5 m/sec.

As indicated earlier, the winter pack ice tends to move from east to west at an average rate of 5 to 7 nm/day (9-13 nm/day) under the influence of the Beaufort Gyre.

Reversals in direction can occur during westerly storms. The combined effect is a predominance of coast-parallel, east-west ice movement that mirrors the pattern of easterly winds punctuated by occasional westerly storms.

By mid-to late winter (mid-January to late April), movement of the landfast ice in sheltered areas such as bays and lagoons virtually ceases due to the continued growth and stability of the sheet ice. In more exposed areas, including central Harrison Bay and immediately offshore of the barrier islands to the west of Prudhoe Bay, midwinter movement of the landfast ice typically varies from a few meters to tens of meters. Exceptions can occur, however: in late February 1989, a 100-kt southwesterly storm removed most of landfast ice from the entire Alaskan Beaufort Sea, leaving the beaches along the coast from Point Barrow to Cape Halkett and the north-facing shorelines of the barrier islands from Thetis to Flaxman exposed to open water.

3. ICE ENCROACHMENT SCENARIOS

3.1 Overview

Ice encroachment events on natural shorelines and man-made facilities tend to occur during two distinct seasons:

- Freeze-Up: early October through mid-January
- Break-Up: late June through early July

These time periods correspond to the "fall" and "spring" seasons referred to by Kovacs (1984).

In the context of this study, "encroachment" refers to the horizontal distance that an ice sheet or individual ice blocks move past the waterline onto the above-water portion of a natural beach or man-made structure. "Work surface encroachment" refers to the horizontal distance that ice moves past the edge of the work surface onto the top of a man-made structure.

If the sheet ice remains intact or nearly intact as it is driven ashore, the phenomenon is called "ice ride-up." If the advance of the ice is halted by the slope and the ice fails in buckling or bending, it breaks up into individual blocks that form an "ice pile-up" either at the shoreline or somewhere on the above-water slope.

An example of an ice ride-up event without significant pile-up occurred in late June 1981 (Vaudrey, 1982) when a 15-20 kt (8-10 m/s) westerly wind drove the 60-75 cm thick ice sheet onto the gently-sloping beach of Pole Island. (Plate 8). The ice encroached up to 15 m over an alongshore distance of roughly 300 m. Ice ride-up events also can occur during early freeze-up, when the young, pliable sheet ice can conform to minor changes in slope and move onshore if suitable storm conditions exist.

The most common ice encroachment event is a combination of ice ride-up and pile-up that occurs when the sheet ice rides up the slope until increasing frictional resistance causes the ice to rubble and form a pile-up. If the pile-up grows to a sufficient height that its peak exceeds the elevation of a man-made facility, ice blocks at the top of the pile can tumble down onto the work surface. Such an event occurred at Endeavor Island, an exploratory island in a water depth of 3.7 m, during the 1982 freeze-up season (Vaudrey, 1983a; Plate 9). When a 20-25 kt (10-13 m/s) easterly storm on October 16-17 was

Plate 8. Ice Ride-Up on Pole Island in late June 1981 (60-75 cm thick sheet ice encroached 15 m onto beach during 20-kt westerly wind.)

Plate 9. 7.6-m High Ice Pile-Up on Endeavor Island in Mid-October 1982 (20-cm blocks encroached 5 m onto work surface during 40-kt SW storm.)

followed by a 30- to 40-kt (15- to 21-m/s) southwesterly storm on the 19th, a 7.6-m pile-up resulted on the west side of the island. The 20-cm thick ice blocks encroached 15 m past the waterline, including 5 m onto the work surface.

As indicated in Section 2, ice motion is governed primarily by wind stress acting on the ice surface. Although factors that include astronomical tide, storm surge, and waves can contribute to the initiation of ride-up and pile-up, the single most important factor is the loss of confinement of the sheet ice. This phenomenon typically results from a reversal in the wind direction, due to the presence of cracks or small leads in the nearshore ice. For instance, an easterly wind may produce the cracks or leads, which subsequently allow the ice to begin moving when the wind direction shifts to westerly. Such was the case during the aforementioned storm in October 1982. As illustrated in Plates 10 and 11, the easterly winds on October 16 and 17 produced broken ice and open water around Shell's Seal Island (an exploratory island in a water depth of 12 m at the site of the present Northstar Production Island). The southwesterly winds that followed on the 19th drove the 20-cm thick ice onto the island side slope, creating a 6.1-m high pile-up on the west side.

Whereas the loss of confinement exerts a profound influence on the initiation and severity of ice ride-up and pile-up events, ice thickness and storm intensity play secondary roles while storm duration plays only a minor role. Although storms of long-duration can keep the ice moving in the offshore region, ride-up and pile-up tend occur during the early stages of such events when the ice first impacts the shoreline or structure. The ice typically moves at a rate of a few hundred meters per hour during the formation of a shoreline pile-up, but comes to rest when the driving force is balanced by the resistance of the shoreline.

In addition to the "driving force" parameters discussed above, ride-up and pile-up events are influenced by shoreline characteristics that include the exposure of the coast, the morphology of the subaerial beach or side slope, and the local bathymetry. For instance, an exposed coast that has a relatively flat subaerial beach fronted by a steep underwater slope will be more susceptible to ice movement and encroachment than the protected shores of shallow bays and lagoons. The relative importance of the parameters that influence ice encroachment is summarized in Table 1.

It should be noted that a vertical wall or tundra bluff does not prevent ice encroachment (Kovacs and Sodhi, 1980; Shapiro, Metzner, and Toovak, 1979). Instead, the ice first forms a pile-up at the base of the bluff, and then moves up the resulting "ice ramp" and onto the bluff top -- a scenario that is more likely to occur when little or no beach exists to provide sliding resistance or accommodate a significant volume of encroaching ice.

Plate 10. Broken Ice and Open Water around Seal Island on October 18, 1982 after Easterly Storm

Plate 11. 6.1-m High Ice Pile-Up on Seal Island that Resulted from SW Storm on October 19, 1982.

Table 1. Parameters that Influence Ice Encroachment

Parameter	*Importance*		
	Slight	*Moderate*	*Significant*
Driving Force			
1. Wind reversal			X
2. Storm intensity		X	
3. Storm duration	X		
Ice Property			
1. Ice thickness		X	
2. Ice cracking			X
3. Flexural strength	X		
Shoreline Characteristics			
1. Beach slope	X		
2. Beach friction		X	
3. Coastal exposure		X	
4. Bathymetry	X		

Representative examples occurred during the 1981 and 1982 freeze-up seasons on the north side of Pingok Island, a natural barrier island located in the vicinity of Oliktok Point (Vaudrey, 1982a and 1984). On both occasions, a sequence of southwesterly winds followed by easterly winds created a substantial pile-up that overtopped the 2-m high bluff and spilled onto the tundra surface (Plates 12 and 13).

3.2 Freeze-Up

As indicated above, ice encroachment events during freeze-up tend to occur within a three-and-a-half-month window between early October and mid-January – a period characterized by frequent storms. In contrast, the ice encroachment window during break-up is much shorter and punctuated by fewer storm events. As a result, more encroachment events tend to occur during freeze-up than break-up.

The relatively long period of exposure to encroachment that occurs during freeze-up is due primarily to the time it takes the newly-forming ice sheet to attain sufficient thickness and coverage to resist displacement from wind stress. The young ice remains highly mobile and susceptible to movements that can produce ice encroachment for roughly four to eight weeks in bays, lagoons, and similar protected regions. After 3.5 months, the ice in the more

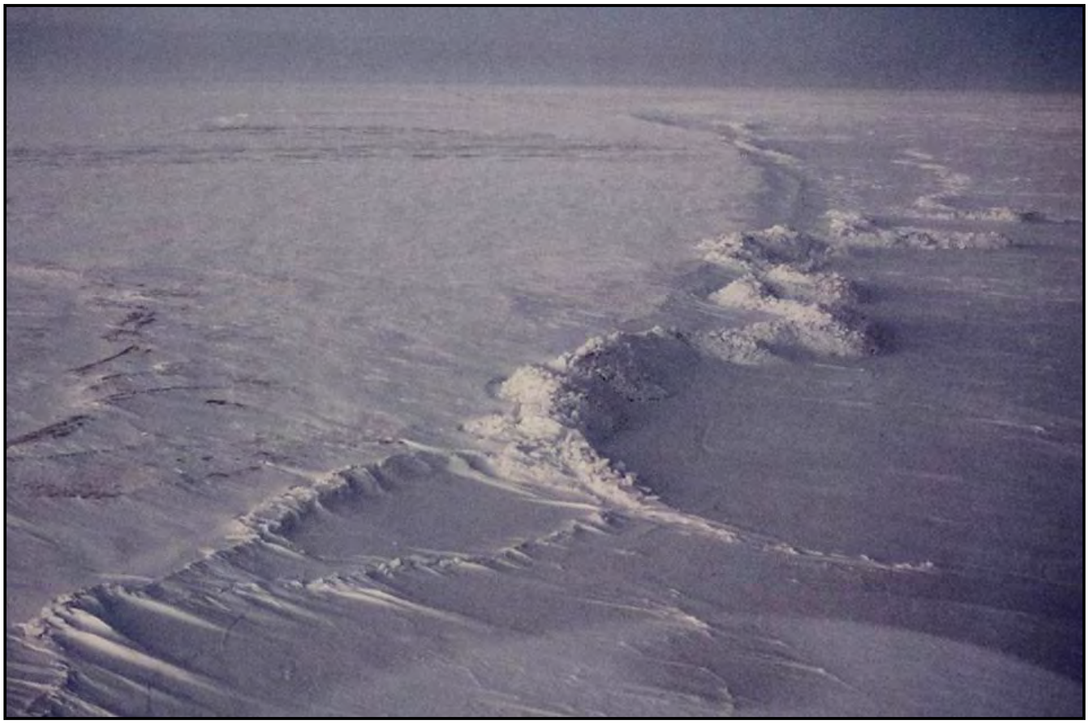


Plate 12. Ice Pile-Up that Overtopped 2-m High Bluff on Pingok Island in Late November 1981

Plate 13. Ice Pile-Up that Overtopped 2-m High Bluff on Pingok Island in Early December 1982 (Note: photo taken during 1983 break-up.)

exposed areas off the mainland coast and barrier islands has attained sufficient thickness to become landfast, and the risk of encroachment is dramatically reduced at these sites as well.

Most freeze-up events are ice pile-ups or combinations of pile-up and ride-up rather than pure ride-ups. The greatest encroachment distances on natural shorelines result from combined ride-up/pile-up events in which 10-15-m wide "fingers" of sheet ice slide as much as 50 to 75 m onto the beach between pile-ups (Plate 14). In the case of man-made facilities, the greatest encroachment distances typically result from pile-ups that cause ice blocks to tumble down onto the work surface.

Plate 14. 3.7-m High Pile-Up/Ride-Up that Occurred on Jeanette Is. in Mid-October 1982 (10-m wide finger of 20-cm thick ice rode 76 m onto south-facing beach.)

3.3 Break-Up

The period of exposure to ice encroachment typically lasts only two to three weeks during the break-up season, from late June through early July. In some years, exposure is limited to a two- to three-day window during which the ice cracks and breaks up into individual floes. The duration of exposure may vary from place to place during any given year, depending on the wind conditions and the strength of the rotting sheet ice.

Although all three types of encroachment events can occur during break-up, pure ride-ups are most common. Because the ice sheet is relatively warm and ductile, it can remain intact while encroaching onto the gently-sloping beaches that are present on many barrier islands (Plate 8). In addition, two stretches of the mainland coast are particularly susceptible to encroachment from ride-up or a combination of ride-up and pile-up: (1) between Lonely and Cape Halkett to the west of Harrison Bay, and (2) in the vicinity of Collinson Point in Camden Bay.

After break-up, the ice sheet is reduced to relatively small, rotten floes that tend to pile up at the shoreline without significant encroachment. Hence, the risk of encroachment is greatest at the moment of break-up and diminishes rapidly thereafter. Occasionally, however, encroachment can occur one to two weeks after the initial break-up if large individual floes are driven ashore.

Although the period of susceptibility to ice encroachment is short during break-up, the consequences can be more severe than during freeze-up because the ice is considerably thicker. As a result, the encroachment distance can be greater before the ice sheet buckles, and the ice can exert a greater load on any obstacles that it encounters.

4. HISTORICAL PILE-UP AND RIDE-UP EVENTS

To provide a basis for the prediction of ice encroachment (to be discussed in Sections 6 and 7), historical ride-up and pile-up events on man-made facilities and natural shorelines in the Alaskan Beaufort Sea were identified using four sources: (1) break-up and freeze-up studies conducted between 1980 and 1985 (Vaudrey, 1981-1986a); (2) two reports prepared by the U.S. Army Cold Regions Research and Engineering Laboratory (Kovacs, 1983; 1984); (3) joint industry studies of the 2009-10 and 2010-11 freeze-up seasons (Coastal Frontiers and Vaudrey & Associates, 2010; 2011); and (4) publicly-available documents describing the encroachment events that have occurred on Northstar Production Island since its construction in 2000 (Coastal Frontiers, 2001; 2002; .2006; 2009).

The bulk of the encroachment data was obtained from a series of 11 consecutive freeze-up and break-up studies that began with the 1980 freeze-up season and ended with the 1985 freeze-up season. The reports were used to compile a list of significant ice pile-up and ride-up events, and the following information was recorded for each event:

- Location;
- Date of occurrence;
- Shoreline type for natural shorelines;
- Nature of event (ride-up, pile-up, or both) for natural shorelines;
- Water depth for man-made facilities;
- Side slope inclination for man-made facilities;
- Ice block thickness;
- Maximum pile-up elevation;
- Encroachment;
- Work surface encroachment for man-made facilities;
- Wind speed;
- Wind direction.

Additional pile-up and ride-up events were identified using the other three sources cited above, as well as the results of the monitoring effort conducted in 2011 (to be recounted in Section 5). The events then were subdivided into the following six categories based on the type of event (pile-up vs. ride-up), the nature of the site (man-made vs. natural), and the degree of exposure (sheltered vs. exposed):

- Ice Pile-Up Events on Sheltered Man-Made Facilities;
- Ice Pile-Up Events on Exposed Man-Made Facilities;
- Ice-Pile-Up Events on Sheltered Natural Shorelines;
- Ice Pile-Up Events on Exposed Natural Shorelines;
- Ice-Ride-Up Events on Sheltered Natural Shorelines;
- Ice Ride-Up Events on Exposed Natural Shorelines.

A separate table of events was prepared for each category, with the results provided in Appendices A through F.

Natural shorelines sustained encroachment from pile-up, ride-up, and combinations of the two. In each instance where both phenomena occurred, the event is included in the appropriate pile-up table and also in the appropriate ride-up table. The pile-up table indicates the encroachment attributable to pile-up, while the ride-up table indicates the encroachment attributable to ride-up. In the case of a combined pile-up/ride-up event on an exposed natural shoreline, for example, the pile-up encroachment would be provided in "Ice Pile-Up Events on Exposed Natural Shorelines (Appendix D) while the ride-up encroachment would be provided in "Ice Ride-Up Events on Exposed Natural Shorelines" (Appendix F).

Although logic would suggest that tabulations should be included for ice ride-up on man-made facilities (both sheltered and exposed), all of the significant encroachment events observed on such structures to date have resulted either from ice pile-up or a combination of pile-up and ride-up in which pile-up predominated. The absence of pure ride-up events may be explained, at least in part, by the relatively steep side slopes that typically characterize man-made facilities. The roughness provided by side slope armor also may serve to initiate pile-ups at the expense of ride-ups. However, a possible exception to the rule excluding pure ride-up events on man-made facilities may exist with respect to unarmored structures with mild side slopes, such as gravel causeways protected by sacrificial beaches. Although quantitative information is lacking, anecdotal accounts suggest that a limited number of ride-up events have occurred on the side slopes of the West Dock and Endicott Causeways.

The primary criterion used to differentiate between "sheltered" and "exposed" locations in Appendices A through F is the degree of exposure to ice movement capable of causing encroachment. For a site to be classified as "sheltered", its susceptibility to significant ice movement typically is limited to two brief periods: (1) the initial four to eight weeks of the freeze-up season, and (2) the two to three weeks that comprise the entire break-up season. This situation tends to prevail at locations with shallow water depths, partial protection from adjacent landforms, or a combination of the two. The four-to-eight week duration of the freeze-up encroachment season is governed by the time required for the ice to attain a thickness of 30 to 45 cm. Thereafter, the ice sheet achieves sufficient confinement to resist displacement. In contrast, an "exposed" location remains susceptible to ice movement for about 3.5 months during freeze-up. The ice thickness needed to provide confinement at such sites is on the order of 90 cm. At break-up, however, the period of exposure is identical to that for protected sites (two to three weeks).

The data contained in Appendices A through F are discussed in the subsections that follow. Table 2 provides an overview, while Table 3 provides a more detailed summary of the pile-up and ride-up events that populate each category. As in the case of Appendices C through F, combined ride-up/pile-up events on natural shorelines are included under both categories in these tables.

Table 2. Overview of Historical Pile-Up and Ride-Up Events

Category	Freeze-Up	Break-Up	Total
Pile-Ups: Sheltered Man-Made Facilities	17	8	25
Pile-Ups: Exposed Man-Made Facilities	19	12	31
Total	36	20	56
Pile-Ups: Sheltered Natural Shorelines[1]	22	8	30
Pile-Ups: Exposed Natural Shorelines[1]	40	5	45
Total	62	13	75
Ride-Ups: Sheltered Natural Shorelines[1]	12	18	30
Ride-Ups: Exposed Natural Shorelines[1]	20	25	45
Total	32	43	75

Note:
1 22 events during freeze-up and 11 events during break-up involved a combination of pile-up and ride-up. Each is included in the appropriate pile-up category and also in the appropriate ride-up category.

Table 3. Summary of Historical Pile-Up and Ride-Up Events

Category/Season	Ice Events	Storms		Period of Exposure		Encroachment[1]		
		East	West	First	Last	Min (m)	Max (m)	Avg (m)
Pile-Ups: Sheltered Man-Made Facilities								
Freeze-Up	17	2	8	Oct 5	Nov 11	0 (0)	30 (6)	8
Break-Up	8	5	1	Jun 28	Jul 7	0 (0)	14 (0)	8
Pile-Ups: Exposed Man-Made Facilities								
Freeze-Up	19	8	9	Oct 8	Jan 23	0 (0)	27 (5)	11
Break-Up	12	6	4	Jun 29	Jul 21	5 (0)	27 (6)	18
Pile-Ups: Sheltered Natural Shorelines								
Freeze-Up	22	16	3	Oct 6	Dec 7	0	30	9
Break-Up	8	5	2	Jun 26	Jul 10	3	34	11
Pile-Ups: Exposed Natural Shorelines								
Freeze-Up	40	12	10	Sep 24	Jan 18	0	36	12
Break-Up	5	3	1	Jun 25	Jul 10	0	45	13
Ride-Ups: Sheltered Natural Shorelines								
Freeze-Up	12	10	2	Sep 22	Dec 7	6	75	32
Break-Up	18	9	4	Jun 24	Jul 10	9	30	17
Ride-Ups: Exposed Natural Shorelines								
Freeze-Up	20	8	6	Sep 24	Dec 5	6	76	29
Break-Up	25	8	4	Jun 25	Jul 11	3	45	15
Freeze-Up Total	108[2]	25[3]	21[3]					
Break-Up Total	65[2]	18[3]	10[3]					
Grand Total	**173[2]**	**43[3]**	**31[3]**					

Notes:

1 For man-made facilities, Work Surface Encroachment is provided in parentheses following Encroachment.

2 Totals have been reduced by 22 freeze-up events and 11 break-up events to account for combined ride-up/pile-up events that are included in both categories for natural shorelines.

3 Totals have been reduced by 31 easterlies and 17 westerlies during freeze-up, and 18 easterlies and 6 westerlies during break-up, to account for storms that caused pile-up and/or ride-up events at multiple sites.

4.1 Pile-Up Events on Sheltered Man-Made Facilities (Appendix A)

Based on the criteria outlined above, all of the man-made facilities on the mainland coast between the Staines and Colville Rivers, along with the islands offshore of the Sagavanirktok and Colville River deltas, represent sheltered locations. These sites include the Point Thomson pads, Bullen Point DEW site, Badami Development, Heald Point Drillsite, West Dock Causeway, Northstar Development pipeline shore crossing, Milne Point F Pad, and Oliktok Dock on the mainland shore; Tern, Duck 3, BF-37, Endeavor, Resolution, and Niakuk 4 exploration islands; the No Name Island exploration pad; and the Endicott Project, Nikaitchuq Spy Island Drillsite (SID), and Oooguruk Offshore Drillsite (ODS) production facilities. The water depths at these sites range from negligible to 6.7 m.

