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Fragments of Old Ice on Cross Island in Beaufort Sea (February 3, 2011)

2010-11 FREEZE-UP STUDY
OF THE
ALASKAN BEAUFORT AND CHUKCHI SEAS

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2010-11 FREEZE-UP STUDY OF THE ALASKAN BEAUFORT AND CHUKCHI SEAS

FINAL REPORT

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EXECUTIVE SUMMARY

This report describes an investigation of the ice conditions that prevailed during the 2010-11 freeze-up season in the Alaskan Beaufort and Chukchi Seas. The study was performed on behalf of Shell Offshore, Inc. ("Shell") and the Bureau of Ocean Energy Management, Regulation, and Enforcement ("BOEMRE"), U.S. Dept. of the Interior, by Coastal Frontiers Corporation and Vaudrey & Associates, Inc.

The 2010-11 Freeze-Up Study was developed with the intent of addressing five specific objectives:

1. Describe the ice conditions that evolve during the freeze-up and early winter seasons, including the development of landfast ice and the early shear zone;
2. Locate and map ice features of interest for the design and operation of offshore facilities, including ice movement lines, leads (linear openings in the sea ice), polynyas (areal openings in the sea ice), grounded rubble piles, first-year ridges, and multi-year floes;
3. Locate and map ice pile-ups on the natural shoreline and on man-made structures, and quantify the dimensions and ice block thicknesses associated with such features;
4. Correlate ice movement and pile-up events with the corresponding meteorological conditions; and
5. Compare the 2010-11 freeze-up season with those documented in the 1980s and in 2009-10.

The study was conducted using a combination of publicly-available data, proprietary data made available by Shell, and aerial reconnaissance missions. The acquisition of publicly-available meteorological data, ice charts, and satellite imagery began in October 2010, and continued through March 2011. Shell provided thirty six high-resolution RADARSAT-2 images acquired between October 3, 2010 and February 13, 2011, as well as the tracks of twelve Iridium telemetry buoys deployed on the sea ice in Camden and Harrison Bays in January and March, 2011. Shell's willingness to contribute these proprietary data at no cost to the project is gratefully acknowledged.

Five aerial reconnaissance missions were conducted near the end of the study period to investigate and expand upon the information acquired from the satellite images. Three of these, consisting of two fixed-wing flights and one helicopter flight, took place in the Beaufort Sea on February 2nd, 3rd, and 4th. The remaining two flights were undertaken in the Chukchi on February 5th and 6th using a fixed-wing aircraft.

The principal study findings are summarized below:

Study Methods

1. ***Satellite Imagery:*** RADARSAT-2 images, if obtained on a weekly basis with a nominal resolution of 100 m, provide an excellent means of tracking the progress of freeze-up and identifying changes in the nature of the ice canopy. They also can be used to investigate large-scale features such as the landfast ice zone, leads and polynyas, and multi-year ice floes. Publicly-available products that include ice charts, low-resolution mosaics prepared from satellite imagery, and AVHRR imagery can be used to confirm and extend the findings derived from the RADARSAT-2 images but are insufficient to support detailed analysis.

2. ***Aerial Reconnaissance Missions:*** Reconnaissance flights provide invaluable opportunities to confirm and refine the findings derived from satellite imagery, and to expand upon those findings with respect to small-scale features and processes. If possible, flights undertaken in early February to document the ice conditions at the end of freeze-up should be preceded by flights in late November or early December both to enhance the interpretation of early-season satellite imagery and to investigate phenomena such as pile-ups that occur when the ice cover is mobile.

Findings for Entire Study Area

1. ***Air Temperatures***: The daily mean air temperatures from September 2010 through May 2011 were the third warmest in the last 41 years, based on freezing-degree days accumulated at Barrow. The total of 6,388 freezing-degree days was 16% less than the average value for the twenty winters from 1970-71 through 1989-90, and 3% less than the value in 2009-10.

2. ***First-Year Ice Growth***: The computed thickness of undeformed first-year ice at the end of the 2010-11 winter season was 159 cm in the Beaufort Sea and 151 cm in the Chukchi Sea, based on the freezing-degree days accumulated at Deadhorse and Barrow, respectively. The thickness in the Beaufort is identical to that in 2009-10, while the thickness in the Chukchi is 3 cm less than the value in 2009-10.

3. ***Multi-Year Ice Floes***: With the exception of small fragments grounded on barrier islands in the Beaufort and embedded in a limited number of first-year floes in the Chukchi, multi-year ice was absent from the nearshore regions of both seas during the 2010-11 freeze-up season. Over the past decade, invasions of large multi-year floes have occurred on two occasions: 2001-02 and 2009-10. This finding suggests that the probability of a multi-year ice invasion in any given year currently is about 20%.