Seventeen pile-up events were documented on the foregoing facilities between 1973 and 2011. The pile-ups were generated by ten different storms, consisting of two easterlies and eight westerlies. In most cases, the storms engendered reversals in wind direction that caused the ice to lose confinement (Section 3.1). The number of pile-ups (17) exceeded the number of storms (10) because some storms created pile-ups at multiple sites. The earliest pile-up occurred on October 5 and the latest on November 11 – a period just over five weeks in length.

Five of the seventeen pile-ups did not encroach above the waterline. The remaining twelve pile-ups produced encroachments ranging from 3 to 30 m. The average encroachment (computed on the basis of all seventeen events) was 8 m. The maximum work surface encroachment, 6 m, occurred on Tern Island in mid-October 1984. As shown in Plates 15 and 16, this event occurred when 15- to 25-kt (8- to 13-m/s) southwesterly winds drove relatively thin ice (8 to 15 cm thick) against the gravel bag side slope and sheetpile dock on the west side of the island and created multiple pile-ups with a maximum height of 7.6 m. A similar circumstance, in which 30- to 40-kt (15- to 21-m/s) westerly winds drove 20-cm blocks onto the work surface of Endeavor Island in October 1982, was illustrated previously in Plate 9.

Eight pile-ups were recorded during the four consecutive break-up seasons from 1981 through 1984. The pile-ups, which resulted from five easterly storms and one westerly, were located on exploration islands in water depths that ranged from 3.0 to 6.7 m. The earliest event occurred on June 28, while the latest occurred on July 7 – a period of only ten days.

Seven of the pile-ups produced encroachments that ranged from 5 to 14 m, while the eighth was confined to the region seaward of the waterline. The average encroachment was

Plate 15. 7.6-m Pile-Up on Tern Island in mid-October 1984 (8-15 cm thick ice blocks encroached 12 m past waterline during 15-25 kt southwesterly storm.)

Plate 16. Work Surface Encroachment of 6 m on Tern Island in Mid-October 1984

8 m. In all cases, the pile-up failed to reach the facility work surface. The 6.9-m pile-up that encroached 14-m onto Tern Island in early July 1984, is shown in Plates 17 and 18.

4.2 Pile-Up Events on Exposed Man-Made Facilities (Appendix B)

The man-made facilities constructed to date in exposed locations in the Alaskan Beaufort Sea consist of exploration pads on Alaska, Challenge, and Jeanette Islands (natural barrier islands); Seal, Sandpiper Northstar, and Mukluk exploration islands, and Northstar Production Island. The water depths range from negligible to 14.9 m.

Nineteen pile-up events were recorded on these facilities between 1980 and 2011. The pile-ups were caused by eight easterly and nine westerly storms that occurred as early as October 8 and as late as January 23. As explained above, the period of exposure to pile-up and encroachment at exposed locations is substantially longer than that at sheltered locations due to the greater thickness of ice required to maintain confinement during storm events (approximately 90 cm at exposed sites vs. 30-45 cm at sheltered sites).

Eleven of the 19 pile-ups extended upslope of the waterline, producing encroachments as large as 27 m. The average value was 11 m. The sole work surface encroachment of 5 m occurred on the Jeanette Island exploration pad in 1981.

Representative pile-up events that occurred at exposed sites during the freeze-up season are shown in Plates 19 through 21. Plate 19 depicts a 7.6-m pile-up on Mukluk Island that formed in late November 1983. The ice did not encroach onto the above-water slopes during this event. Two years later, in mid-November 1985, an 11.5-m pile-up on Sandpiper Island encroached 5 m past the waterline onto the gravel bag armor (Plate 20). The largest encroachment, 27 m, was recorded on Northstar Production Island in late January 2008. As shown in Plate 21, a 30- to 40-kt (15- to 21-m/s) westerly storm produced a 14.3-m pile-up that engulfed the concrete mat slope protection system but was contained by a sheetpile wall that encircles the island work surface.

Twelve pile-ups were documented during six break-up seasons between 1981 and 2005. The pile-ups occurred between June 29 and July 21 in response to six easterly and four westerly storms, and involved the same four exploration islands and one production island impacted by freeze-up events.

Each of the pile-ups produced encroachment. The magnitudes ranged from 5 to 27 m with an average value of 18 m. The sole work surface encroachment, 6 m, was

Plate 17. 6.9-m Pile-Up on Tern Island in Early July 1984 (60-120 cm thick ice blocks encroached 14 m onto gravel bag armor during 20- to 25-kt westerly storm.)

Plate 18. Detailed View of 6.9-m Pile-Up on Tern Island in Early July 1984

Plate 19. 7.6-m Pile-Up on Mukluk Island in Late November 1983 (60-65 cm thick ice blocks piled up at waterline during 30- to 35-kt easterly storm.)

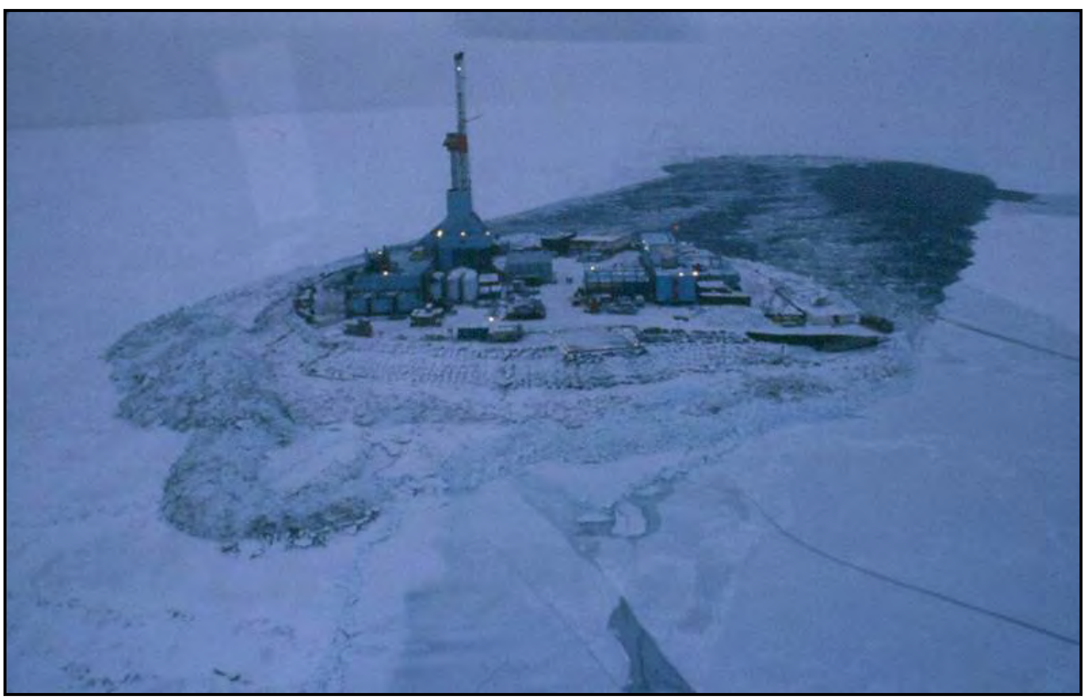


Plate 20. 11.5-m Pile-Up on Sandpiper Island in Mid-November 1985 (50-cm thick ice blocks encroached 5 m onto gravel bag armor during 30- to 40-kt westerly storm.)

Plate 21. 14.3-m Pile-Up on Northstar Production Island in Late January 2008 (60-90 cm thick ice blocks encroached 27 m onto concrete mat during 30- to 40-kt westerly storm; Coastal Frontiers, 2009.)

recorded on Northstar Island (an exploration facility located approximately 5 nm west northwest of the current Northstar Production Island) in 1985.

Plate 22 illustrates a 9.1-m pile-up that occurred on Northstar Production Island in early July 2002. Ice blocks up to 1.5 m thick encroached 27 m onto the concrete mat slope protection system under the influence of 10- to 20-kt (5- to 10-m/s) westerly winds. As in the case of the January 2008 freeze-up event, the advancing ice was halted by the sheetpile wall at the perimeter of the work surface.

4.3 Pile-Up Events on Sheltered Natural Shorelines (Appendix C)

Ice pile-up and ride-up have been monitored on the natural shorelines of the Alaskan Beaufort Sea between Barter Island and Point Barrow. With the exception of the region that lies east of Collinson Point in Camden Bay, the entire mainland coast in this extended stretch may be classified as sheltered. While some portions are protected by barrier islands, others are fronted by wide areas of shallow water and/or punctuated by bays and headlands that cause the ice to become landfast (*i.e.*, confined) within one to two months after the

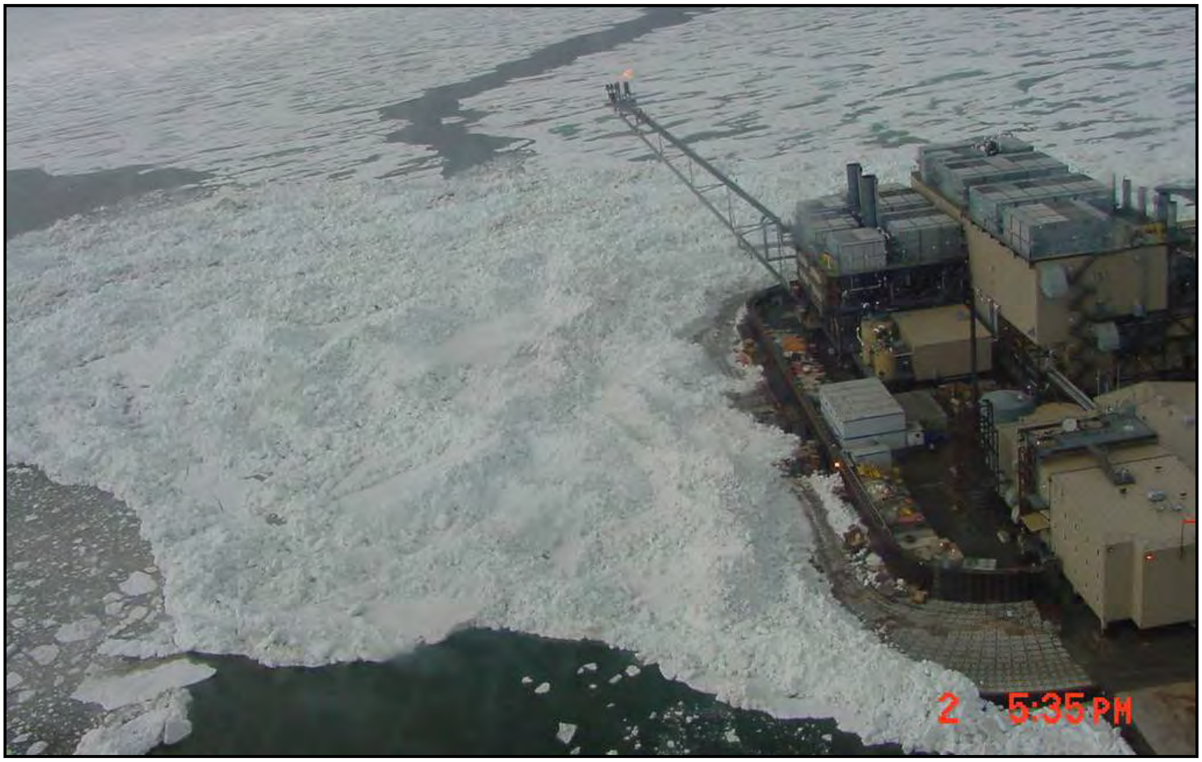


Plate 22. 9.1-m Pile-Up on Northstar Prod. Is. in Early July 2002 (1.0-1.5 m thick ice blocks encroached 27 m onto concrete mat during 10- to 20-kt westerly wind.)

initiation of freeze-up. The only barrier islands that may be classified as sheltered consist of No Name Island (which lies south of Cross Island), and the islands from Stump to Bertoncini that constitute the eastern portion of the Jones Island chain.

Twenty two pile-up events (fourteen pure pile-ups and eight combinations of pile-up and ride-up) were noted on sheltered natural shorelines during eight freeze-up seasons between 1979 and 2011. The pile-ups were caused by sixteen easterly and three westerly storms. Although the period of occurrence extended from October 6 to December 7, only two of the pile-ups took place after November 16.

For the eighteen pile-ups for which data are available, the encroachments varied from negligible to 30 m while averaging 9 m. Seven of the pile-ups occurred at coastal bluffs, with a maximum measured encroachment of 10 m.

Eight pile-ups (two pure pile-ups and six combinations of pile-up and ride-up) were recorded on sheltered natural shorelines during the four consecutive break-up seasons from 1981 through 1984. All of the events occurred in a 15-day window commencing on June 26 and ending on July 10. Five of pile-ups resulted from easterly storms, and two from westerly storms.

For the six pile-ups for which data are available, the encroachments ranged from 3 to 34 m. The average value was 11 m. In two cases, the pile-ups overtopped coastal bluffs (both of which were located near Pogik Bay). One of these events, which occurred in late June, 1983, is shown in Plates 23 and 24. Ice blocks up to 75 cm thick created a 3-m pile-up that overtopped a 2-m bluff and encroached 12 m onto the tundra. The driving force was a 15- to 20-kt (8- to 10 m/s) northeasterly wind.

4.4 Pile-Up Events on Exposed Natural Shorelines (Appendix D)

Exposed natural shorelines in the Alaskan Beaufort Sea are found on all of the barrier islands except No Name and the eastern portion of the Jones Island chain (as indicated in Section 4.3), and on that portion of the mainland coast located to the east of Collinson Point.

Forty pile-ups (twenty six pure pile-ups and fourteen combinations of pile-up and ride-up) were observed on exposed natural shorelines during eight freeze-up seasons between 1979 and 2011, including eight in 2011 alone. All but three of the events took place on barrier islands, with the remainder occurring on the mainland shore. The pile-ups resulted from twenty two storms, consisting of twelve easterlies and ten westerlies that took place between September 24 and January 18.

Encroachment data are available for thirty seven of the forty pile-up events. Six of the pile-ups were limited to the region seaward of the waterline, while the remainder produced encroachments that varied from 3 to 36 m. The average encroachment was 12 m.

Representative examples are displayed in Plates 25 and 26. The former shows a 1.7-m pile-up that encroached 6 m onto the north shore of Thetis Island in late September 1980, while the latter shows a much larger, 10.6-m pile-up that encroached 36 m across the entire width of Spy Island in early December 1982.

Two recent pile-ups observed on the west end of Narwhal Island during the 2011 freeze-up season are illustrated in Plate 27. The first, which formed on October 31 in response to a 20- to 25-kt (10- to 13-m/s) southwesterly storm, attained a height of 4 m and encroached 5 m onto the beach. The second, which followed on November 13 during a 15-to 25-kt (8 to 13-m/s) westerly storm, was characterized by a height of 7.6 m and encroachment distance of 20 m.

Plate 23. 3-m Pile-Up near Pogik Bay in Late June 1983 (45-75cm thick ice blocks overtopped 2-m bluff and encroached 12 m onto tundra during a 15- to 20-kt westerly storm.)

Plate 24. Detailed View of 3-m Pile-Up near Pogik Bay in Late June 1983

Plate 25. 1.7-m Shoreline Pile-Up on Thetis Island in Late September 1980 (8-10 cm thick ice blocks encroached 6 m onto beach during 15- to 20-kt westerly storm.)

Plate 26. 10.6-m Pile-Up on Spy Island in Early December 1982 (60-90 cm thick ice blocks encroached 36 m across full width of island during 20- to 25-kt easterly storm.)

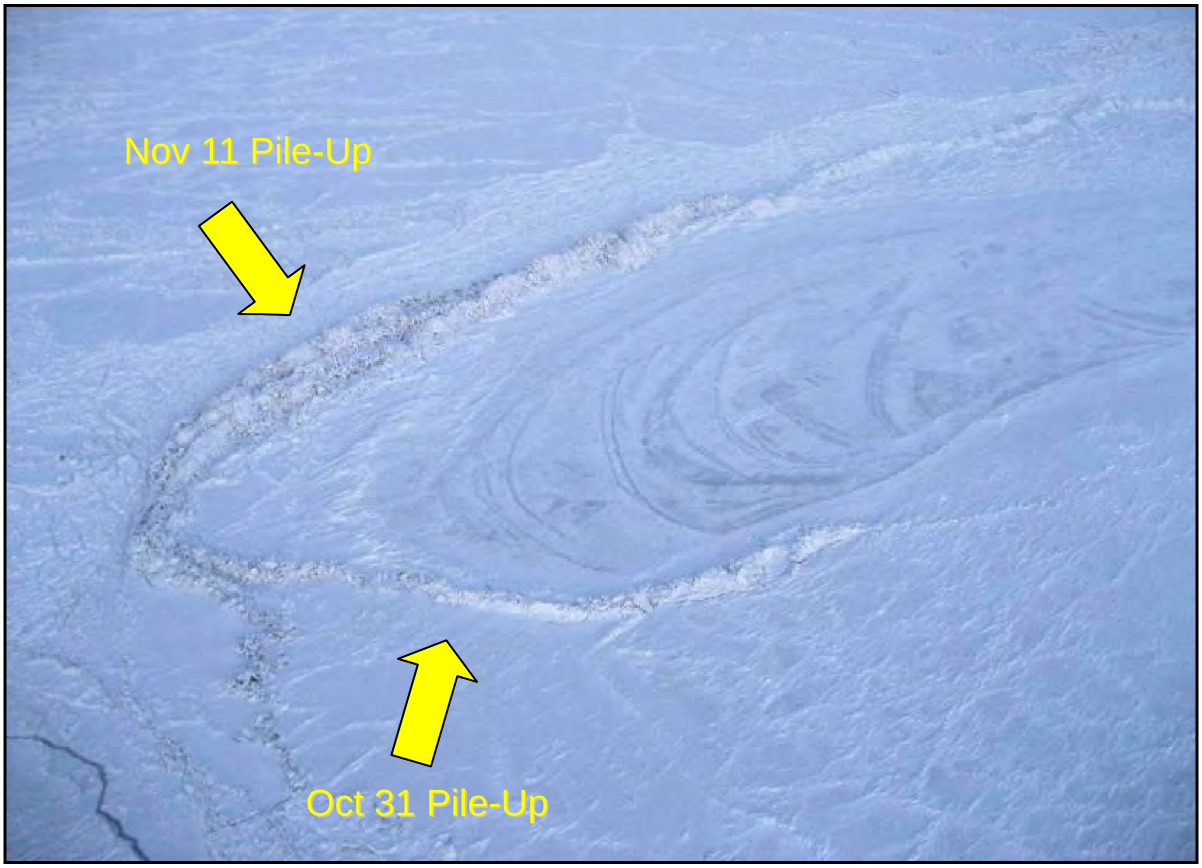


Plate 27. 4-m Pile-Up that Formed on Southwest Side of Narwhal Is. on Oct. 31, 2011, and 7.6-m Pile-Up that Formed on Northwest Side on Nov. 13, 2011 (20-cm thick ice blocks encroached 4 m during 20- to 25-kt southwesterly storm in October; 30-cm thick ice blocks encroached 20 m during 15- to 25-kt westerly storm in November.)

Five pile-ups (all combinations of pile-up and ride-up) were observed on exposed natural shorelines during the 1981, ’82, ’84, and ‘85 break-up seasons. The pile-ups occurred between June 29 and July 10 in response to three easterly storms and one westerly storm.

Three of the five pile-ups took place on barrier islands and produced no encroachment. The other two events, which occurred on the mainland shore in Camden Bay, caused encroachments of 18 and 45 m. The average value was 13 m.

4.5 Ride-Up Events on Sheltered Natural Shorelines (Appendix E)

Twelve ride-up events (four pure ride-ups and eight combinations of ride-up and pile-up) were documented on sheltered natural shorelines during the 1979 through 1984 freeze-up seasons. The ride-ups were caused by ten easterly and two westerly storms, with the earliest occurring on September 22 and the latest on December 7.

With the exception of two events on barrier islands, the ride-ups took place on the mainland shore. The encroachments ranged from a minimum of 6 m to a maximum of 75 m while averaging 32 m.