Findings for Beaufort Sea

1. ***Late Summer:*** The pack ice reached its seasonal minimum extent in mid-September 2010. Its total area was slightly lower than in 2009, and the third lowest since 1979. The distance between the ice edge and the coast ranged from about 120 nm (222 km) off Barter Island to more than 200 nm (370 km) off Point Barrow. By month-end, the distance had decreased to 100 nm (185 km) off Barter Island but remained steady at 200 nm (370 km) off Point Barrow.

2. ***Freeze-Up***: Freeze-up in the nearshore region of the Alaskan Beaufort Sea occurred on October 11, 2010, after about 80 freezing degree days (FDD) had accumulated at Deadhorse Airport. This timing is 11 days earlier than in 2009 but 7 days later than the average computed for the 11 years from 1980 through 1985 and 1987 through 1991. Complete freeze-up occurred on November 2^{nd}, at which time 305 FDD had accumulated.

3. ***Wind Regime:*** Winds tended to be light and variable during freeze-up and early winter. Based on the average daily wind directions recorded at Deadhorse Airport, easterlies and westerlies occurred with equal frequency. Storm events with average daily wind speeds exceeding 15 kt occurred on 19 occasions during the six-month period from October 2010 through March 2011. Eight of the storms were easterlies, while eleven were westerlies. Only two easterly storms occurred after December 1^{st}: a one-day event on December 4^{th}, and a two-day event on January 2^{nd} and 3^{rd}.

4. ***Landfast Ice:*** The landfast ice zone remained narrow and unstable during the 2010-11 freeze-up season due to a lack of both easterly storms and sustained easterly winds. Although three easterly storm events occurred in November 2010, the ice was too thin and weak to become securely grounded at that time. Thereafter, when the ice became sufficiently thick to generate competent rubble, the easterly storms needed to energize the process failed to materialize. In the western Beaufort, the landfast ice edge passed through Weller Bank but had not reached its other typical anchor point on Stamukhi Shoal at the end of January. In the central Beaufort, the landfast ice edge was located in close proximity to the barrier islands east of Prudhoe Bay and within 10 nm (19 km) of the shoreline in Camden Bay at this time.

5. ***Multi-Year Ice Floes:*** In contrast to 2009-2010, large multi-year ice floes did not invade the nearshore region of the Alaskan Beaufort Sea during the 2010-11 freeze-up season. Between November 2010 and mid-February 2011, such floes remained north of the 71°N parallel in the eastern Beaufort and the 72°N parallel in the western Beaufort.

6. ***Fragments of Old Ice:*** Notwithstanding the absence of large multi-year ice floes from the nearshore area, grounded fragments of old ice with diameters ranging from 1 to 5.5 m were observed on the seaward shorelines of many of the barrier islands. The fragments originated from a band of grounded ice that persisted in the nearshore area between Flaxman Island and Smith Bay throughout the 2010 open-water season. Similar accumulations of old ice fragments were observed on the shorelines of the barrier islands during the 1981 and 1982 freeze-up seasons.

7. ***Thermal Cracks:*** Thermal cracks with extruded ridges were present in the semi-protected region between the Sagavanirktok River Delta and Leffingwell Lagoon. They probably formed during a four-day period at the end of November when the air temperatures fell and then rose abruptly. In the past, cracks of this nature have disrupted ice road operations.

8. ***Ice Pile-Ups:*** Only one ice pile-up was observed in the Alaskan Beaufort Sea in 2010-11. It was located at the Oooguruk Offshore Drillsite in the shallow waters of the Colville River Delta, and consisted of 10- to 15-cm thick plates that were stacked against the south corner and southwest side in multiple waves with heights of 3 m. The pile-up did not encroach beyond the waterline area of the island's gravel-bag armor.

Findings for Chukchi Sea

1. ***Freeze-Up:*** Freeze-up in the Chukchi Sea began during the first week in October but progressed slowly due to above-normal air temperatures and a prolonged easterly storm that dislodged the newly-formed landfast ice from the coast in mid-month. Complete coverage in the nearshore region occurred on November 4th, after 265 FDD had accumulated at Barrow Airport. The entire Chukchi Sea north of Cape Lisburne became ice-bound on December 7th, coincident with the accumulation of 959 FDD. Whereas freeze-up in the Chukchi began a full month earlier in 2010 than in 2009, it ended one week later.

2. ***Wind Regime:*** The wind data recorded at Barrow Airport suggest that two contrasting wind regimes prevailed in the Chukchi Sea during the 2010-11 freeze-up season. From October 1, 2010, through January 15, 2011, easterlies occurred more than 75%

of the time and constituted eight of the ten storm events. From January 16th through March 31st, easterlies and westerlies occurred with nearly equal frequency while six of the eight storm events were westerlies.

3. ***Landfast Ice:*** Except in Peard Bay, Kasegaluk Lagoon, and the semi-protected area east of Point Franklin, the landfast ice that developed off the coast between Barrow and Point Lay was confined to a narrow strip that remained unstable through mid-February 2011. The paucity of westerly storms through mid-January limited the production of grounded rubble, thereby leaving the nearshore ice susceptible to break-out and removal during periods of easterly winds. When a coastal reconnaissance flight was conducted on February 5th, the edge of the fast ice was located 0.7 nm (1.2 km) off Barrow, 0.5 nm (0.9 km) off Point Belcher, and 0.1 nm (200 m) off Point Lay. Even the semi-protected region that lies to the east of Icy Cape was virtually bereft of landfast ice at the time of the flight.

4. ***Coastal Flaw Lead:*** The distinctive flaw lead that opens off the Chukchi Sea coast in response to easterly winds and closes in response to westerly winds was detected on five occasions during the 2010-11 freeze-up season: late December, early January, late January, and twice in the first half of March. The dimensions of the lead varied substantially, from an estimated 50 nm (93 km) long by 5 nm (9 km) wide in late December to 140 nm (259 km) long by up to 60 nm (111 km) wide in late January. The feature's persistence also varied, from as little as several days during each appearance in March to about a week in early January. Whenever it was open, the lead left the ice in the nearshore zone susceptible to movement and deformation until it refroze.

5. ***Nearshore vs. Offshore Ice Cover:*** A significant contrast between heavily-deformed ice in the nearshore pack and relatively undeformed ice in the offshore pack was noted during the aerial reconnaissance flights conducted in February 2010. A similar but less-pronounced difference existed in February 2011. The nearshore zone contained ridges and rubble fields interspersed with small-to-moderate-sized first-year floes. Although significant ice deformation was evident, it was less prevalent than that observed a year earlier due to the paucity of westerly storms during the freeze-up season. At distances greater than about 60 nm (111 km) from the coast, where the influence of the coastal flaw lead tends to diminish, the ice cover evidenced less deformation and consisted largely of vast first-year pans with diameters as large as 5 nm (9 km).

6. ***Multi-Year Ice Floes:*** The large multi-year ice floes that entered the offshore portion of the Alaskan Beaufort Sea in November began arriving in the northern Chukchi Sea in mid-December. These floes remained well offshore throughout the 2010-11 freeze-

up season, with the southern boundary located approximately 60 nm (111 km) off Barrow at the end of December and 180 nm (333 km) off Barrow at the end of March.

7. ***Fragments of Old Ice:*** Although the large multi-year ice floes remained north of the 72°N parallel during the freeze-up season, fragments of old ice embedded in first-year floes were observed in Shell's Burger Prospect during the reconnaissance flight conducted on February 6th. They comprised less than 5% of the ice cover, while their maximum horizontal dimensions ranged from one hundred to several hundred meters. The fragments may have broken off from the perennial pack ice in sizes that were too small and concentrations that were too low to be detected in RADARSAT-2 imagery. Alternatively, they may have drifted west from the nearshore band of grounded ice that persisted in the Alaskan Beaufort Sea throughout the 2010 open-water season.

8. ***Ice Pile-Ups:*** Twenty seven ice pile-ups were observed on the Chukchi Sea coast in February 2011, representing eight more than a year earlier. The piles were composed of blocks estimated to be 30 to 40 cm thick. They probably formed in mid-November, when loosely-consolidated ice was driven ashore by winds that shifted from east to west and accelerated to 25 kt. The largest pile-ups were located between Point Belcher and Wainwright, where one ice pile attained both the maximum estimated height of 8 m and maximum estimated encroachment distance of 40 m onto the beach. The longest ice pile, stretching 2,300 m alongshore with a height of 3 m, also occurred in this region.

Freeze-Up in Recent Years vs. the 1980s

1. ***Air Temperatures:*** Since the 1970s, progressively warmer winter seasons have caused the number of freezing-degree days at Barrow to decline at an average rate of 45 FDD/yr.

2. ***Winds:*** Since the early 1980s, the frequency of storm events at Barrow during the mid-winter months of January through April has increased by about one third.