Eighteen ride-up events (twelve pure ride-ups and six combinations of ride-up and pile-up) were observed during the five consecutive break-up seasons from 1981 through 1985. Nine were associated with easterly storms, while four were associated with westerlies. The period of occurrence was limited to two and a half weeks: June 24 through July 10.

Eight of the break-up events took place on barrier islands, while ten took place on the mainland shore. The encroachment distances varied from 9 to 30 m, while the ice thickness varied from 50 cm to 1.5 m. The average encroachment was 17 m.

4.6 Ride-Up Events on Exposed Natural Shorelines (Appendix F)

Twenty ride-up events (six pure ride-ups and fourteen combinations of ride-up and ride-up) were noted on exposed natural shorelines during the six freeze-up seasons starting in 1979 and ending in 1984. The events resulted from eight easterly and six westerly storms. The exposure window was virtually identical to that for ride-up on protected shorelines, with the earliest occurrence on September 24 and the latest on December 5.

Seventeen of the ride-ups were located on barrier islands, with the remaining three on the mainland shore. The encroachments ranged from 6 to 76 m and averaged 29 m.

During the five break-up seasons from 1981 through 1985, twenty five ride-up events (twenty pure ride-ups and five combinations of ride-up and ride-up) were documented on exposed natural shorelines. All but three of these occurred on barrier islands. Of the twelve storms that generated the ride-ups, eight were easterlies and four were westerlies. As in the case of freeze-up, the period of occurrence closely resembled that for ride-up on protected shorelines: June 25 through July 11.

The break-up events produced encroachments that varied from 3 to 45 m. The average value was 15 m. The ice thickness ranged from 30 cm to 1.5 m. An extensive ride-up that extended 2 nm (3.7 km) along the shoreline of Camden Bay is shown in Plate 28. The ride-up occurred on June 27, 1983, in response to a 15- to 20-kt easterly storm. The maximum encroachment was 43 m.

Plate 28. Ride-Up in Camden Bay in Late June 1983 (60-90 cm thick ice sheet encroached 43 m onto beach along 2-nm stretch during 15- to 20-kt easterly storm.)

4.7 Overview of Historical Events

An overview of the historical pile-up and ride-up data tabulated in Appendices A through F and summarized in Tables 2 and 3 is presented below:

Exposure

- During both freeze-up and break-up, pile-up and ride-up events capable of producing ice encroachment tend to occur more frequently at exposed sites than sheltered sites (whether man-made facilities or natural shorelines).
- The encroachments that result from pile-up and ride-up events tend to be greater at exposed sites than sheltered sites (whether man-made facilities or natural shorelines).

Nature of Site

- Natural shorelines are subject to encroachment from ice pile-up, ice ride-up, and combinations of the two. Historically, the largest encroachments have resulted from events that involve ride-up during freeze-up. The maximum recorded value is 76 m.

- Man-made facilities are subject to encroachment from ice pile-up and combinations of pile-up and ride-up. Encroachment tends not to occur from pure ride-up, however, due the relatively steep, rough side slopes that typically are present. Although the maximum historical encroachment on a man-made facility, 30 m, occurred during freeze-up, values nearly as large have been recorded during break-up.

Type of Event

- While the number of events can vary appreciably from year to year, pile-ups and ride-ups at natural shorelines tend to occur with equal frequency over the long term.
- Most pile-up events take place during freeze-up, when the ice is relatively thin and brittle. Conversely, the majority of ride-up events take place during break-up, when the ice is thick and ductile.

Seasonality and Storms

- Of the 173 pile-up, ride-up, and combination events that are summarized in Table 3, about 60% (108 events) occurred during freeze-up and 40% (65 events) during break-up.
- The 173 ice events were caused by 74 different storms with sustained wind speeds that always equaled or exceeded 15 kt (8 m/s) and typically equaled or exceeded 20 kt (10 m/s).
- In most cases, the storms were preceded or accompanied by changes in wind direction that caused the ice to lose confinement.
- During freeze-up, the storms that triggered ice events reflected a near-equal split between easterlies and westerlies (25 east vs. 21 west). During break-up, easterly storms predominated (18 east vs. 10 west).

5. 2011 PILE-UP AND RIDE-UP EVENTS

To gain additional insight into the factors that cause encroachment, the wind and ice conditions that prevailed during the 2011 break-up and freeze-up seasons were monitored using publicly-available data while pile-up and ride-up events were investigated on an opportunistic basis. Wind data acquired at the Prudhoe Bay West Dock Seawater Treatment Plant (STP) were downloaded from the National Ocean Service website (National Ocean Service, 2012). The ice conditions were monitored with the aid of MODIS (Moderate Resolution Imaging Spectro-radiometer) satellite imagery (NASA, 2012) and ice charts produced by the National Ice Center (2012).

During break-up, opportunistic monitoring of encroachment events was undertaken by contacting the operators of coastal and offshore facilities after significant storm events had taken place. As a result, the monitoring was limited to man-made facilities and did not extend to natural shorelines. During freeze-up, the information provided by facility operators was augmented with aerial observations made in November 2011 and February 2012 while conducting the 2011-12 Freeze-Up Study of the Alaskan Beaufort and Chukchi Seas (Coastal Frontiers and Vaudrey, in progress). The flights provided an opportunity to observe natural shorelines as well as man-made facilities.

5.1 Break-Up

Wind data for the months of June and July, consisting of the sustained speed and direction, are plotted in Figures 4 and 5, while ice charts bracketing the break-up period are provided in Figures 6 and 7. Salient points are summarized below:

June 2011 (Figure 4)

- Easterly winds predominated, occurring 94% of the time.
- Easterly storms with sustained wind speeds exceeding 20 kt (10 m/s) occurred on eight occasions. The two most severe storms, with maximum sustained wind speeds of 34 kt (18 m/s), took place during the first ten days of the month.
- No westerly storms were recorded. The maximum sustained westerly wind speed was limited to 16 kt.
- Significant changes in wind direction, from strong easterly to strong westerly or vice-versa, did not occur.
- Break-up in the nearshore region of the Alaskan Beaufort Sea occurred during the last week June and first week in July, during which time the ice concentration decreased from greater than 90% to less than 10% (Figures 6 and 7).

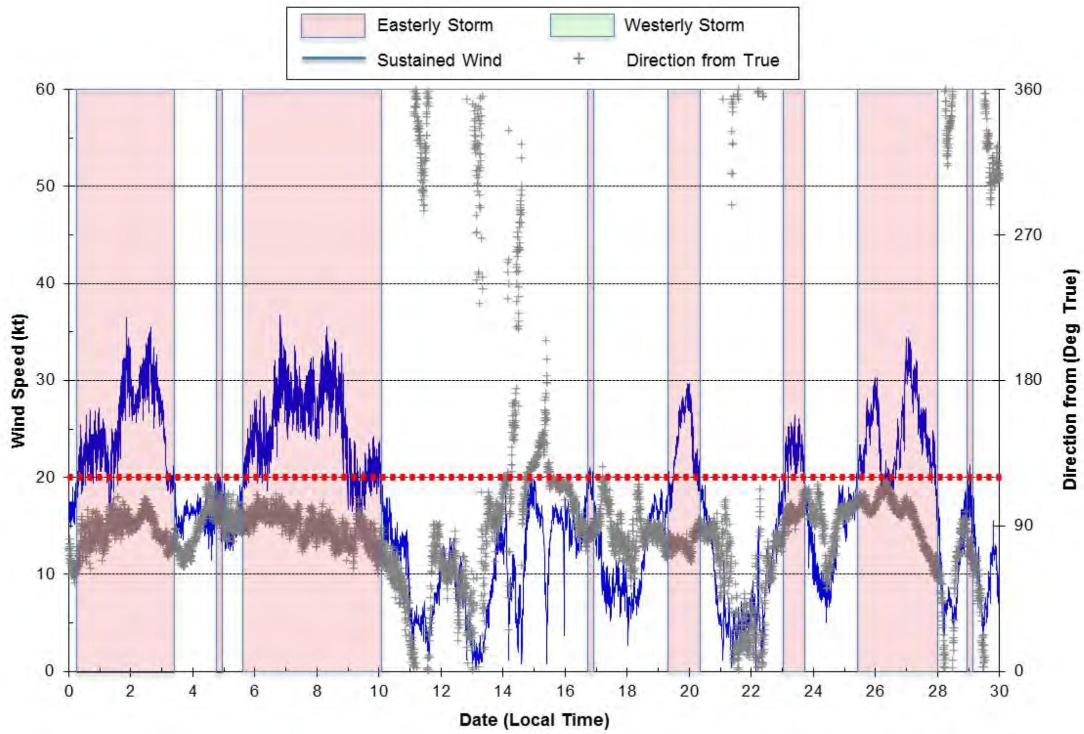


Figure 4. Wind Data Recorded at West Dock STP in June 2011

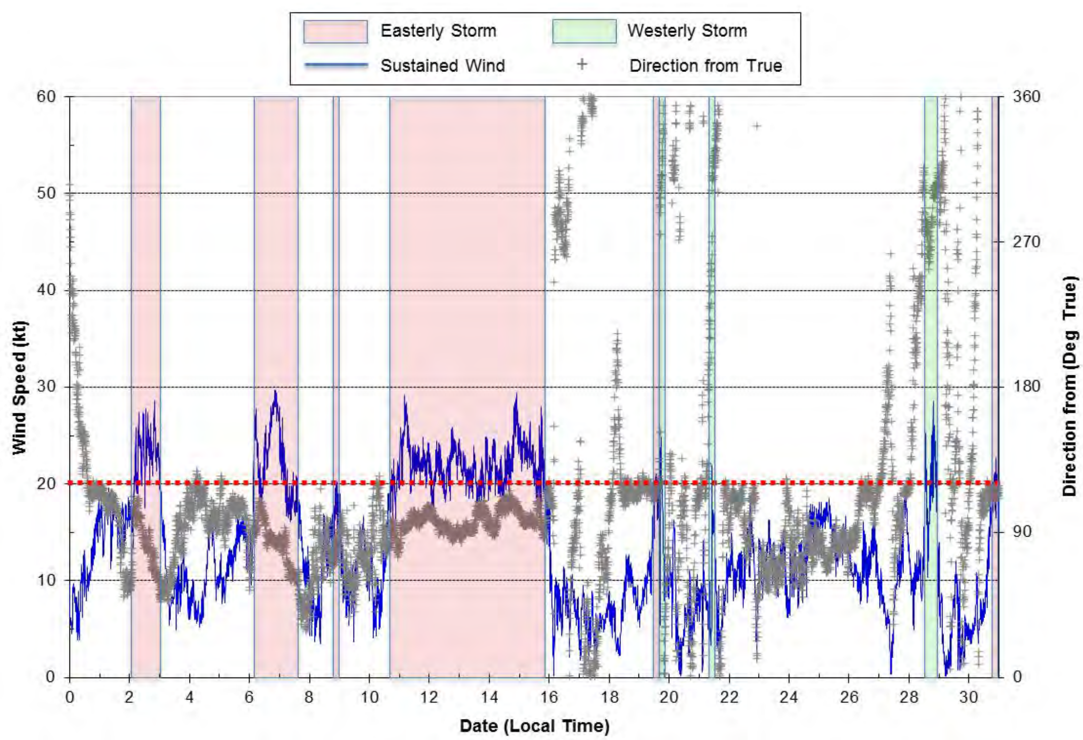
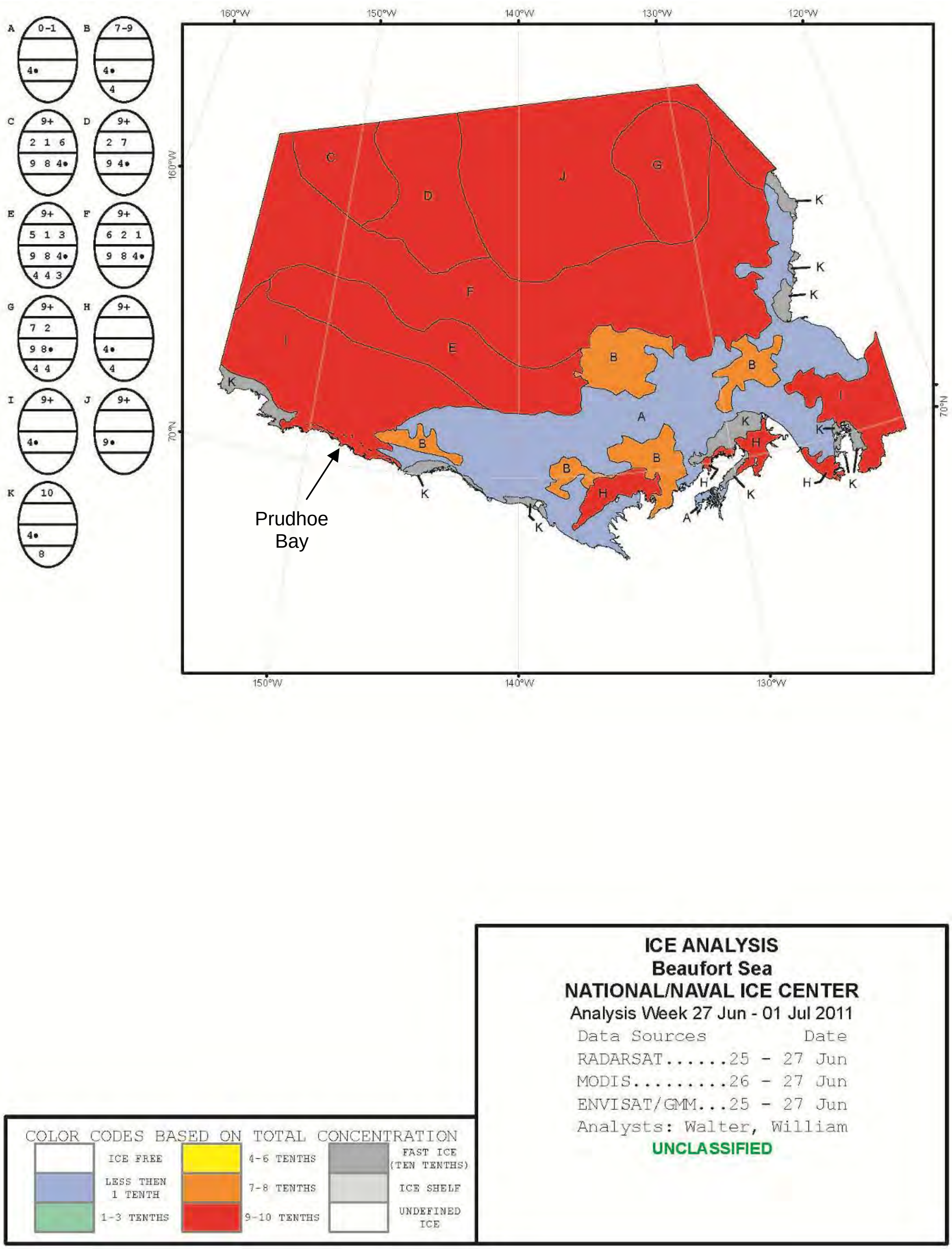
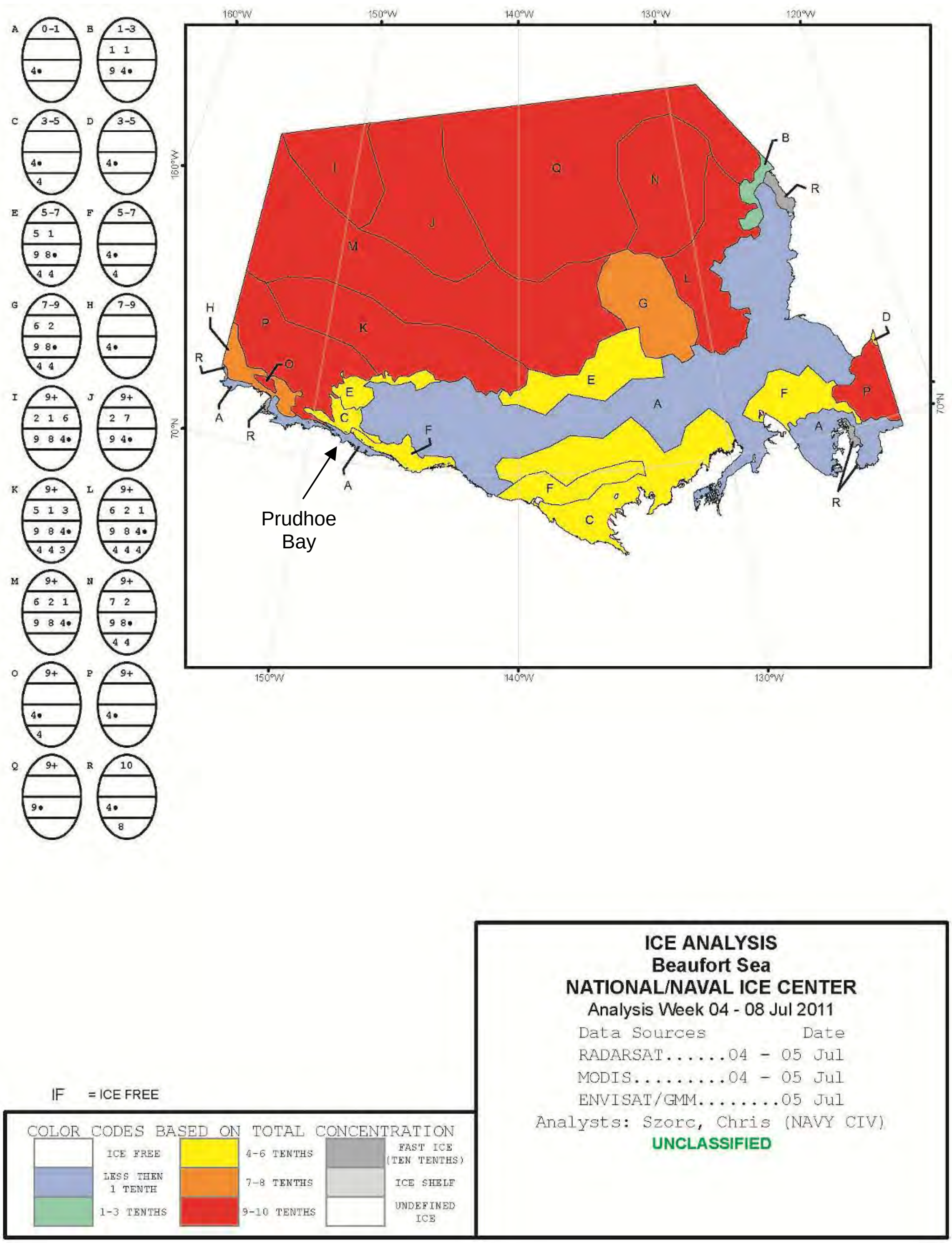


Figure 5. Wind Data Recorded at West Dock STP in July 2011



After: National Ice Center, 2012

Figure 6. Beaufort Sea Ice Conditions in Late June 2011



After: National Ice Center, 2012

Figure 7. Beaufort Sea Ice Conditions in Early July 2011

July 2011 (Figure 5)

- Easterly winds predominated, occurring 90% of the time.
- Easterly storms occurred on six occasions. The three most severe events, with maximum sustained wind speeds approaching 30 kt (15 m/s), took place during the first half of the month.
- Westerly storms occurred on three occasions during the second half of the month. The maximum sustained westerly wind speed of 29 kt (15 m/s) occurred on July 29.
- The only significant change in wind direction was recorded on the 20th, when a brief easterly storm with a maximum sustained speed of 21 kt (11 m/s) was followed by a brief westerly that peaked at 25 kt (13 m/s).

No pile-up events were reported on man-made facilities during break-up. This outcome may be explained in large part by the absence of changes in wind direction capable of causing the ice to lose confinement until long after the occurrence of break-up. Also noteworthy is the fact that the most two severe storms, with maximum wind speeds in excess of 30 kt (15 m/s), took place in early June when the ice was comparatively strong and resistant to displacement.

5.2 Freeze-Up

Figures 8 through 11 portray the wind conditions that prevailed during the months of October, November, and December 2011, and January 2012. The ice conditions at the time of freeze-up are shown in Figures 12 and 13. Key points are as follows:

October 2011 (Figure 8)

- Ice began to form in the sheltered, nearshore waters of the Alaskan Beaufort Sea in mid-October.
- Freeze-up in the nearshore region occurred at the end of October (Figure 12).
- Easterly winds predominated, occurring 77% of the time.
- Easterly storms with sustained wind speeds exceeding 20 kt (10 m/s) occurred on eight occasions. The two most severe storms, with maximum sustained wind speeds of 47 and 52 kt (24 and 27 m/s), peaked on the 15th and 25th, respectively.
- A brief southwesterly storm occurred on the morning of the 31st, followed by a brief westerly storm in the evening. The maximum sustained westerly wind speed, 28 kt (14 m/s), was associated with the first of these two events.

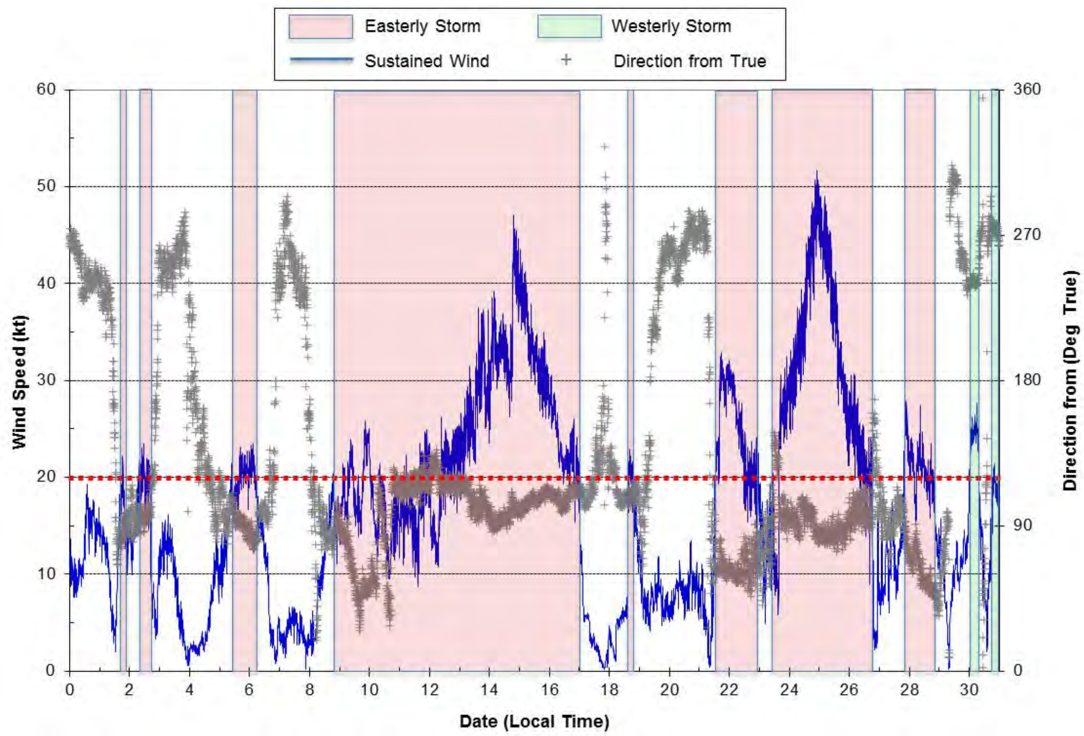


Figure 8. Wind Data Recorded at West Dock STP in October 2011

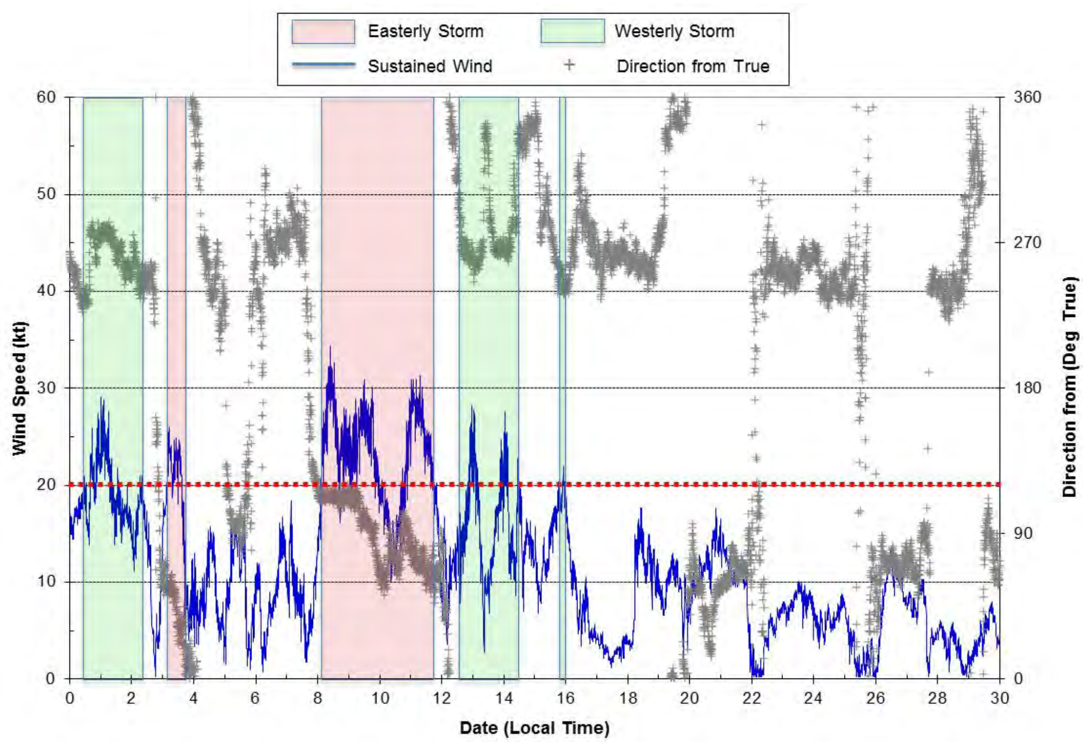


Figure 9. Wind Data Recorded at West Dock STP in November 2011

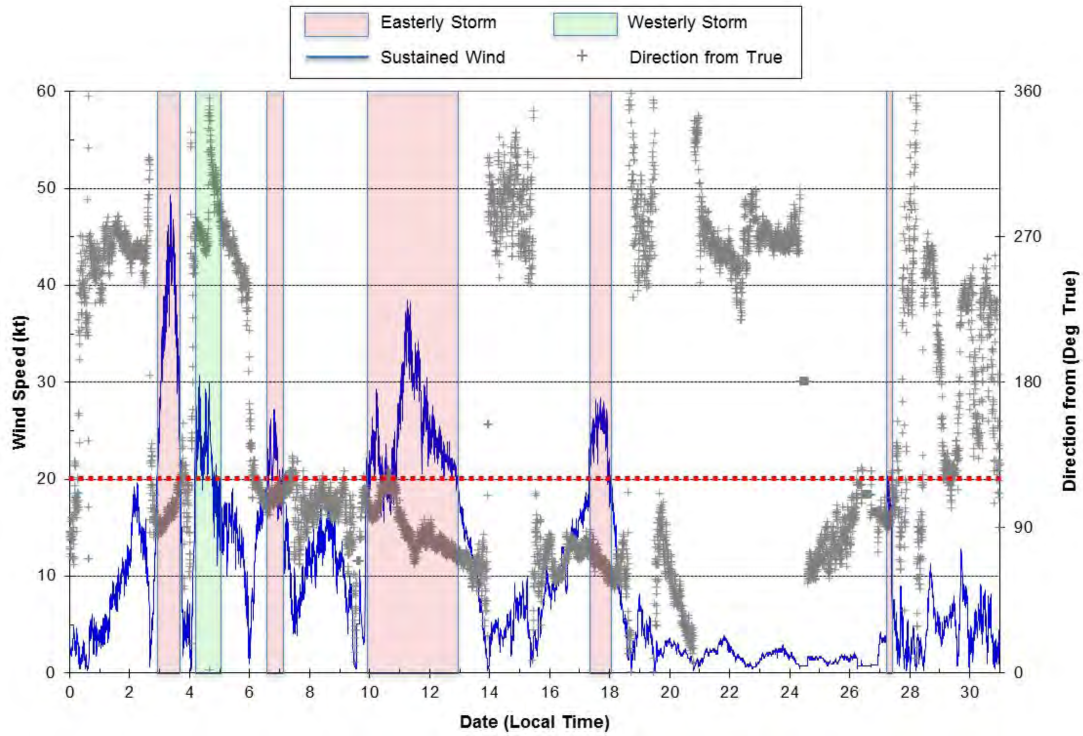


Figure 10. Wind Data Recorded at West Dock STP in December 2011

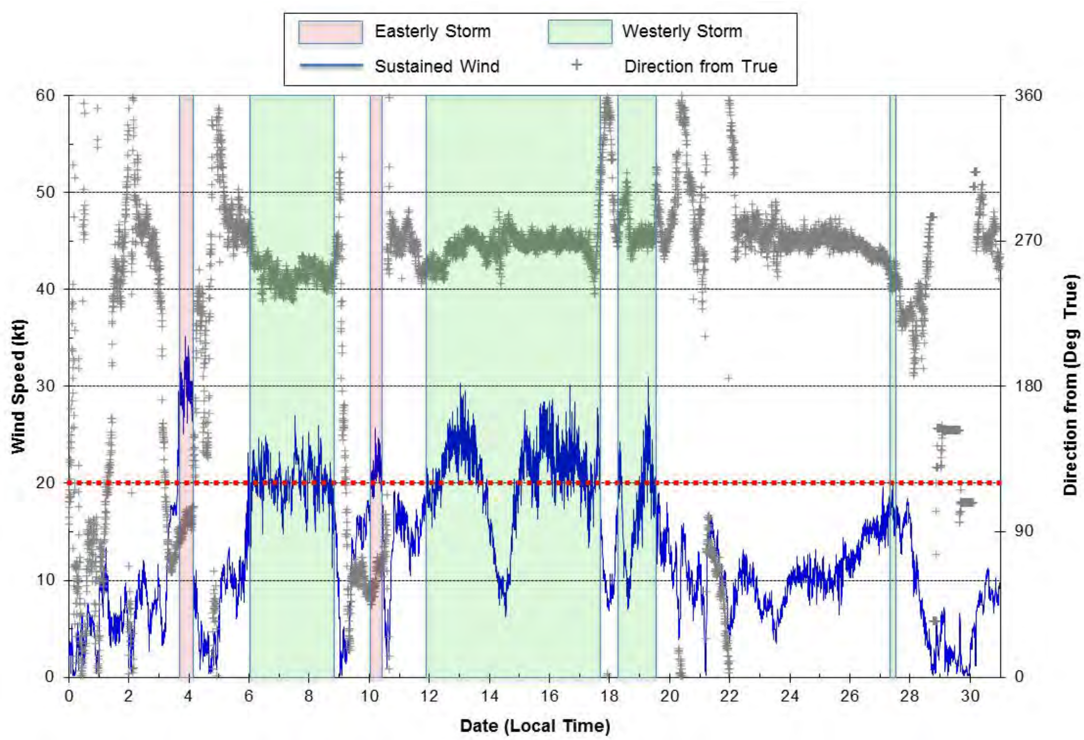
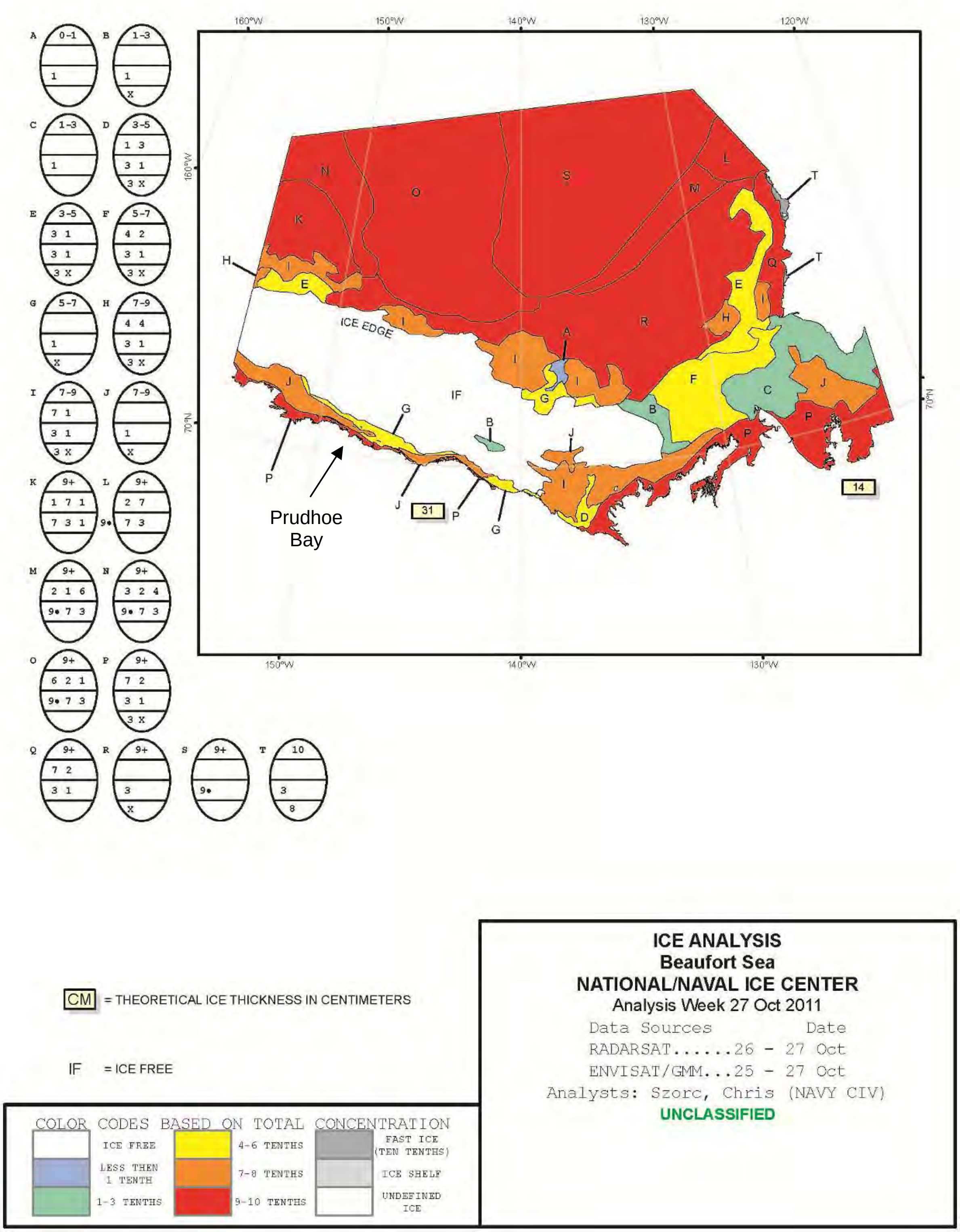
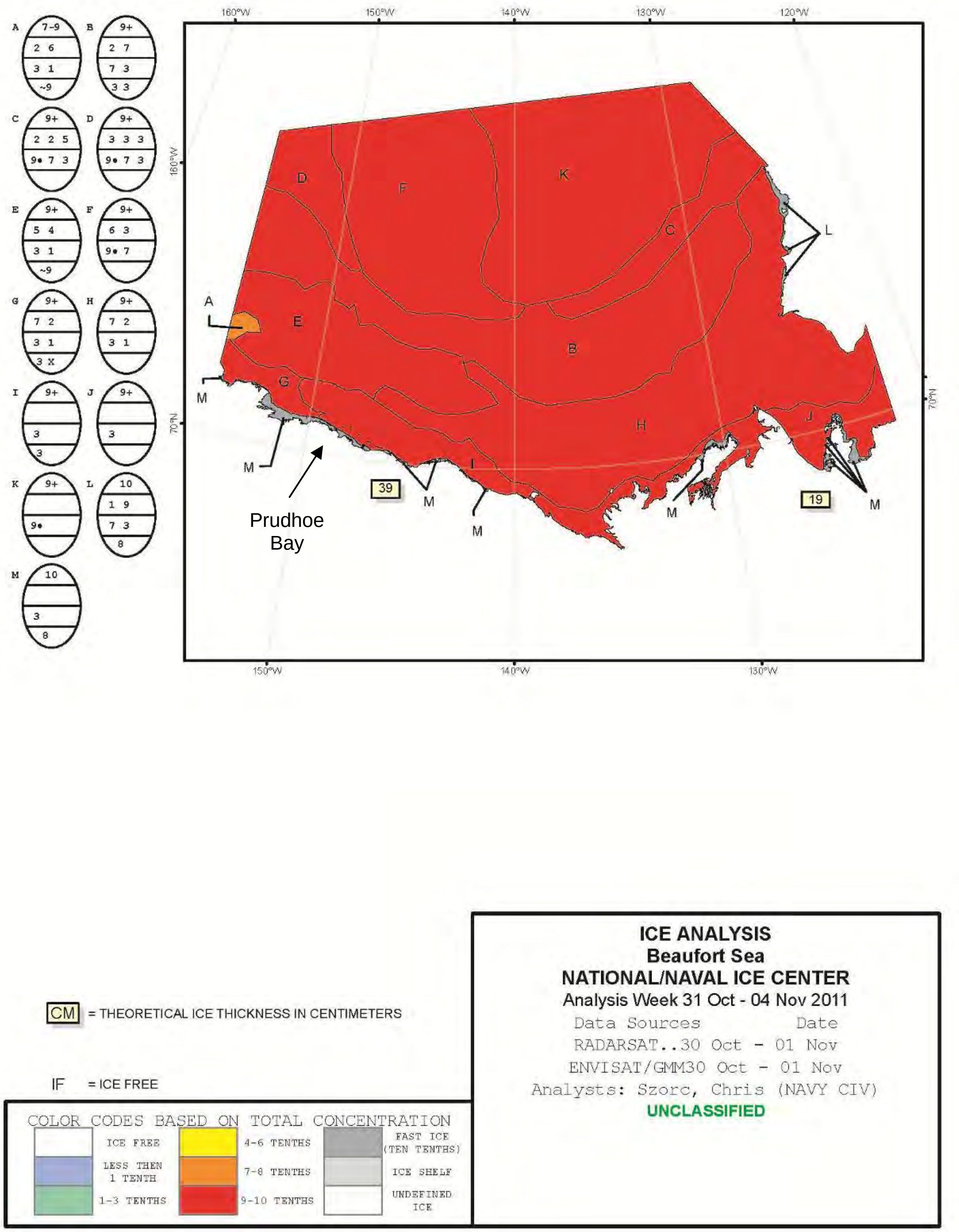


Figure 11. Wind Data Recorded at West Dock STP in January 2012



After: National Ice Center, 2012

Figure 12. Beaufort Sea Ice Conditions in Late October 2011



After: National Ice Center, 2012

Figure 13. Beaufort Sea Ice Conditions in early November 2011

- A significant change in wind direction took place at the end of the month, when an easterly storm on the 28th and 29th was followed by the aforementioned southwesterly storm on the morning of the 31st.

November 2011 (Figure 9)

- Freeze-up in the offshore portion of the Alaskan Beaufort Sea occurred at the beginning of November (Figure 13).
- Westerly winds predominated, occurring 61% of the time.
- All of the storm activity, consisting of three westerlies and two easterlies, took place during the first half of the month. The most severe westerly, with a maximum sustained wind speed of 29 kt (15 m/s), peaked on the 2nd, while the most severe easterly, with a maximum sustained wind speed of 34 kt (18 m/s), peaked on the 9th.
- Significant changes in wind direction occurred on two occasions: (1) the westerly storm that peaked on the 2nd was followed by an easterly storm on the 4th, and (2) the easterly storm that peaked on the 9th and continued until the 12th was followed by a westerly storm on the 13th.

December 2011 (Figure 10)

- Easterly winds predominated, occurring 60% of the time.
- Easterly storms occurred on five occasions. The most severe event, with a maximum sustained wind speed of 49 kt (25 m/s), took place on the 3rd and 4th.
- The sole westerly storm occurred on the 5th and 6th. The maximum sustained wind speed was 31 kt (16 m/s).
- Significant changes in wind direction took place on both ends of the westerly storm, which was preceded by the severe easterly event on the 3rd and 4th and followed by another easterly on the 7th and 8th.

January 2012 (Figure 11)

- Westerly winds predominated, occurring 79% of the time.
- Westerly storms occurred on four occasions. The most severe event peaked at 31 kt (16 m/s) on the 19th and 20th.
- Easterly storms took place on the 4th through 5th and on the 11th. The maximum sustained wind speed of 35 kt (18 m/s) was associated with the first of these two events.

- Two significant changes in wind direction occurred in response to a three-storm sequence: the easterly on the 4th and 5th; a westerly on the 6th through 9th, and the second easterly on the 11th.