3. ***Freeze-Up:*** The onset of freeze-up has slipped by about two weeks in the Alaskan Beaufort Sea and one month in the Chukchi Sea relative to the 1980s. Freeze-up in the nearshore region currently tends to occur during the third week in October in the Beaufort, and during the first week in November in the northern Chukchi.

4. ***First-Year Ice Growth:*** Based on air temperature alone, the thickness of undeformed first-year ice attained during an average winter has decreased by about 10% relative to that attained in the early to mid-1980s. However, increased snowfall may be causing a greater reduction in the ice thickness. Other temperature-related factors, including

reduced ice production in leads and decreased consolidation of ridges, probably exert a greater impact on ice behavior than reduced ice thickness.

5. ***Landfast Ice Development and Stability*****:** The locations and shapes of the landfast ice zones and the associated leads and polynyas tended to follow the same general patterns in 2009-10 and 2010-11 as in previous decades, but the landfast ice developed more slowly while the lead widths and polynya sizes tended to increase. Additional differences in the Beaufort Sea included the absence of a stable, grounded shear zone to the east of Prudhoe Bay in both years, and a smaller, less stable landfast ice zone to the west of Prudhoe Bay in 2010-11. In the Chukchi, the data acquired in mid-winter of 2010 and 2011 suggest that the coastal flaw lead attains greater widths and may persist longer than in the 1980s.

6. ***Multi-Year Ice:*** The probability of large multi-year ice floes invading the Alaskan Beaufort and Chukchi Seas in any given year is less than in the 1980s. This conclusion follows in part from the location of the ice edge, which has retreated farther to the north in recent summers, and in part from warmer air temperatures and increased storm frequencies, which have reduced the likelihood that remnants of the Beaufort Sea shear zone will survive the summer melt season to become second-year floes. Nevertheless, as demonstrated in 2009-10, the possibility of encountering multi-year ice floes and gouges in the sea floor inflicted by such floes cannot be ruled out for developments in either the Beaufort or Chukchi. Furthermore, fragments of old ice analogous to those observed in 2010-11 may be present even if large multi-year floes remain well offshore.

7. ***Pack Ice Movement:*** The average drift rate measured for pack ice was 6 nm/day (11 km/day) in 2009-10 and 4.8 nm/day (8.9 km/day) in 2010-11. The former is comparable to that obtained in the 1980s, while the latter is somewhat lower in apparent response to the reduced frequency of easterly storms and sustained easterly winds that prevailed during the 2010-11 freeze-up season. These findings differ from those of Walsh and Eicken (2007), who suggested that thinner sea ice in the winter may lead to increased ice movement.

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2010-11 FREEZE-UP STUDY OF THE ALASKAN BEAUFORT AND CHUKCHI SEAS

1. INTRODUCTION

This report describes an investigation of the ice conditions that prevailed during the 2010-11 freeze-up season in the Alaskan Beaufort and Chukchi Seas. The study was performed as a joint-industry project on behalf of Shell Offshore, Inc. ("Shell") and the Bureau of Ocean Energy Management, Regulation, and Enforcement ("BOEMRE"), U.S. Department of the Interior, by Coastal Frontiers Corporation and Vaudrey & Associates, Inc.

As shown in Figure 1, the study area includes the nearshore portion of the Beaufort Sea from Barter Island on the east to Point Barrow on the west, and the northern portion of the Chukchi Sea bounded by the shoreline between Point Barrow and Point Lay, the 73.5°N parallel, and the 168°W meridian. The boundaries in the Beaufort Sea were selected to encompass Shell's prospects in Camden and Harrison Bays as well as all existing oil and gas developments operated by others, while those in the Chukchi were selected to encompass Hanna Shoal and prospects that included Burger and Crackerjack.

During freeze-up, the ice cover in the study area consists primarily of thin, flexible sheets of newly-formed ice. It also may contain much thicker, more durable multi-year floes that have survived one or more summer melt seasons. Frequent storms tend to disturb the first-year ice before it attains sufficient thickness to resist displacement. As a result, the multi-year floes can travel great distances and attain relatively high speeds in open water. Potential concerns for oil and gas facilities include impact loads on fixed structures such as man-made islands and platforms, displacement of floating structures such as drillships, and ice gouging in the vicinity of subsea pipelines.

In addition to multi-year ice movements, the storms during freeze-up and early winter can produce significant ride-up and pile-up events when the ice encounters obstacles such as natural coastlines, shoals, and man-made islands. A recent example occurred on January 23, 2008, when westerly winds caused a pile-up with a maximum height of 14 m above sea level on Northstar Production Island (Plate 1; Coastal Frontiers, 2009). The storms also can cause substantial deformation of the first-year ice, leading to the formation of rubble and ridges that can survive the ensuing open-water season to become multi-year floes with embedded multi-year ridges.