Ten ice pile-ups were observed during freeze-up reconnaissance flights conducted in late November 2011 and early February 2012. As shown in Table 4, one was located on a sheltered natural shoreline (No Name Island), eight on exposed barrier islands and shoals, and one on an exposed man-made facility (Northstar Production Island). The maximum pile-up elevation, 8 m, was found on Pole Island, while the maximum encroachment of 20 m and maximum alongshore extent of 1,200 m occurred on both Pole and Narwhal Islands. Two of the pile-ups on Narwhal Island are shown in Plate 27, while the pile-up on Northstar Production Island is shown in Plate 29. Each of the ten events is included in the appropriate tabulation in the Appendices.

Table 4. Ice Pile-Up Events that Occurred during 2011 Freeze-Up Season

Location	Date	Ice Block Thickness (cm)	Max. Pile-Up Elevation[1] (m)	Encroach-ment (m)	Length Alongshore (m)
No Name Island[2]	10/31/11	20	2	10	500
Narwhal Island[3]	10/31/11	20	4	5	300
Narwhal Shoal[3]	10/31/11	20	4	0	200
Narwhal Shoal[3]	10/31/11	20	3	3	200
Jeanette Island[3]	10/31/11	20	5	10	300
Karluk Island[3]	10/31/11	20	2	0	300
Narwhal Island[3]	11/13/11	20	7.6	20	1,200
Pole Island[3]	11/13/11	30	6	0	1,200
Pole Island[3]	11/13/11	30	8	20	1,100
Northstar Prod. Is.[4]	11/13/11	30	4	5	200

Notes:
1 Vertical datum is MLLW
2 Sheltered natural shoreline
3 Exposed natural shoreline
4 Exposed man-made facility

Plate 29. 4-m Pile-Up on Northstar Production Island in mid-November 2011 (30-cm thick ice blocks encroached 5 m onto concrete mat during 15- to 25-kt westerly storm)

Based on the timing of the aerial observations, the orientations of the pile-ups, and the thicknesses of the ice blocks, six of the pile-ups appear to have formed on October 31 in response to a two-storm sequence: an easterly storm on the 27th and 28th followed by a southwesterly on the 31st that caused the ice to lose confinement (Figure 8). The remaining four pile-ups, which were composed of thicker blocks and tended to be larger, appear to have formed two weeks later under similar circumstances: an easterly on November 9-12 followed by a westerly on November 13-15 (Figure 9).

It is noteworthy that the three-storm sequence in early December 2011 (Figure 10) caused two significant changes in wind direction but failed to initiate pile-up or ride-up events. A possible explanation is that the first storm, an easterly with sustained winds as high as 49 kt (25 m/s), induced rubble formation and grounding off north-facing shorelines. The grounded ice blocks, estimated to be 60 cm thick, were sufficiently strong to resist displacement by the two storms that followed. This situation differs from those in late October and mid-November, when the ice was much thinner (20-30 cm) and therefore more susceptible to displacement during storm events.

6. STATISTICAL ANALYSIS OF PILE-UP HEIGHT

Ice encroachment represents a key design parameter for coastal and offshore facilities in the Alaskan Beaufort Sea, including man-made islands, coastal pads, and pipeline shore crossings. After summarizing prior attempts to quantify encroachment and the related processes of ridge and rubble formation, this section presents a statistical method for estimating pile-up heights on man-made structures and natural shorelines from the historical data contained in Appendices A through F. The next section (Section 7) illustrates how pile-up heights can be used to predict encroachment.

In their overview of ice pile-up and ride-up observations, Kovacs and Sodhi (1988) include a brief review of studies conducted in the 1970s and 1980s. These studies ranged from the early theoretical investigation of Parmerter and Coon (1973), who used an energy method for modeling ridge building processes, to later model tests by Timco and Sayed (1986), who performed experiments in the National Research Council ice tank in Ottawa. Another noteworthy investigation was performed by Croasdale (1980), who used a two-dimensional failure analysis of an ice sheet moving against a wide, sloping structure.

More recently, a number of numerical simulations (Barker, Timco, and Sayed, 2001; Timco and Barker, 2002; Barker and Croasdale, 2004; Paavilainen, *et al*., 2011) and model ice tests have been undertaken to explain ice rubble processes and predict the pile-up heights that occur when sea ice impacts the coast. Unfortunately, these numerical and physical models have been unable to replicate actual ice behavior on a consistent basis – an outcome that probably stems from complex interactions between the parameters presented in Table 1 (driving forces, ice properties, and shoreline characteristics). As Kovacs and Sodhi (1988) concluded more than two decades ago, "…there is no way to predict where an onshore ice movement event will occur, or, if one is expected at a particular site, whether it will result in ice piling on the beach or in ice being driven far inland."

6.1 Pile-Ups on Man-Made Facilities

As discussed in Section 4, all of the significant ice encroachment events observed on man-made facilities to date have resulted either from pure pile-ups or combinations of pile-up and ride-up in which pile-up has predominated. In consequence, the prediction of encroachment on such structures will be based on events that involve pile-ups -- a scenario illustrated schematically in Figure 14.

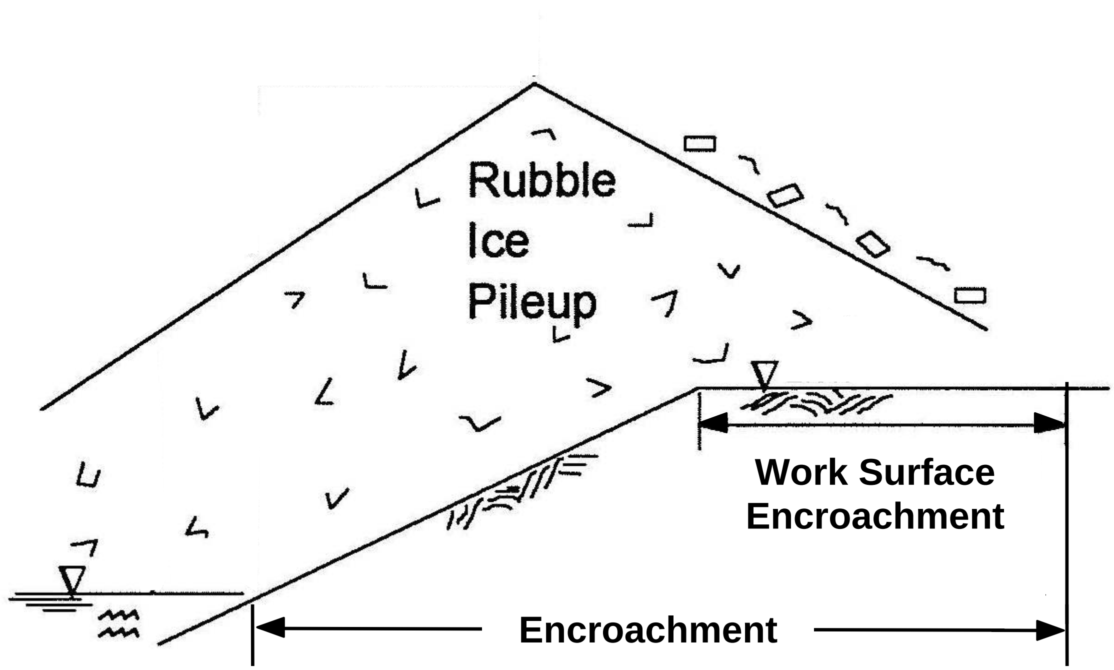


Figure 14. Schematic Representation of Encroachment Resulting from Ice Pile-Up

Because our present understanding of pile-up mechanics remains limited, the approach adopted for the prediction of encroachment involves a statistical extrapolation of historical pile-up characteristics. The method involves four primary steps:

1. Selecting historical pile-up events that occurred under similar circumstances from Appendix A (sheltered sites) or Appendix B (exposed sites);
2. Performing an extremal analysis to estimate the pile-up elevation associated with the desired return period;
3. Estimating the pile-up geometry; and
4. Computing the work surface encroachment based on the structure geometry.

In selecting historical pile-up events that occurred under similar circumstances (Step 1), relevant considerations include degree of exposure, water depth, geographic proximity, and side slope characteristics. The extremal analysis (Step 2) involves computing the cumulative probability of each event, plotting the pile-up elevation of each event on lognormal probability paper (Benjamin and Cornell, 1970), drawing a straight-line approximation through the data, and reading off the pile-up elevation for each cumulative probability that corresponds to a desired return period.

The cumulative probability (P_i) of each event is computed using Equation (1), while the return period (RP) is computed using Equation (2):

$$P_i\ (\%) = \frac{i}{(n+1)} \qquad (1)$$

where i = event rank (lowest to highest) in terms of pile-up height
n = number of events

$$RP\ (\text{yr}) = \frac{100}{(100 - P_i)} \qquad (2)$$

Sample computations of pile-up elevations on sheltered and exposed man-made facilities are provided below in Sections 6.1.1 and 6.1.2. Steps 3 and 4 of the predictive method outlined above (estimating the pile-up geometry and computing the work surface encroachment) will be addressed in Section 7.

6.1.1. Sheltered Man-Made Facilities

Eight representative events were selected from Appendix A to illustrate the derivation of ice pile-up elevation statistics for sheltered man-made facilities. The water depth, freeboard, and side slope at each of the facilities involved, as well as the storm date, ice block thickness, and ice pile-up elevation for each event, are presented in Table 5. Seven of the events occurred during freeze-up, from early October to mid-November, while one occurred during break-up in early July. The events are statistically independent because each was caused by a different storm.

Seven of the eight events selected for inclusion in Table 5 occurred at island sites, while one occurred at a facility on the mainland shore. The sites cover a wide geographic area, from the Oooguruk Offshore Drillsite (ODS) on the west to the Bullen Point Dew Site on the east. It should be noted that if the analysis of pile-up heights pertains to a particular project, the selection process should focus on similar types of facilities in relative proximity to that site to the extent permitted by the data available.

The pile-up elevations in Table 5 were used in concert with Equation (1) to derive the distribution data shown in Table 6. The results then were plotted on lognormal probability paper, and a straight-line approximation was drawn through the data (Figure 15). The cumulative probabilities corresponding to return periods of 10, 20, 50, and 100 years were computed using Equation (2), allowing a scale of return periods to be added to the probability plot. As shown in Figure 15, the predicted pile-up elevations range from 8 m above MLLW for the 10-year event (corresponding to a cumulative probability of 90%) to 11 m above MLLW for the 100-year event (corresponding to a cumulative probability of 99%).

Table 5. Representative Ice Pile-Up Events on Sheltered Man-Made Facilities

Facility	*Water Depth (m)*	*Freeboard (m)*	*Slope (H:V)*	*Event Date*	*Ice Block Thickness (cm)*	*Ice Pile-Up Elevation (m, MLLW)*
Oooguruk ODS	1.4	4.0	3:1	10/7/10	10-15	3.0
Endicott MPI	3.0	4.6	3:1	10/18/85	20-25	4.2
Duck 3 Is.	3.0	4.6	3:1	10/5/85	8-12	4.8
Bullen Pt.	1.8	1.5	20:1	11/11/73	30	5.3
Endicott MPI	3.0	4.6	3:1	10/9/85	12-15	5.8
BF-37 Is.	5.5	3.4	3:1	10/21/82	25	6.1
Tern Is.	6.7	4.3	3:1	7/7/84	60-120	6.8
Endeavor Is.	3.7	4.0	3:1	10/19/82	20	7.6

Table 6. Ice Pile-Up Distribution Data for Sheltered Man-Made Facilities

Pile-Up Event (i)	*Probability of Event (p_i, %)*	*Cumulative Probability of Event (P_i, %)*	*Pile-Up Elevation (m, MLLW)*
1	11.1	11.1	3.0
2	11.1	22.2	4.2
3	11.1	33.3	4.8
4	11.1	44.4	5.3
5	11.1	55.6	5.8
6	11.1	66.7	6.1
7	11.1	77.8	6.8
8	11.1	88.9	7.6

6.1.2. Exposed Man-Made Facilities

As shown in Table 7, fifteen representative events were chosen from Appendix B to illustrate the derivation of ice pile-up height statistics for exposed man-made facilities. Twelve of these occurred during freeze-up, from early October to late January, and three during break-up, in late June or early July. All of the events are statistically independent by virtue of their occurrence in response to different storms.

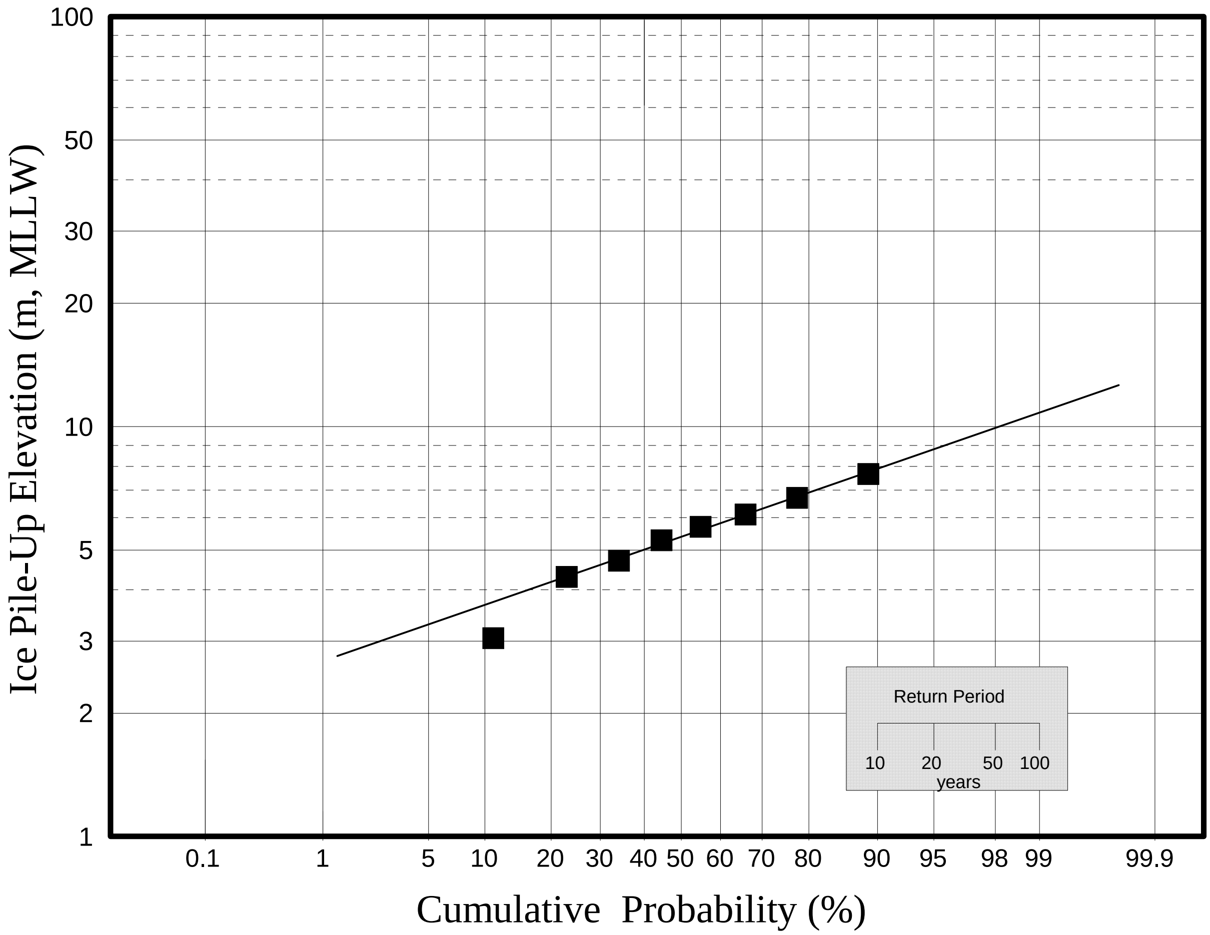


Figure 15. Predicted Ice Pile-Up Elevations on Sheltered Man-Made Facilities

With the exception of a pile-up on the Jeanette Island exploration pad, all of the events occurred on man-made exploration islands. Nine took place at the same location – the site occupied by Seal Island from 1982 until 1994, and Northstar Production Island from 2000 through the present. Mukluk Island was the westernmost site, while the Jeanette Island Pad was the easternmost.

The analysis of pile-up elevations was conducted in the manner described above for man-made facilities at sheltered locations, with the distribution data listed in Table 8 and plotted in Figure 16. The predicted elevations increase from 12 m above MLLW for the 10-year event to 20 m above MLLW for the 100-year event.

Table 7. Representative Ice Pile-Up Events on Exposed Man-Made Facilities

Facility	*Water Depth (m)*	*Freeboard (m)*	*Slope (H:V)*	*Event Date*	*Ice Block Thickness (cm)*	*Ice Pile-Up Elevation (m, MLLW)*
Seal Is.	11.9	7.0	3:1	10/9/83	10-15	2.6
Northstar Prod. I.	11.6	4.9	3:1+bench	11/4/09	25	3.0
Seal Is.	11.9	7.0	3:1	10/16/84	8-18	3.3
Mukluk Is.	14.6	6.4	3:1	10/9/83	10-20	3.7
Northstar Is.	13.7	6.1	3:1	10/18/85	20-25	3.8
Northstar Prod. I.	11.6	4.9	3:1+bench	11/13/11	30	5.0
Seal Is.	11.9	7.0	3:1	10/14/85	20-25	5.4
Jeanette Is. Pad	1.8	2.0	20:1	11/24/81	55-60	6.1
Seal Is.	11.9	7.0	3:1	10/19/82	20	6.1
Mukluk Is.	14.6	6.4	3:1	10/22/84	20-25	6.1
Sandpiper Is.	14.9	6.1	3:1	7/5/85	60-120	6.7
Northstar Prod. I.	11.6	4.9	3:1+bench	6/29/05	100-365	7.5
Northstar Prod. I.	11.6	4.9	3:1+bench	7/1/02	100-150	9.1
Sandpiper Is.	14.9	6.1	3:1	11/11/85	50	11.5
Northstar Prod. I.	11.6	4.9	3:1+bench	1/23/08	60-90	14.3

Table 8. Ice Pile-Up Distribution Data for Exposed Man-Made Facilities

Pile-Up (i)	*Probability of Event (p_i, %)*	*Cumulative Probability of Event (P_i, %)*	*Pile-Up Elevation (m, MLLW)*
1	6.25	6.2	2.6
2	6.25	12.5	3.0
3	6.25	18.8	3.3
4	6.25	25.0	3.7
5	6.25	31.2	3.8
6	6.25	37.5	5.0
7	6.25	43.8	5.4
8	6.25	50.0	6.1
9	6.25	56.2	6.1
10	6.25	62.5	6.1
11	6.25	68.8	6.7
12	6.25	75.0	7.5
13	6.25	81.2	9.1
14	6.25	87.5	11.5
15	6.25	93.8	14.3

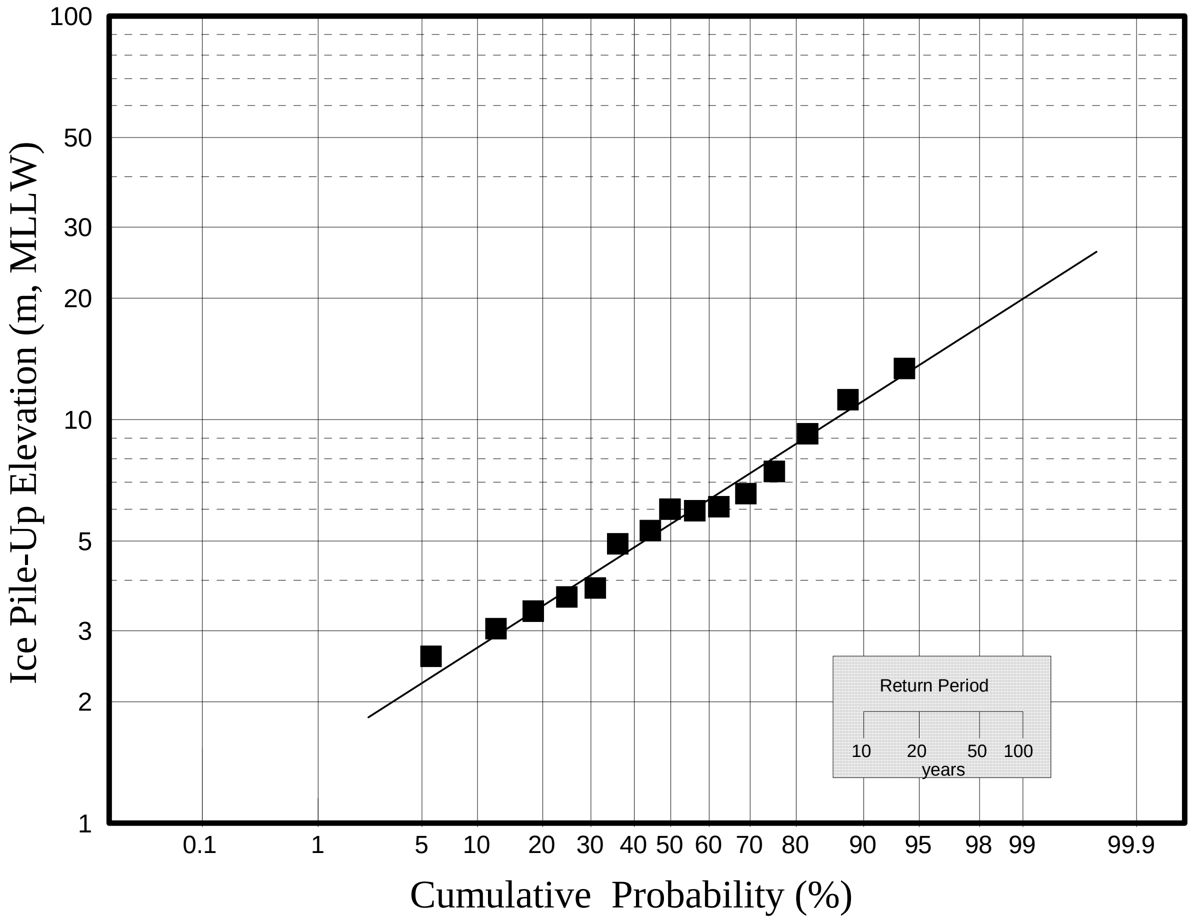


Figure 16. Predicted Ice Pile-Up Elevations on Exposed Man-Made Facilities

It should be noted that no man-made facilities have been constructed outside the landfast ice zone to date. If such facilities ultimately are installed, they will remain susceptible to ice pile-up and possible encroachment during the entire winter ice season.

6.2 Pile-Ups on Natural Shorelines

As explained at the outset of Section 4, natural shorelines are subject to encroachment from pile-up, ride-up, and combinations of the two. Pile-up elevations on natural shorelines can be predicted using the method outlined above for man-made facilities (Section 6.1) in conjunction with the historical data provided in Appendices C and D. The results then can be used to compute encroachment (Section 7). Sample predictions of pile-up elevations will be presented in Sections 6.2.1 and 6.2.2.

Unfortunately, reliable methods that can be used to predict the encroachment that results from ice ride-up on a natural shoreline do not exist. While the encroachment produced by ice pile-up is likely to govern for steep-sided coastal structures such as gravel pads (per Sections 6.1.1 and 6.1.2), encroachment from ride-up may constitute an important design consideration for facilities that include pile-founded buildings and pipeline VSMs (vertical support members) located on the tundra near the coast. In such instances, the historical ride-up events profiled in Appendix E or F can be consulted to develop a first-order estimate of the encroachment that could result from ride-up (with particular emphasis on events that occurred on a similar type of shoreline and in the general vicinity of the proposed project). This estimate then can be compared with the encroachment predicted on the basis of pile-up (illustrated below in Sections 6.2.1 and 6.2.2), with the larger value adopted as the basis for design.

6.2.1. Sheltered Natural Shorelines

Eleven events were selected from Appendix C to illustrate the computation of ice pile-up elevation statistics for sheltered natural shorelines. As shown in Table 9, seven occurred during freeze-up, from early October to early December, and four occurred at break-up, in late June and early July. All of these events are statistically independent.

Table 9. Representative Ice Pile-Up Events on Sheltered Natural Shorelines

Site	*Shoreline Type*	*Estimated Slope (H:V)*	*Event Date*	*Ice Block Thickness (cm)*	*Ice Pile-Up Elevation (m, MLLW)*
No Name Is.	Beach	20:1	7/9/83	90-120	1.7
Konganevik Pt.	Beach	20:1	6/27/84	60-120	2.1
Long Is.	Beach	20:1	11/2/83	40-45	2.7
Tangent Pt.	Bluff	20:1	10/9/83	15-20	3.0
Stump Is.	Beach	20:1	11/9/83	13-15	3.3
No Name Is.	Beach	20:1	7/1/81	20-25	3.4
Long Is.	Beach	20:1	7/10/82	60-120	3.8
Lonely	Beach	20:1	11/13/82	50	5.0
Tangent Pt.	Beach	20:1	12/7/82	80	5.3
Bertoncini Is.	Beach	20:1	10/17/82	15-20	6.1
Lonely	Beach	20:1	11/10/81	55	7.0

Five of the pile-ups occurred on the mainland shore, from Tangent Point on the west to Konganevik Point on the east. The remaining six took place on sheltered barrier islands in the central portion of the Alaskan Beaufort Sea.

The distribution data for the eleven pile-up events are listed in Table 10 and plotted in Figure 17. The predicted pile-up elevation for the 10-year event is 7 m, while that for the 100-year event is 12 m (MLLW).

Table 10. Ice Pile-Up Distribution Data for Sheltered Natural Shorelines

Pile-Up (i)	*Probability of Event (p_i, %)*	*Cumulative Probability of Event (P_i, %)*	*Pile-Up Elevation (m, MLLW)*
1	8.33	8.3	1.7
2	8.33	16.7	2.1
3	8.33	25.0	2.7
4	8.33	33.3	3.0
5	8.33	41.7	3.3
6	8.33	50.0	3.4
7	8.33	58.3	3.8
8	8.33	66.7	5.0
9	8.33	75.0	5.3
10	8.33	83.3	6.1
11	8.33	91.7	7.0

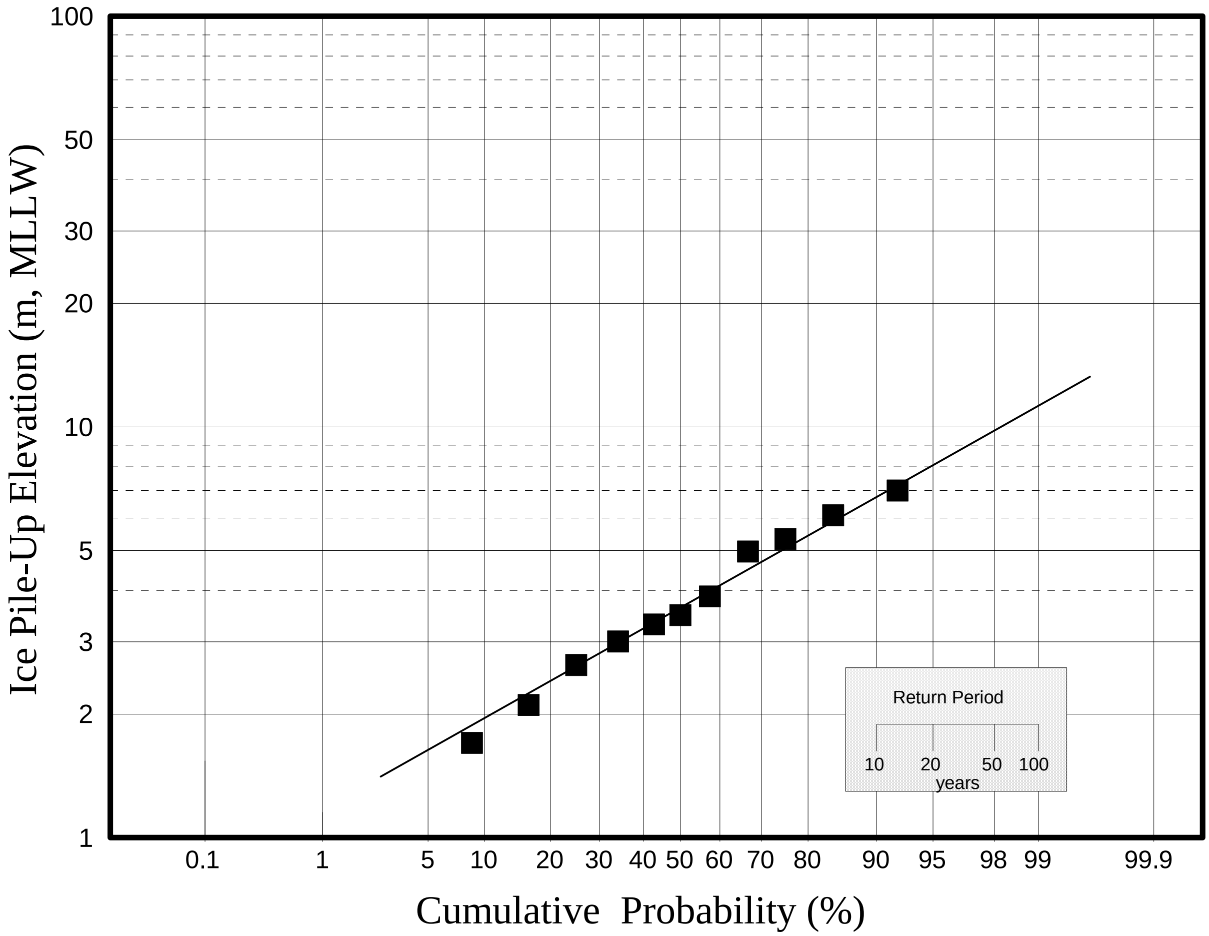


Figure 17. Predicted Ice Pile-Up Elevations on Sheltered Natural Shorelines

6.2.1. Exposed Natural Shorelines

Table 11 presents fourteen statistically-independent events that were selected from Appendix D to illustrate the derivation of ice pile-up elevation statistics for exposed natural shorelines. Twelve of the events occurred during freeze-up, from early October to mid-January, and two occurred at break-up in late June.

Table 11. Representative Ice Pile-Up Events on Exposed Natural Shorelines

Site	*Shoreline Type*	*Estimated Slope (H:V)*	*Event Date*	*Ice Block Thickness (cm)*	*Ice Pile-Up Elevation (m, MLLW)*
Cross Is.	Beach	20:1	10/29/82	10-25	2.4
Cross Is.	Beach	20:1	11/2/83	35-45	2.7
Jeanette Is.	Beach	20:1	10/19/82	20	3.7
Narwhal Is.	Beach	20:1	10/31/11	20	4.0
Camden Bay	Beach	20:1	6/25/85	90-120	4.6
Duchess Is.	Beach	20:1	6/29/81	50-65	5.4
Anderson Pt.	Beach	20:1	10/27/84	15-20	6.1
Collinson Pt.	Beach	20:1	1/18/84	105-120	6.9
Thetis Is.	Beach	20:1	10/8/80	20	7.6
Pole Is.	Beach	20:1	11/13/11	30	8.0
Reindeer Is.	Beach	20:1	11/30/83	55-60	8.4
Spy Is.	Beach	20:1	11/24/81	60-70	9.9
Spy Is.	Beach	20:1	12/7/82	60-90	10.6
Tapkaluk Is.	Beach	20:1	11/10/81	55	11.7

Eleven of the pile-ups took place on exposed barrier islands, while three took place on the mainland shore in Camden Bay. The westernmost site, in the Tapkaluk Islands, lies east of Point Barrow; the easternmost sites are located in Camden Bay.

Table 12 presents the distribution data for the fourteen pile-up events, while Figure 18 provides the plot that allows pile-up elevations to be estimated for various return periods. The elevations range from 11 m (MLLW) for the 10-year event to 18 m for the 100-year event.

6.3 Overview of Predicted Ice Pile-Up Elevations

The predictions of ice pile-up elevation that were developed in Sections 6.1 and 6.2 for return periods of 10, 20, 50, and 100 years are provided in Table 13. As expected, the elevations at exposed sites exceed those at sheltered sites for both man-made facilities and

Table 12. Ice Pile-Up Distribution Data for Exposed Natural Shorelines

Pile-Up (i)	*Probability of Event (p_i, %)*	*Cumulative Probability of Event (P_i, %)*	*Pile-Up Elevation (m, MLLW)*
1	6.67	6.7	2.4
2	6.67	13.3	2.7
3	6.67	20.0	3.7
4	6.67	26.7	4.0
5	6.67	33.3	4.6
6	6.67	40.0	5.3
7	6.67	46.7	6.1
8	6.67	53.3	6.8
9	6.67	60.0	7.6
10	6.67	66.7	8.0
11	6.67	73.3	8.3
12	6.67	80.0	9.9
13	6.67	86.7	10.6
14	6.67	93.3	11.7

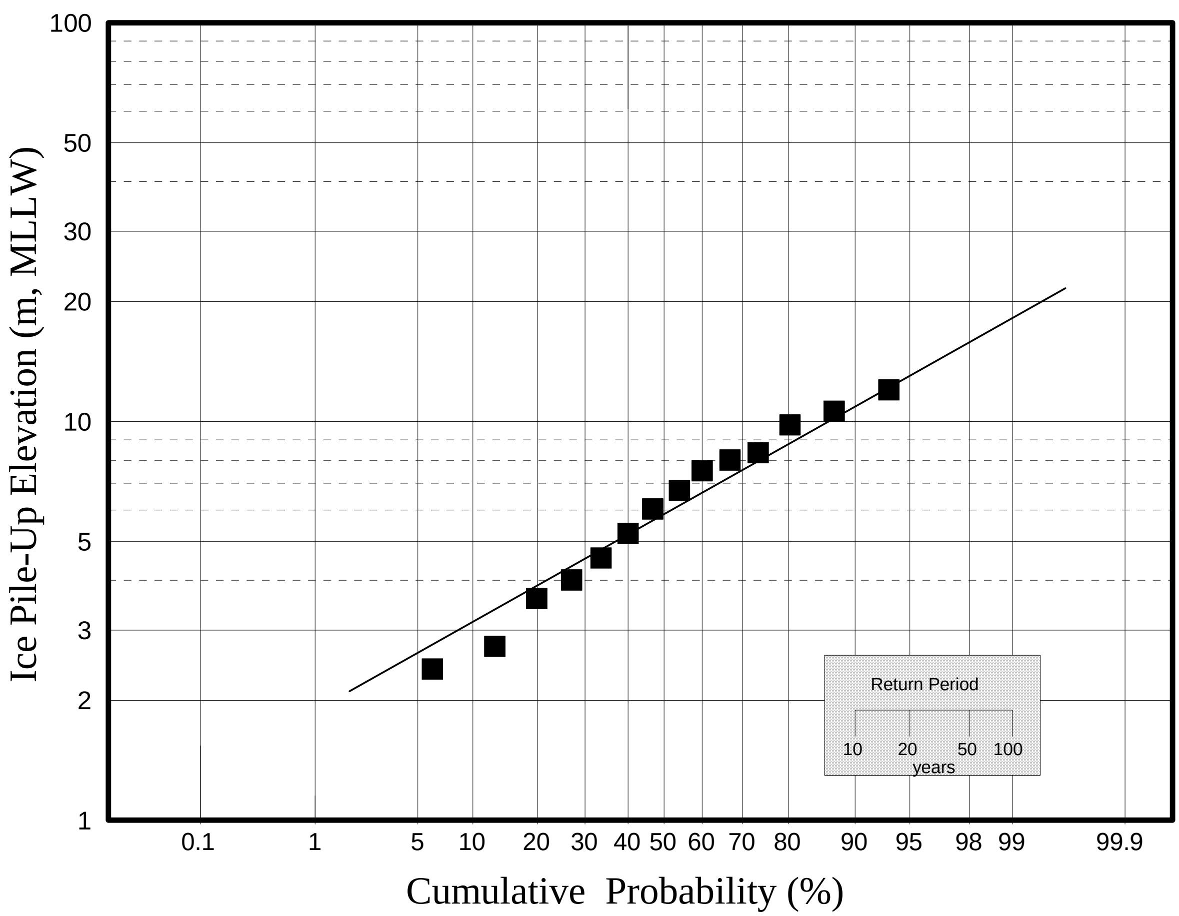


Figure 18. Predicted Ice Pile-Up Elevations on Exposed Natural Shorelines

Table 13. Predicted Ice Pile-Up Elevations[1, 2]

Category	Return Period (yr)			
	10	20	50	100
Man-Made Facilities				
Sheltered	**8 m**	**9 m**	**10 m**	**11 m**
Exposed	**12 m**	**15 m**	**17 m**	**20 m**
Natural Shorelines				
Sheltered	**7 m**	**8 m**	**10 m**	**12 m**
Exposed	**11 m**	**13 m**	**16 m**	**18 m**

Notes:
1 Pile-up elevations shown are not site-specific and should not be used for facility design.
2 Vertical datum is MLLW.

natural shorelines. The elevations at man-made facilities tend to be greater than or equal to those at natural shorelines with the same degree of exposure, but the differences are slight.

The values in Table 13 were derived without imposing an arbitrary limit on pile-up elevations. Timco and Barker (2002) suggested an upper bound of 15 m, based on a plot of ice pile-up height versus ice block thickness that is reproduced as Figure 19. This hypothesis appears flawed, however, in that pile-up elevations as high as 22 m have been measured in the Alaskan and Canadian Arctic (Kovacs and Sodhi, 1980 and 1988; Vaudrey, 1980 and 1985).

It should be noted that the pile-up elevations in Table 13 were derived for illustrative purposes only. They are not intended to portray the elevations anticipated at specific sites, and in consequence should not be used for purposes of facility design.

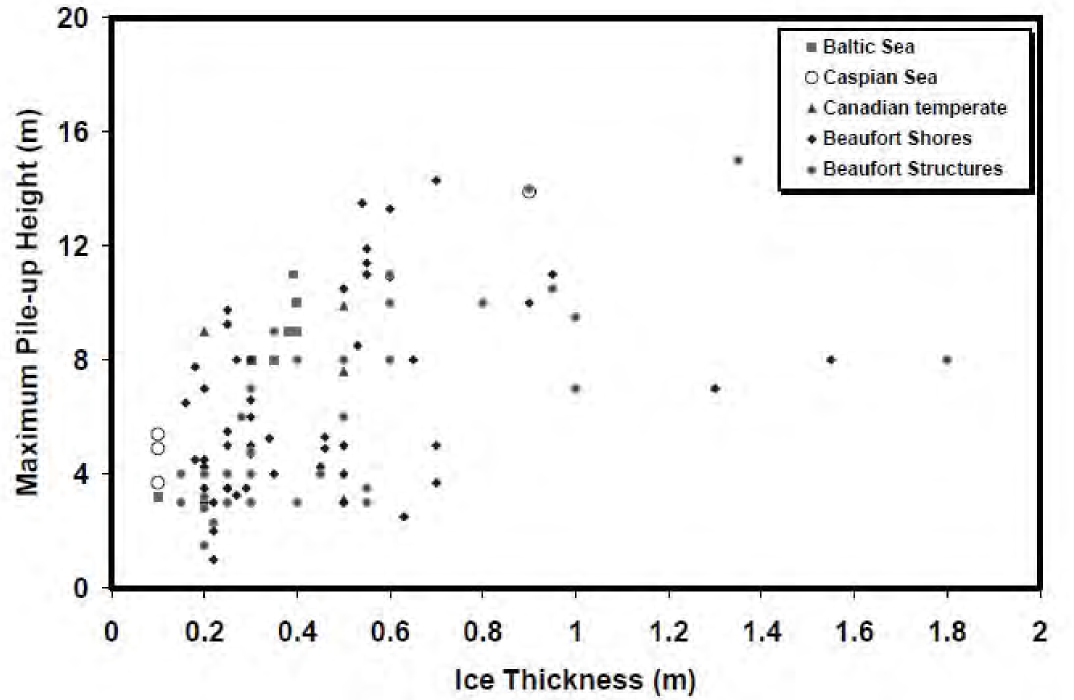


Figure 19. Maximum Pile-Up Height vs. Ice Thickness from Full-Scale and Model Test Data (Timco and Barker, 2002)

7. PREDICTION OF ENCROACHMENT

The encroachment that results from ice pile-up can be predicted from the elevation of the pile-up, the geometric characteristics of the pile-up, and the geometric characteristics of the man-made side slope or natural beach on which the pile-up occurs. The elevation of the pile-up that corresponds to the desired return period can be computed using the method outlined in Section 6. Although project-specific considerations may warrant otherwise, the *de facto* standard for coastal and nearshore facilities in the Alaskan Beaufort Sea has been to adopt a design ice event with a return period equal to five times the anticipated service life. In the case of a production island with an anticipated service life of 20 years, for example, the prediction of encroachment would be based on the 100-year pile-up.