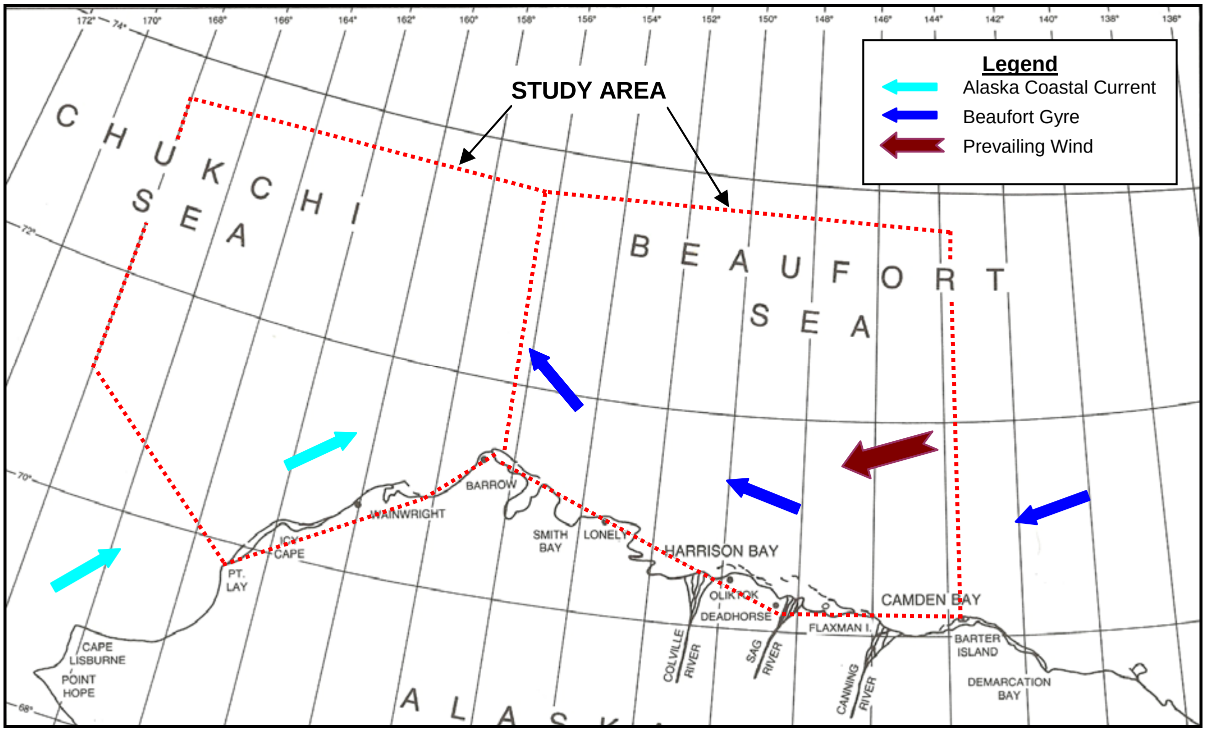


Figure 1. Study Area

Plate 1. Ice Pile-Up Formed on Northstar Production Island in January, 2008 (Coastal Frontiers, 2009)

The foregoing phenomena, along with the curtailment of vessel navigation and the increasing viability of the ice sheet as a platform for transportation and construction, imply that an understanding of freeze-up is essential for the safe design and operation of offshore oil and gas facilities. To this end, six freeze-up studies were conducted as joint-industry projects from 1980-81 through 1985-86 (Vaudrey, 1981; 1982; 1983; 1984; 1985; 1986). Each study was largely observational in nature, and included aerial surveys conducted at intervals of two to three weeks from early October until early December. In some instances, an additional aerial survey was made at the end of January to record late-freeze-up ice movements caused by storms occurring after the early-December visit. The primary objectives of these annual studies were twofold: (1) observe and record major ice movement events and their effects on man-made islands and structures, and (2) document the size and distribution of multi-year floes, the locations of major first-year ridges and rubble fields, and the zonation of the nearshore ice.

Between 1986 and 2008, freeze-up processes were investigated primarily through the analysis of satellite imagery (Vaudrey, 1988-1992; Eicken, *et al*., 2006). The resulting information, although useful in its own right, lacked some of the detail provided by the earlier observational studies. Specifically, items such as the age and character of multi-year floes and the locations and composition of ice pile-ups could not be extracted from the satellite-based data. To remedy this deficiency, Shell (a participant in the original freeze-up studies) and BOEMRE commissioned a study of the 2009-10 freeze-up season that combined remote sensing with on-site observations. The project included an analysis of meteorological data, ice charts, and satellite imagery in concert with a series of aerial reconnaissance missions conducted in early February, 2010 (Coastal Frontiers and Vaudrey, 2010).