7.1 Pile-Up Geometry

The geometric characteristics of the pile-up that are needed for the prediction of encroachment are illustrated in Figure 20. The location of the peak relative to the waterline, l, typically varies between one half and two thirds of the horizontal distance (L) from the waterline to edge of the work surface (or, in the case of a natural shoreline, from the waterline to the peak elevation of the shoreline profile). The smaller value ($l = 0.5L$) may be appropriate for sheltered sites, while the larger value ($l = 0.67L$) is appropriate for exposed sites.

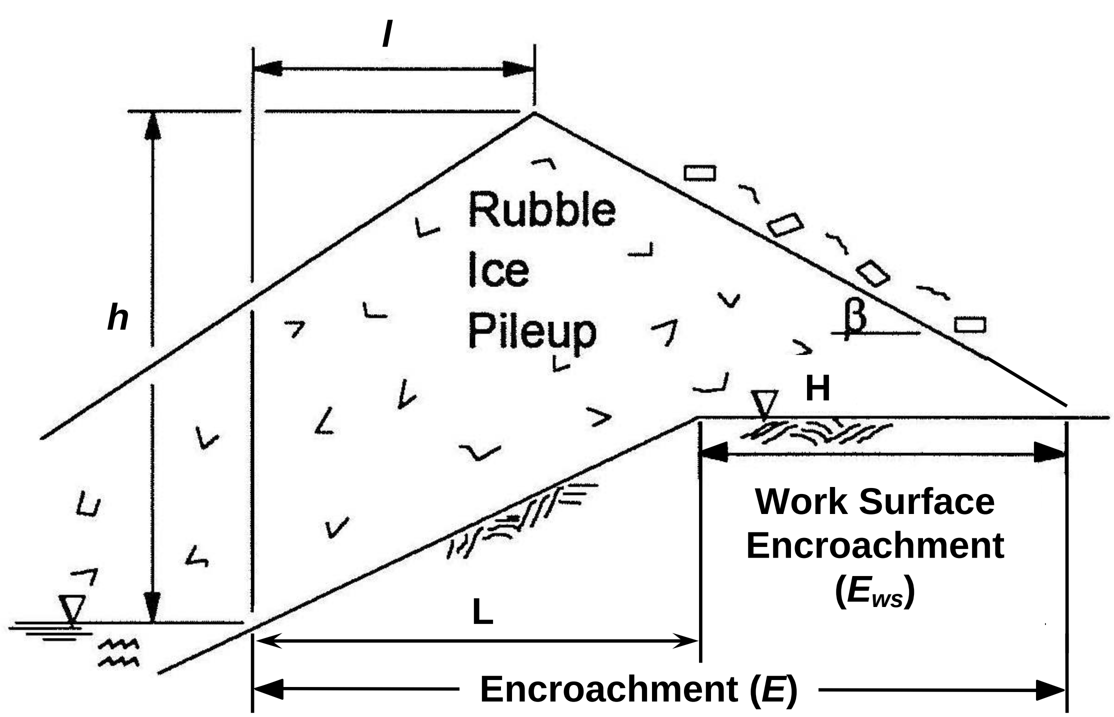


Figure 20. Geometric Parameters Used in Predicting Encroachment

Encroachment depends not only on the location of the pile-up peak, but also on the slope of the landward side of the pile, β. Kovacs and Sodhi (1980) reported that angles greater than or equal to 30° have been measured at shoreline pile-ups along the Alaskan Beaufort Sea coast and at ice pile-ups along the western coast of Banks Island in Canada. Grounded rubble piles also tend to exhibit angles of repose that equal or exceed this value. Because encroachment increases with decreasing values of β, 30° is adopted as a conservative lower bound for the purpose of developing predictions.

7.2 Structure/Shoreline Geometry

As shown in Figure 20, the side slope configuration of a man-made structure exerts a significant influence on encroachment. In addition to the horizontal distance between the waterline and the edge of the work surface (L), the elevation of the work surface (H) must be specified to predict encroachment and work surface encroachment. Similarly, in the case of a natural shoreline, the horizontal distance between the waterline and the peak elevation of the shoreline profile (L), and the elevation of the land that lies inland of the peak profile elevation (H), are required.

7.3 Sample Computations

Sample computations of encroachment are provided in Table 14 for man-made facilities and natural shorelines in both sheltered and exposed locations. The computations are based on the predicted pile-up elevations shown in Table 13 for a return period of 100 years, and as such might be applicable to projects with intended service lives of 20 years. It should be noted, however, that the computations are not intended to portray the encroachments anticipated at specific sites, and should not be used for purposes of facility design.

The assumptions and procedures adopted for the sample computations are summarized below:

- In the case of man-made facilities, the side slope is inclined at 3(H):1(V) and the work surface elevation (H) is 6 m above MLLW;
- In the case of natural shorelines, the beach is inclined at 20(H):1(V) until leveling off at a peak elevation (H) 2 m above MLLW;
- The peak of the pile-up is located half the distance from the waterline to the work surface edge at sheltered sites ($l = 0.5L$), and two thirds of the distance at exposed sites ($l = 0.67L$);
- The landward side of the pile-up is inclined at 30° ($\beta = 30°$).

Table 14. Predicted Ice Encroachments[1,2]

Category	$h^{3,4}$ (m, MLLW)	β (°)	Slope[5] (H:V)	H^3 (m, MLLW)	L (m)	l^6 (m)	Encroachment (m)	Work Surface Encroachment (m)
Man-Made Facilities								
Sheltered	11	30	3:1	6	18	9.0	**17.7**	**0.0**
Exposed	20	30	3:1	6	18	12.0	**36.3**	**18.3**
Natural Shorelines								
Sheltered	12	30	20:1	2	40	20.0	**37.3**	**n/a**
Exposed	18	30	20:1	2	40	26.7	**54.4**	**n/a**

Notes:

1 Encroachments shown are not site-specific and should not be used for facility design.
2 Variables are defined in Figure 20.
3 Vertical datum is MLLW.
4 Predicted pile-up elevations represent 100-year values from Table 13.
5 "Slope" indicates inclination of facility side slope or natural beach.
6 It is assumed that $l = 0.5L$ for Sheltered Facilities and $l = 0.67L$ for Exposed Facilities.

- Encroachment (*E*) is computed according to Equation (3):

$$E = l + \frac{(h-H)}{\tan \beta} \qquad (3)$$

- Work Surface Encroachment (E_{ws}) is computed according to Equation (4), with the restriction that the result cannot be less than zero:

$$E_{ws} = E - \mathrm{L} \qquad (4)$$

7.4 Implications of Encroachment

If ice encroaches onto the work surface of a man-made structure, it can cause extensive damage to items in its path. Similarly, ice that encroaches onto a natural shoreline can damage facilities such as pipelines supported by VSMs. In consequence, if the predictive methods outlined in this report indicate that a potential for encroachment exists at a particular site, a buffer zone or setback should be established to accommodate the design encroachment event. The buffer zone should remain free of all items of value during the windows of exposure that occur during freeze-up and break-up (Section 4). It may be occupied during the remainder of the year, however.

Even if ice does not encroach onto the work surface of a man-made facility, it can damage the armor that protects the side slope. Such damage tends to be most severe during break-up, when the ice is thicker than during freeze-up. A representative example is provided in Plate 30, which shows 4 cubic-yard gravel bags at the waterline of Tern Island that were damaged during break-up in 1982. In the event of a significant encroachment event on a man-made facility with armored side slopes, the impacted area should be inspected immediately after break-up to ensure that the slope protection system has not been compromised.

Encroaching ice also can disturb natural beaches and sacrificial beaches on man-made facilities. The plowing that resulted from ice encroachment on Karluk Island in 1981 is illustrated in Plate 31.

Plate 30. Gravel Bags at Waterline of Tern Island Damaged by Ice Encroachment on June 30, 1982

Plate 31. Gravel Beach on Karluk Island Bulldozed by Ice Ride-Up on June 27, 1981

8. CONCLUSIONS AND RECOMMENDATIONS

1. Ice encroachment can occur when moving ice impacts a fixed body such as a man-made structure or natural shoreline. If the ice remains intact or nearly intact as it is driven onshore, the phenomenon is referred to as "ride-up". If the ice fails in buckling or bending and breaks into individual blocks as it moves ashore, the phenomenon is referred to as "pile-up".

2. The ice motion that causes encroachment is governed primarily by wind stress on the ice surface. Although factors that include astronomical tide, storm surge, and waves can contribute to the initiation of pile-up and ride-up, the single most important factor is the loss of confinement of the sheet ice. This situation typically arises from a reversal in the wind direction.

3. Historical data from the Alaskan Beaufort Sea indicate that sustained wind speeds greater than or equal to 15 kt (8 m/s) are necessary to initiate pile-up and ride-up events. The events can result from both easterly and westerly storms, which usually are associated with changes in the wind direction.

4. Ice encroachment events tend to occur during two distinct seasons: freeze-up and break-up. Most pile-ups occur during freeze-up, when the ice is thin and brittle, while most ride-ups occur during break-up, when the ice is thick and ductile.

5. At sheltered locations where ice movement is limited by shallow water depths and/or partial protection from adjacent landforms, the typical periods of exposure to ice encroachment are as follows:

   Freeze-Up: early October through early December (2 months);

   Break-Up: late June through early July (2 to 3 weeks).

   At exposed locations, the period of exposure is considerably longer during freeze-up but comparable at break-up:

   Freeze-Up: early October through mid-January (3.5 months);

   Break-Up: late June through early July (2 to 3 weeks).

6. Natural shorelines are subject to encroachment from pile-up, ride-up, and combinations of the two. Historically, the largest encroachments have resulted from events that involve ride-up during freeze-up. The maximum recorded value is 76 m.

7. Man-made facilities are subject to encroachment from pile-up and combinations of pile-up and ride-up. Encroachment tends not to occur from pure ride-up, however, due the relatively steep, rough side slopes that typically are present. The maximum recorded value of 30 m occurred during freeze-up, but encroachments of comparable magnitude have been documented during break-up as well.

8. Ice encroachment represents a key design parameter for coastal and offshore facilities in the Alaskan Beaufort Sea. The encroachment that results from pile-up can be predicted using: (1) a statistical extrapolation of historical pile-up elevations that have occurred under similar circumstances; (2) the geometric characteristics of the pile-up; and (3) the geometric characteristics of the man-made side slope or natural beach on which the pile-up occurs.

9. Reliable methods that can be used to predict the encroachment that results from ice ride-up on a natural shoreline do not exist. However, historical ride-up events can be consulted to develop a first-order estimate of the encroachment that could result from this phenomenon (with particular emphasis on events that occurred on a similar type of shoreline and in the general vicinity of the proposed project). The result then can be compared with the encroachment predicted on the basis of ice pile-up, with the larger value adopted as the basis for design.

10. To facilitate the prediction of encroachment, one hundred and seventy three historical pile-ups, ride-ups, and combination events have been identified from freeze-up studies, break-up studies, and publicly-available documents pertaining to the Alaskan Beaufort Sea. The events, which are tabulated in the appendices of this report, have been subdivided into six categories based on the type of event (pile-up vs. ride-up), the degree of exposure (sheltered vs. exposed), and the nature of the site (man-made vs. natural).

11. If a project site is susceptible to encroachment, a buffer zone or setback should be established to accommodate the design encroachment event. The buffer zone should remain free of all items of value during the windows of exposure that occur during freeze-up and break-up. It may be occupied during the remainder of the year, however.

12. Even if ice does not encroach onto the work surface of a man-made facility, it can damage the armor that protects the side slope. Such damage tends to be most severe during break-up, when the ice is thicker than during freeze-up. In the event of a significant encroachment event on a man-made facility with armored side slopes, the

impacted area should be inspected immediately after break-up to ensure that the slope protection system has not been compromised.

13. On those occasions during freeze-up and break-up when coastal and offshore operations could be impacted by ice encroachment, particular vigilance should be maintained when a change in wind direction is accompanied by wind speeds greater than or equal to 15 kt (8 m/s).

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APPENDIX A

ICE PILE-UP EVENTS ON SHELTERED MAN-MADE FACILITIES

Ice Pile-Up Events on Sheltered Man-Made Facilities

Location	Date	Water Depth (m)	Side Slope (H):(V)	Ice Block Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[1] (m)	Work Surface Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
Freeze-Up Events									
1973 Freeze-Up									
Bullen Pt. DEW Station[3]	11/11/1973	1-2	20:1	30	5.4	30	5	45-50	260
1980 Freeze-Up									
None observed									
1981 Freeze-Up									
BF-37 Is. (Exxon)	10/8/1981	5.5	3:1	10-15	3.0	0	0	15-20	050
1982 Freeze-Up									
Endeavor Is. (Sohio)	10/19/1982	3.7	3:1	20	7.6	15	5	30-40	260
BF-37 Is. (Exxon)	10/19/1982	5.5	3:1	20	4.6	9	3	30-40	260
Duck-3 Is. (Exxon)	10/19/1982	3.0	3:1	20	3.7	10	0	30-40	260
BF-37 Is. (Exxon)	10/21/1982	5.5	3:1	25	6.1	12	0	10-15	320
1983 Freeze-Up									
None observed									
1984 Freeze-Up									
Tern Is. (Shell)	10/16/1984	6.7	3:1	8-15	7.6	12	6	15-25	230
Duck-3 Is. (Exxon)	10/16/1984	3.0	3:1	12-15	5.4	9	0	15-25	230
BF-37 Is. (Exxon)	10/16/1984	5.5	2-m scarp	8-15	3.0	0	0	15-25	230
Resolution Is. (Sohio)	10/16/1984	2.4	3:1	8-12	1.5	6	0	15-25	230
1985 Freeze-Up									
Duck-3 Is. (Exxon)	10/5/1985	3.0	3:1	8-12	4.8	3	0	10-15	220
Endicott MPI (BP)	10/9/1985	3.0	3:1	12-15	5.8	16	3	15-20	060
Duck-3 Is. (Exxon)	10/9/1985	3.0	3:1	12-15	5.8	3	0	15-20	060
BF-37 Is. (Exxon)	10/14/1985	5.5	2-m scarp	25	6.9	0	0	25-30	240
Endicott MPI (BP)	10/18/1985	3.0	3:1	20-25	4.2	0	0	25-35	300
Tern Is. (Shell)	10/18/1985	6.7	3:1	20-25	6.7	12	0	25-35	300

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Ice Pile-Up Events on Sheltered Man-Made Facilities

Location	Date	Water Depth (m)	Side Slope (H):(V)	Ice Block Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroach-ment[1] (m)	Work Surface Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
2009 Freeze-UP									
None Observed									
2010 Freeze-Up									
Oooguruk ODS (Pioneer)	10/7/2010	1.4	3:1	10-15	3.0	0	0	10-15	260
2011 Freeze-Up									
None Observed									
Break-Up Events									
1981 Break-Up									
BF-37 Is. (Exxon)	6/29/1981	5.5	3:1	60-90	1.3	0	0	15-20	050
1982 Break-Up									
Tern Is. (Shell)	6/30/1982	6.7	3:1	90-180	5.2	12	0	15-20	060
Duck-3 Is. (Exxon)	7/4/1982	3.0	3:1	90-120	2.1	9	0	15-20	050
1983 Break-Up									
Tern Is. (Shell)	6/28/1983	6.7	3:1	90-150	0	5	0	15-20	060
Duck-3 Is. (Exxon)	6/28/1983	3.0	3:1	150	0	9	0	15-20	060
1984 Break-Up									
Endeavor Is. (Sohio)	7/3/1984	3.7	3:1	45-75	1.9	12	0	20-25	080
Tern Is. (Shell)	7/7/1984	6.7	3:1	60-120	6.9	14	0	20-25	260
Duck-3 Is. (Exxon)	7/7/1984	3.0	3:1	45	0	6	0	20-25	260
1985 Break-Up									
None Observed									

Ice Pile-Up Events on Sheltered Man-Made Facilities

Notes:

[1] "Encroachment" represents the maximum horizontal distance that ice moved past the waterline.

[2] "Work Surface Encroachment" represents the maximum horizontal distance that ice moved past the work surface edge.

[3] Data derived from Kovacs (1983).

APPENDIX B

ICE PILE-UP EVENTS ON EXPOSED MAN-MADE FACILITIES

Ice Pile-Up Events on Exposed Man-Made Facilities

Location	Date	Water Depth (m)	Side Slope (H):(V)	Ice Block Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroach-ment[1] (m)	Work Surface Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
Freeze-Up Events									
1980 Freeze-Up									
None observed									
1981 Freeze-Up									
Challenge Is. Pad (BP)	10/8/1981	1-2	20:1	15	1.5	8	0	15-20	050
Jeanette Is. Pad (Chevron)	11/24/1981	1-2	20:1+3:1	55-60	6.1	25	5	15-20	060
1982 Freeze-Up									
Seal Is. (Shell)	10/19/1982	11.9	3:1	20	6.1	6	0	30-40	260
1983 Freeze-Up									
Seal Is. (Shell)	10/9/1983	11.9	3:1	10-20	2.7	2	0	15-20	100
Mukluk Is. (Sohio)	10/9/1983	14.6	3:1	10-20	3.8	5	0	15-20	100
Mukluk Is. (Sohio)	10/20/1983	14.6	3:1	15-25	5.1	8	0	10-15	280
Seal Is. (Shell)	11/2/1983	11.9	3:1	35-45	5.5	2	0	10-15	060
Mukluk Is. (Sohio)	11/8/1983	14.6	3:1	35-40	5.3	0	0	10-20	100
Mukluk Is. (Sohio)	11/30/1983	14.6	3:1	60-65	7.6	0	0	30-35	080
1984 Freeze-Up									
Seal Is. (Shell)	10/16/1984	11.9	3:1	8-18	3.4	0	0	15-25	230
Mukluk Is. (Sohio)	10/22/1984	14.6	3:1	8-25	6.1	12	0	20-25	060
Mukluk Is. (Sohio)	10/27/1984	14.6	3:1	25	6.1	0	0	20-25	300
1985 Freeze-Up									
Seal Is. (Shell)	10/14/1985	11.9	3:1	20-25	5.4	0	0	25-30	240
Northstar Is. (Am. Hess)	10/18/1985	13.7	3:1	20-25	3.8	0	0	25-35	300
Mukluk Is. (Sohio)	11/11/1985	14.6	3:1	50	9.9	0	0	30-40	250
Sandpiper Is. (Shell)	11/11/1985	14.9	3:1	50	11.5	5	0	30-40	250
2008 Freeze-Up									
Northstar Prod. Is. (BP)	1/23/2008	11.6	3:1+Bench	60-90	14.3	27	0	30-40	280

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Ice Pile-Up Events on Exposed Man-Made Facilities

Location	Date	Water Depth (m)	Side Slope (H):(V)	Ice Block Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroach-ment[1] (m)	Work Surface Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
2009 Freeze-Up									
Northstar Prod. Is. (BP)	11/4/2009	11.6	3:1+Bench	25	3.0	0	0	25	110
2010 Freeze-Up									
None Observed									
2011 Freeze-Up									
Northstar Prod. Is. (BP)	11/13/2011	11.6	3:1+Bench	30	4.0	5	0	15-25	280
Break-Up Events									
1981 Break-Up									
None observed									
1982 Break-Up									
Seal Is. (Shell)	7/4/1982	11.9	3:1	90-335	6.9	15	0	15-20	050
Seal Is. (Shell)	7/9/1982	11.9	3:1	180	0	5	0	20-25	070
Seal Is. (Shell)	7/11/1982	11.9	3:1	30-90	0	9	0	15-20	070
1983 Break-Up									
None observed									
1984 Break-Up									
Seal Is. (Shell)	7/21/1984	11.9	3:1	30-60	0	6	0	10-15	300
1985 Break-Up									
Sandpiper Is. (Shell)	7/5/1985	14.9	3:1	60-120	6.7	12	0	15-20	300
Northstar Is. (Am. Hess)	7/5/1985	13.7	3:1	90-135	4.6	21	6	15-20	300
Sandpiper Is. (Shell)	7/6/1985	14.9	3:1	60-120	4.6	9	0	25-30	060
Northstar Is. (Am. Hess)	7/6/1985	13.7	3:1	60-120	4.6	6	0	25-30	060
Seal Is. (Shell)	7/7/1985	11.9	3:1	45-105	3.0	12	0	15-20	090
2000 Break-Up									
Northstar Prod. Is. (BP)	7/2/2000	11.6	3:1+Bench	150-180	9.1	27	0	15-20	295

Ice Pile-Up Events on Exposed Man-Made Facilities

Location	Date	Water Depth (m)	Side Slope (H):(V)	Ice Block Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroach-ment[1] (m)	Work Surface Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
2002 Break-Up									
Northstar Prod. Is. (BP)	7/1/2002	11.6	3:1+Bench	100-150	9.1	27	0	10-20	270
2005 Break-Up									
Northstar Prod. Is. (BP)	6/29/2005	11.6	3:1+Bench	100-365	7.5	8	0	10-15	60

Notes:

[1] "Encroachment" represents the maximum horizontal distance that ice moved past the waterline.

[2] "Work Surface Encroachment" represents the maximum horizontal distance that ice moved past the work surface edge.

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APPENDIX C

ICE PILE-UP EVENTS ON SHELTERED NATURAL SHORELINES

Ice Pile-Up Events on Sheltered Natural Shorelines

Location	Date	Shoreline Type	Event[1]	Ice Block Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
Freeze-Up Events								
1979 Freeze-Up								
Cape Halkett (tundra)[3]	11/6/1979	Bluff	Both	25	3.5	u/k	25-30	090
Drew Pt. (tundra)[3]	11/16/1979	Bluff	P/U	40	6.1	10	15-20	040
1980 Freeze-Up								
Bertoncini Is.	10/10/1980	Beach	P/U	12-15	2.0	12	20-25	060
Drew Pt.[3]	10/20/1980	Beach	Both	30	3.0	u/k	15-20	070
Pogik Bay (tundra)[3]	11/16/1980	Bluff	Both	50	5.0	u/k	30-35	060
1981 Freeze-Up								
Cape Halkett (tundra)	11/10/1981	Bluff	P/U	45-50	1.6	5	40-45	070
Lonely[3]	11/10/1981	Beach	Both	55	7.0	u/k	40-45	070
1982 Freeze-Up								
Bertoncini Is.	10/17/1982	Beach	P/U	15-20	6.1	9	20-25	070
No-Name Is.	10/17/1982	Beach	P/U	15-20	6.1	18	20-25	070
Lonely[4]	11/13/1982	Beach	P/U	50	5.0	8	25-30	070
Tangent Pt.	12/7/1982	Beach	Both	80	5.3	15	20-25	060
1983 Freeze-Up								
Pogik Bay	10/6/1983	Sand Bar	Both	12-15	1.7	3	20-25	300
Tangent Pt. (tundra)	10/9/1983	Bluff	P/U	15-20	3.0	5	15-25	070
Long Is.	11/2/1983	Beach	Both	40-45	2.7	25	10-15	060
Stump Is.	11/9/1983	Beach	P/U	50	3.4	30	10-20	040
Lonely	11/20/1983	Beach	Both	60-75	1.7	3	15-20	060
1984 Freeze-Up								
Cape Halkett (tundra)	10/16/1984	Bluff	P/U	8-15	2.4	3	15-20	170
Pogik Bay (tundra)	10/27/1984	Bluff	P/U	20-25	3.8	6	20-25	320
Lonely	11/16/1984	Beach	P/U	50	3.3	3	25-35	100

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Ice Pile-Up Events on Sheltered Natural Shorelines

Location	Date	Shoreline Type	Event[1]	Ice Block Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
1985 Freeze-Up								
None observed								
2009 Freeze-Up								
Long Is.	11/4/2009	Beach	P/U	25	2.5	0	20-25	080
Cottle Is.	11/4/2009	Beach	P/U	25	4.0	0	20-25	080
2011 Freeze-Up								
No Name Is.	10/31/2011	Beach	P/U	20	2	10	20-25	240
Break-Up Events								
1981 Break-Up								
Lonely	6/26/1981	Beach	Both	50	4.0	u/k	15-20	280
Pogik Bay (tundra)	6/26/1981	Bluff	Both	50	3.0	u/k	15-20	280
No Name Is.	7/1/1981	Beach	Both	75-120	3.4	3	35-40	240
1982 Break-Up								
Long Is.	7/10/1982	Beach	Both	60-120	3.8	6	15-20	070
1983 Break-Up								
Pogik Bay (tundra)	6/28/1983	Bluff	P/U	45-75	3.0	12	15-20	060
Pogik Bay	7/7/1983	Sand Bar	Both	120-150	2.4	4	10-15	050
No Name Is.	7/9/1983	Beach	Both	90-120	1.7	9	10-15	060
1984 Break-Up								
Konganevik Pt.	6/27/1984	Beach	P/U	60-120	2.1	34	15-20	060
1985 Break-Up								
None Observed								

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Ice Pile-Up Events on Sheltered Natural Shorelines

Notes:

[1] "P/U" denotes pile-up only; "Both" denotes combined pile-up and ride-up.

[2] "Encroachment" represents the maximum horizontal distance that ice moved past the waterline. In the case of events that included both pile-up and ride-up, only the encroachment that resulted from pile-up is shown. The encroachment from ride-up is provided in Appendix E. "u/k" indicates that the encroachment from pile-up is unknown.

[3] Data derived from Kovacs (1983).

[4] Data derived from Kovacs (1984).

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APPENDIX D

ICE PILE-UP EVENTS ON EXPOSED NATURAL SHORELINES

Ice Pile-Up Events on Exposed Natural Shorelines

Location	Date	Shoreline Type	Event[1]	Ice Block Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
Freeze-Up Events								
1979 Freeze-Up								
Arey Is.[3]	12/5/1979	Beach	Both	50	4.6	u/k	30-35	260
1980 Freeze-Up								
Thetis Is.	9/24/1980	Beach	Both	8-10	1.7	6	15-20	280
Spy Is.	9/24/1980	Beach	Both	5-8	1.4	4	15-20	280
Jeanette Is.	9/24/1980	Beach	Both	3-5	1.0	5	15-20	280
Thetis Is.	10/8/1980	Beach	P/U	20	7.6	8	20-25	320
Collinson Pt.[3]	10/18/1980	Beach	Both	30	4.0	u/k	15-20	070
1981 Freeze-Up								
Challenge Is.	10/8/1981	Beach	P/U	15	1.5	8	15-20	050
Cross Is.	10/8/1981	Beach	P/U	15	3.3	8	15-20	050
Tapkaluk Is.[3]	11/10/1981	Beach	Both	55	11.7	u/k	25-30	060
Jeanette Is.	11/24/1981	Beach	Both	55-60	6.1	25	15-20	060
Pingok Is. (tundra)	11/24/1981	Bluff	P/U	60-70	6.1	15	15-20	060
Spy Is.	11/24/1981	Beach	P/U	60-70	9.9	30	15-20	060
Thetis Is.	11/24/1981	Beach	P/U	60-70	8.4	35	15-20	060
1982 Freeze-Up								
Thetis Is.	10/17/1982	Beach	P/U	15-20	1.7	6	20-25	070
Spy Is.	10/17/1982	Beach	P/U	15-20	1.7	5	20-25	070
Cross Is.	10/17/1982	Beach	P/U	15-20	2.7	9	20-25	070
Jeanette Is.	10/19/1982	Beach	Both	20	3.7	10	30-40	260
Karluk Is.	10/19/1982	Beach	Both	20	2.4	6	30-40	260
Cross Is.	10/29/1982	Beach	Both	10-25	2.4	6	12-15	100
Long-Spy Is.	12/7/1982	Beach	P/U	60-90	10.6	36	20-25	060

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Ice Pile-Up Events on Exposed Natural Shorelines

Location	Date	Shoreline Type	Event[1]	Ice Block Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
1983 Freeze-Up								
Spy Is.	10/6/1983	Beach	Both	12-15	1.4	9	25-35	260
Cross Is.	11/2/1983	Beach	Both	35-45	2.7	8	10-15	060
Pingok Is. (tundra)	11/2/1983	Bluff	P/U	40-45	2.7	25	10-15	060
Flaxman Is. (tundra)	11/20/1983	Bluff	P/U	55	2.4	9	15-20	080
Cross Is.	11/20/1983	Beach	Both	55	6.9	15	15-20	080
Reindeer Is.	11/30/1983	Beach	P/U	55-60	8.4	25	30-35	070
Collinson Pt.	1/18/1984	Beach	P/U	105-120	6.9	35	25-30	320
1984 Freeze-Up								
Anderson Pt.	10/27/1984	Beach	P/U	15-20	6.1	4	20-25	320
Cross Is.	12/2/1984	Beach	Both	75	7.6	25	20-25	080
1985 Freeze-Up								
None observed								
2009 Freeze-Up								
Stockton Is.	11/4/2009	Beach	P/U	25	2.5	0	20-25	080
Flaxman Is.	11/4/2009	Beach	P/U	25	1.5	0	20-25	080
Arey Is.	12/10/2009	Beach	P/U	60	7.5	0	15-20	290
2011 Freeze-Up								
Narwhal Is.	10/31/2011	Beach	P/U	20	4	5	20-25	240
Narwhal Is.	10/31/2011	Beach	P/U	20	4	0	20-25	240
Narwhal Is.	10/31/2011	Beach	P/U	20	3	3	20-25	240
Jeanette Is.	10/31/2011	Beach	P/U	20	5	10	20-25	240
Karluk Is.	10/31/2011	Beach	P/U	20	2	0	20-25	240
Narwhal Is.	11/13/2011	Beach	P/U	30	7.6	20	15-25	280
Pole Is.	11/13/2011	Beach	P/U	30	6	0	15-25	280
Pole Is.	11/13/2011	Beach	P/U	30	8	20	15-25	280

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Ice Pile-Up Events on Exposed Natural Shorelines

Location	Date	Shoreline Type	Event[1]	Ice Block Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
Break-Up Events								
1981 Break-Up								
Duchess Is.	6/29/1981	Beach	Both	50-65	5.4	0	15-20	050
Belvedere Is.	6/29/1981	Beach	Both	75-90	6.9	0	15-20	050
1982 Break-Up								
Argo Is.	7/10/1982	Beach	Both	90	3.0	0	15-20	070
1983 Break-Up								
None Observed								
1984 Break-Up								
Camden Bay	6/27/1984	Beach	Both	105-120	6.9	45	15-20	060
1985 Break-Up								
Camden Bay	6/25/1985	Beach	Both	90-120	4.6	18	15-20	310

Notes:

1 "P/U" denotes pile-up only; "Both" denotes combined pile-up and ride-up.

2 "Encroachment" represents the maximum horizontal distance that ice moved past the waterline. In the case of events that included both pile-up and ride-up, only the encroachment that resulted from pile-up is shown. The encroachment from ride-up is provided in Appendix F. "u/k" indicates that the encroachment from pile-up is unknown.

3 Data derived from Kovacs (1983).

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APPENDIX E

ICE RIDE-UP EVENTS ON SHELTERED NATURAL SHORELINES

Ice Ride-Up Events on Sheltered Natural Shorelines

Location	Date	Shoreline Type	Event[1]	Ice Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
Freeze-Up Events								
1979 Freeze-Up								
Cape Halkett (tundra)[3]	11/6/1979	Bluff	Both	25	3.5	30.0	25-30	090
Cape Simpson[3]	11/16/1979	Beach	R/U	40	n/a	16.0	15-20	040
1980 Freeze-Up								
Atigaru Pt.	9/22/1980	Beach	R/U	5-8	n/a	6.0	20-25	090
No Name Is.	10/8/1980	Beach	R/U	15	n/a	36.0	20-25	320
Drew Pt.[3]	10/20/1980	Beach	Both	30	3.0	75.0	15-20	070
Pogik Bay (tundra)[3]	11/16/1980	Bluff	Both	50	5.0	35.0	30-35	060
1981 Freeze-Up								
Lonely[3]	11/10/1981	Beach	Both	55	7.0	25.0	25-30	060
1982 Freeze-Up								
Tangent Pt.	12/7/1982	Beach	Both	80	5.3	65.0	20-25	060
1983 Freeze-Up								
Pogik Bay	10/6/1983	Sand Bar	Both	12-15	1.7	23.0	20-25	300
Long Is.	11/2/1983	Beach	Both	40-45	2.7	25.0	10-15	060
Lonely	11/20/1983	Beach	Both	60-75	1.7	36.0	15-20	060
1984 Freeze-Up								
Pogik Bay	11/16/1984	Sand Bar	R/U	50	n/a	15.0	25-35	100
1985 Freeze-Up								
None observed								

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Ice Ride-Up Events on Sheltered Natural Shorelines

Location	Date	Shoreline Type	Event[1]	Ice Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
Break-Up Events								
1981 Break-Up								
Lonely	6/26/1981	Beach	Both	50	4.0	30.0	15-20	280
Pogik Bay (tundra)	6/26/1981	Bluff	Both	50	3.0	15.0	15-20	280
No Name Is.	6/27/1981	Beach	R/U	95-105	n/a	12.0	15-20	270
No Name Is.	7/1/1981	Beach	Both	75-120	3.4	12.0	35-40	240
1982 Break-Up								
Long Is.	7/10/1982	Beach	Both	60-120	3.8	18.0	15-20	070
1983 Break-Up								
Konganevik Pt.	6/24/1983	Beach	R/U	90-120	n/a	12.0	20-25	060
Lonely	6/28/1983	Beach	R/U	60-120	n/a	15.0	15-20	060
Bullen Pt.	6/28/1983	Sand Bar	R/U	60-90	n/a	12.0	15-20	060
Pogik Bay	6/28/1983	Sand Bar	R/U	90-120	n/a	24.0	15-20	060
Pogik Bay	7/7/1983	Sand Bar	Both	120-150	2.4	30.0	10-15	050
No Name Is.	7/9/1983	Beach	Both	90-120	1.7	18.0	10-15	060
1984 Break-Up								
Stump Is.	6/26/1984	Beach	R/U	90-120	n/a	9.0	15-20	020
Long Is.	6/26/1984	Beach	R/U	90-120	n/a	12.0	15-20	020
Brownlow Pt.	6/27/1984	Sand Bar	R/U	45-60	n/a	15.0	15-20	060
1985 Break-Up								
No-Name Is.	7/5/1985	Beach	R/U	60-120	n/a	15.0	10-15	300
Lonely	7/5/1985	Beach	R/U	60-120	n/a	9.0	10-15	300
Cape Simpson	7/6/1985	Beach	R/U	30-60	n/a	24.0	10-15	050
No Name Is.	7/7/1985	Beach	R/U	90-120	n/a	30.0	15-20	080

Ice Ride-Up Events on Sheltered Natural Shorelines

Notes:

[1] "R/U" denotes ride-up only; "Both" denotes combined ride-up and pile-up.

[2] "Encroachment" represents the maximum horizontal distance that ice moved past the waterline. In the case of events that included both ride-up and pile-up, only the encroachment that resulted from ride-up is shown. The encroachment from pile-up is provided in Appendix C.

[3] Data derived from Kovacs (1983).

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APPENDIX F

ICE RIDE-UP EVENTS ON EXPOSED NATURAL SHORELINES

Ice Ride-Up Events on Exposed Natural Shorelines

Location	Date	Shoreline Type	Event[1]	Ice Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
Freeze-Up Events								
1979 Freeze-Up								
Collinson Pt[3]	11/16/1979	Beach	R/U	50	n/a	50	20-25	070
Anderson Pt.[3]	12/5/1979	Beach	R/U	55	n/a	20	35-40	260
Arey Is.[3]	12/5/1979	Beach	Both	50	4.6	60	30-35	260
1980 Freeze-Up								
Thetis Is.	9/24/1980	Beach	Both	8-10	1.7	18	15-20	280
Spy Is.	9/24/1980	Beach	Both	5-8	1.4	15	15-20	280
Reindeer Is.	9/24/1980	Beach	R/U	3-5	n/a	9	15-20	280
Jeanette Is.	9/24/1980	Beach	Both	3-5	1.0	29	15-20	280
Collinson Pt.[3]	10/18/1980	Beach	Both	30	4.0	25	15-20	070
1981 Freeze-Up								
Belvedere Is.	10/4/1981	Beach	R/U	5-8	n/a	8	20-25	250
Karluk Is.	10/4/1981	Beach	R/U	5-8	n/a	6	20-25	250
Tapkaluk Is.[3]	11/10/1981	Beach	Both	55	11.7	25	25-30	060
Jeanette Is.	11/24/1981	Beach	Both	55-60	6.1	45	15-20	060
1982 Freeze-Up								
Jeanette Is.	10/19/1982	Beach	Both	20	3.7	76	30-40	260
Karluk Is.	10/19/1982	Beach	Both	20	2.4	18	30-40	260
Cross Is.	10/29/1982	Beach	Both	5-25	2.4	6	12-15	100
1983 Freeze-Up								
Spy Is.	10/6/1983	Beach	Both	12-15	1.4	15	25-35	260
Cross Is.	11/2/1983	Beach	Both	35-45	2.7	40	10-15	060
Cross Is.	11/20/1983	Beach	Both	55	6.9	55	15-20	080

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Ice Ride-Up Events on Exposed Natural Shorelines

Location	Date	Shoreline Type	Event[1]	Ice Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
1984 Freeze-Up								
Spy Is.	10/27/1984	Beach	R/U	18-20	n/a	21	20-25	320
Cross Is.	12/2/1984	Beach	Both	75	7.6	37	20-25	080
1985 Freeze-Up								
None observed								
Break-Up Events								
1981 Break-Up								
Pole Is.	6/27/1981	Beach	R/U	60-75	n/a	15.0	15-20	270
Karluk Is.	6/27/1981	Beach	R/U	75-120	n/a	20.0	15-20	270
Jeanette Is.	6/27/1981	Beach	R/U	75-90	n/a	15.0	15-20	270
Leavitt Is.	6/27/1981	Beach	R/U	60	n/a	3.0	15-20	270
Duchess Is.	6/29/1981	Beach	Both	50-65	5.4	9.0	15-20	050
Belvedere Is.	6/29/1981	Beach	Both	75-90	6.9	6.0	15-20	050
1982 Break-Up								
Pole Is.	7/8/1982	Beach	R/U	60-90	n/a	9.0	10-15	060
Belvedere Is.	7/8/1982	Beach	R/U	30-60	n/a	14.0	10-15	060
Cross Is.	7/10/1982	Beach	R/U	30-150	n/a	9.0	15-20	070
Argo Is.	7/10/1982	Beach	Both	90	3.0	14.0	15-20	070
Belvedere Is.	7/11/1982	Beach	R/U	60	n/a	9.0	15-20	060
Alaska Is.	7/11/1982	Beach	R/U	60-90	n/a	12.0	15-20	060
1983 Break-Up								
Camden Bay	6/27/1983	Beach	R/U	60-90	n/a	43.0	15-20	080
McClure Is.	6/28/1983	Beach	R/U	60-90	n/a	18.0	15-20	060
Stockton Is.	6/28/1983	Beach	R/U	90-150	n/a	16.0	15-20	060
Tapkaluk Is.	7/9/1983	Beach	R/U	90	n/a	12.0	10-15	060
Karluk Is.	7/9/1983	Beach	R/U	60-90	n/a	5.0	10-15	060

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Ice Ride-Up Events on Exposed Natural Shorelines

Location	Date	Shoreline Type	Event[1]	Ice Thickness (cm)	Max. Pile-Up Elevation (m, MLLW)	Encroachment[2] (m)	Wind Speed (kt)	Wind Direction (°T)
1984 Break-Up								
Camden Bay	6/27/1984	Beach	Both	105-120	6.9	45.0	15-20	060
Arey Is.	6/27/1984	Beach	R/U	90-120	n/a	9.0	15-20	060
1985 Break-Up								
Arey Is.	6/25/1985	Beach	R/U	60-120	n/a	12.0	15-20	310
Barter Is.	6/25/1985	Beach	R/U	90-120	n/a	24.0	15-20	310
Camden Bay	6/25/1985	Beach	Both	90-120	4.6	18.0	15-20	310
Karluk Is.	7/3/1985	Beach	R/U	60-90	n/a	14.0	20-25	240
Pole Is.	7/3/1985	Beach	R/U	60-90	n/a	15.0	20-25	240
Tapkaluk Is.	7/5/1985	Beach	R/U	60-90	n/a	12.0	10-15	300

Notes:

[1] "R/U" denotes ride-up only; "Both" denotes combined ride-up and pile-up.

[2] "Encroachment" represents the maximum horizontal distance that ice moved past the waterline. In the case of events that included both ride-up and pile-up, only the encroachment that resulted from ride-up is shown. The encroachment from pile-up is provided in Appendix D.

[3] Data derived from Kovacs (1983).

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