To document the interannual variability inherent in freeze-up processes, a program similar to that in 2009-10 was conducted in 2010-11 with five specific objectives:

1. Describe the ice conditions that evolve during the freeze-up and early winter seasons, including the development of landfast ice and the early shear zone;
2. Locate and map ice features of interest for the design and operation of offshore facilities, including ice movement lines, leads (linear openings in the sea ice), polynyas (areal openings in the sea ice), grounded rubble piles, first-year ridges, and multi-year floes;
3. Locate and map ice pile-ups on the natural shoreline and on man-made structures, and quantify the dimensions and ice block thicknesses associated with such features;

4. Correlate ice movement and pile-up events with the corresponding meteorological conditions; and
5. Compare the 2010-11 freeze-up season with those documented in the 1980s and in 2009-10.

The acquisition of publicly-available meteorological data, ice charts, and satellite imagery began in October 2010 and continued through March 2011. These data were supplemented with RADARSAT-2 images that were provided to the project at no cost by Shell. In addition, Shell provided the tracks of twelve Iridium telemetry buoys deployed on the sea ice in Camden and Harrison Bays in January and March, 2011. Shell's willingness to contribute these proprietary data is gratefully acknowledged.

Five aerial reconnaissance missions were conducted near the end of the study period to investigate and expand upon the information acquired from the satellite images. Three of these, consisting of two fixed-wing flights and one helicopter flight, took place in the Beaufort Sea on February 2nd, 3rd, and 4th. The remaining two flights were undertaken in the Chukchi on February 5th and 6th using a fixed-wing aircraft.

It is important to recognize that the ice regimes in the Beaufort and Chukchi Seas differ markedly due to factors that include geography, meteorology, and oceanography. Whereas the Beaufort Sea coast is oriented nearly east-west, the Chukchi coast trends northeast-southwest (Figure 1). As a result, the easterly winds that tend to prevail in both regions push the ice along the Beaufort Sea coast but away from the Chukchi coast. In the Beaufort, the alongshore winds coupled with flat nearshore slopes produce such extensive landfast ice growth that the ice seasons (freeze-up, winter, and break-up) are defined in large part by the condition of this ice. In the Chukchi, the landfast ice growth is limited not only by the offshore winds but also by a nearshore sea bottom that tends to be relatively steep. As a result, the seasons are blurred by the constant ice motion and formation of new ice occurring offshore of a small strip of landfast ice that clings to the shoreline.

The pronounced difference in ice regimes that characterizes freeze-up and mid-winter also prevails during the break-up and summer seasons. While the Beaufort Gyre transports the pack ice from east to west in the Beaufort Sea, the Alaska Coastal Current, which carries warm water north from the Bering Sea (Figure 1), contributes to the retreat of the ice edge in the Chukchi.

The remainder of this report provides a detailed account of the 2010-11 Freeze-Up Study. To provide historical context, the findings of the seven prior joint-industry studies (1980-81 through 1985-81, and 2009-10) are summarized in Section 2. Data acquisition and analysis are discussed in Section 3, which covers the aerial reconnaissance missions in addition to the data obtained from all other sources. As the Beaufort and Chukchi Seas represent different ice regimes, the study findings are presented separately for each region. Section 4 describes the development of freeze-up, the conditions observed during the field trip in early February, and the conditions that evolved through the end of March, in the Beaufort Sea. Section 5 provides comparable information for the Chukchi Sea. The 2010-11 freeze-up season is compared with those of the early 1980s and 2009-10 in Section 6. Conclusions are presented in Section 7, followed by references in Section 8. Figures, tables, and plates are interspersed with the text, while three large-format drawings that portray the observations made during the aerial reconnaissance flights are provided in Appendix A. The digital data files that were used in conducting the study are provided on a CD in Appendix B. The CD, which is attached to the back cover, also contains a digital version of this report (including Appendix A).

The horizontal datum for all geographic coordinates presented in the text and the accompanying graphical products is the North American Datum of 1983 (NAD83). Some of the graphical products also include a grid referenced to the Universal Transverse Mercator (UTM) Datum, NAD83, with units of meters. UTM Zone 6 is used in the central Beaufort Sea, UTM Zone 5 in the western Beaufort Sea, and UTM Zone 4 in the Chukchi Sea.

The vertical datum is Mean Sea Level (MSL). MSL lies only 8 cm above Mean Lower Low Water (MLLW) at Point Hope, which represents the closest National Ocean Service (NOS) tide station in the Chukchi Sea, and 10 cm above MLLW at Prudhoe Bay, which represents the only NOS tide gauge in the Beaufort Sea (National Ocean Service, 2011). For purposes of this report, the differences between MSL and MLLW (which represents the vertical datum for all NOS nautical charts of the area) are assumed to be negligible.

Units are provided in the SI system, with three exceptions: (1) distances are provided in nautical miles (nm) to maintain consistency with the use of geographic coordinates; (2) wind speeds are provided in knots (kt), again to maintain consistency with the use of geographic coordinates; and (3) freezing degree days ("FDD") are provided using the Fahrenheit rather than Celsius scale to provide greater resolution and maintain consistency with past freeze-up reports. In the case of nautical miles and knots, the corresponding values in SI units are provided in parentheses.

Throughout this report, the locations of ice features are described relative to geographic points of interest that include bays, rivers, lagoons, points of land, natural and man-made islands, and coastal villages. For ease of reference, these features are shown in Figures 2 (Central Beaufort Sea), 3 (Western Beaufort Sea), and 4 (Chukchi Sea).

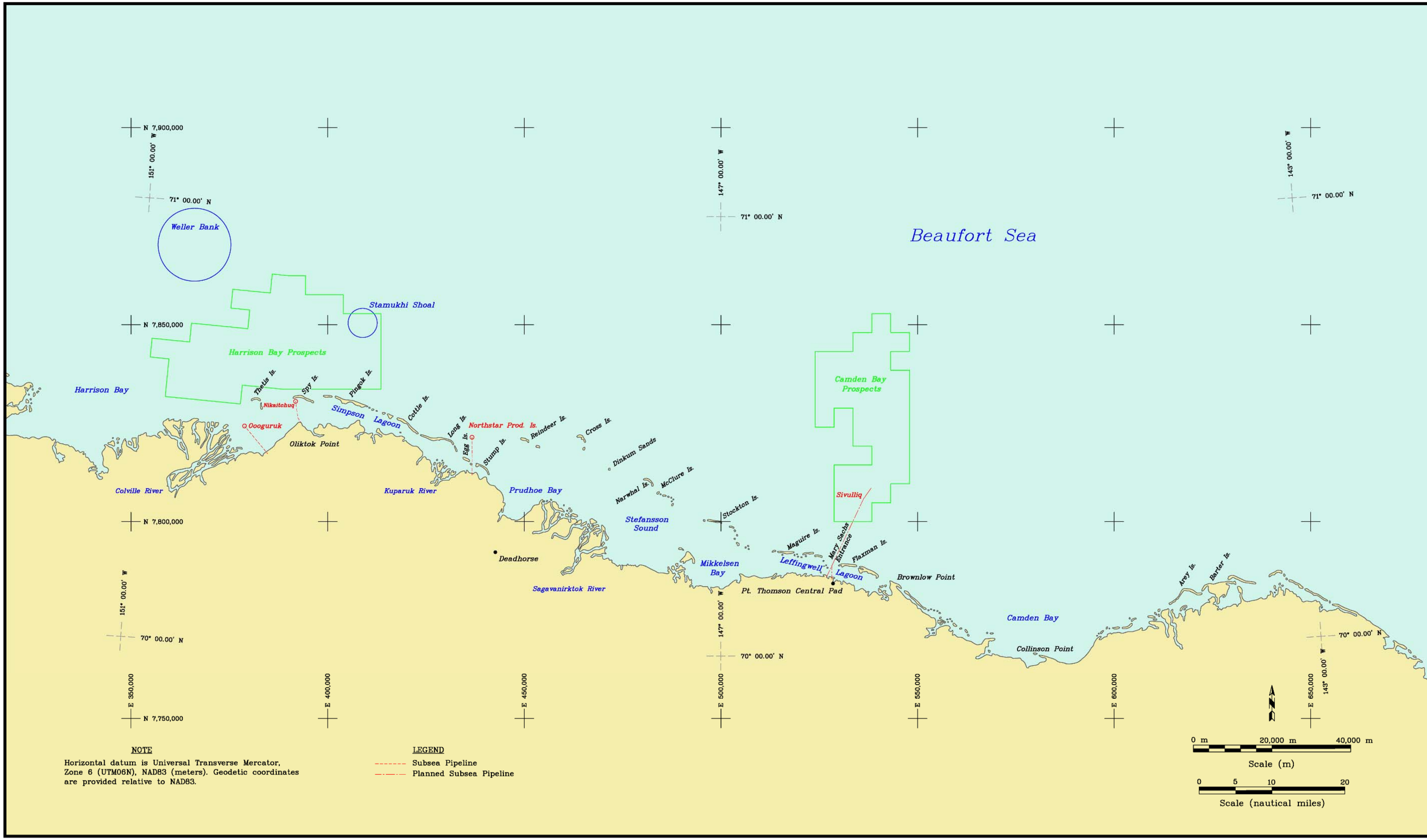


Figure 2. Geographic Points of Interest in Central Beaufort Sea

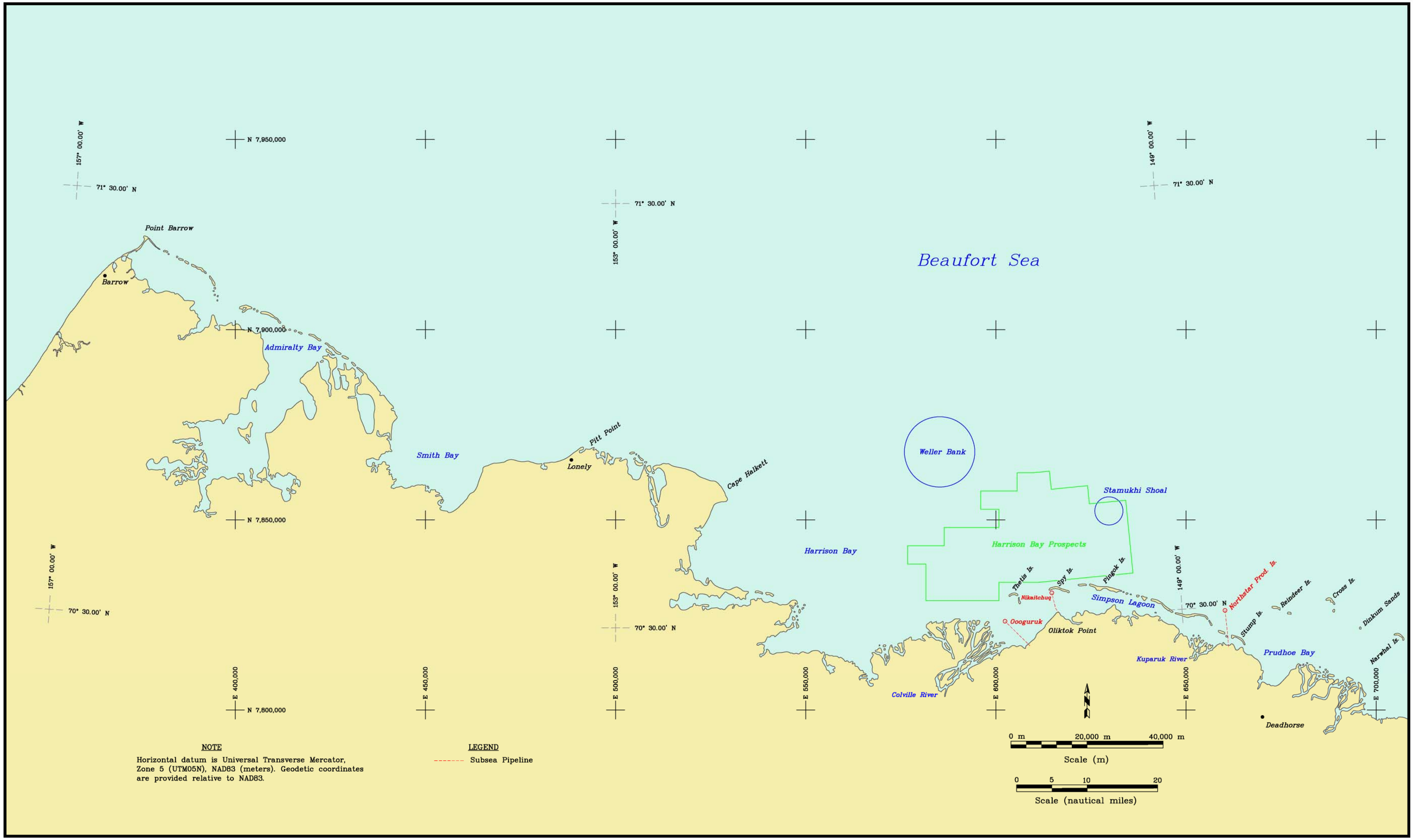


Figure 3. Geographic Points of Interest in Western Beaufort Sea

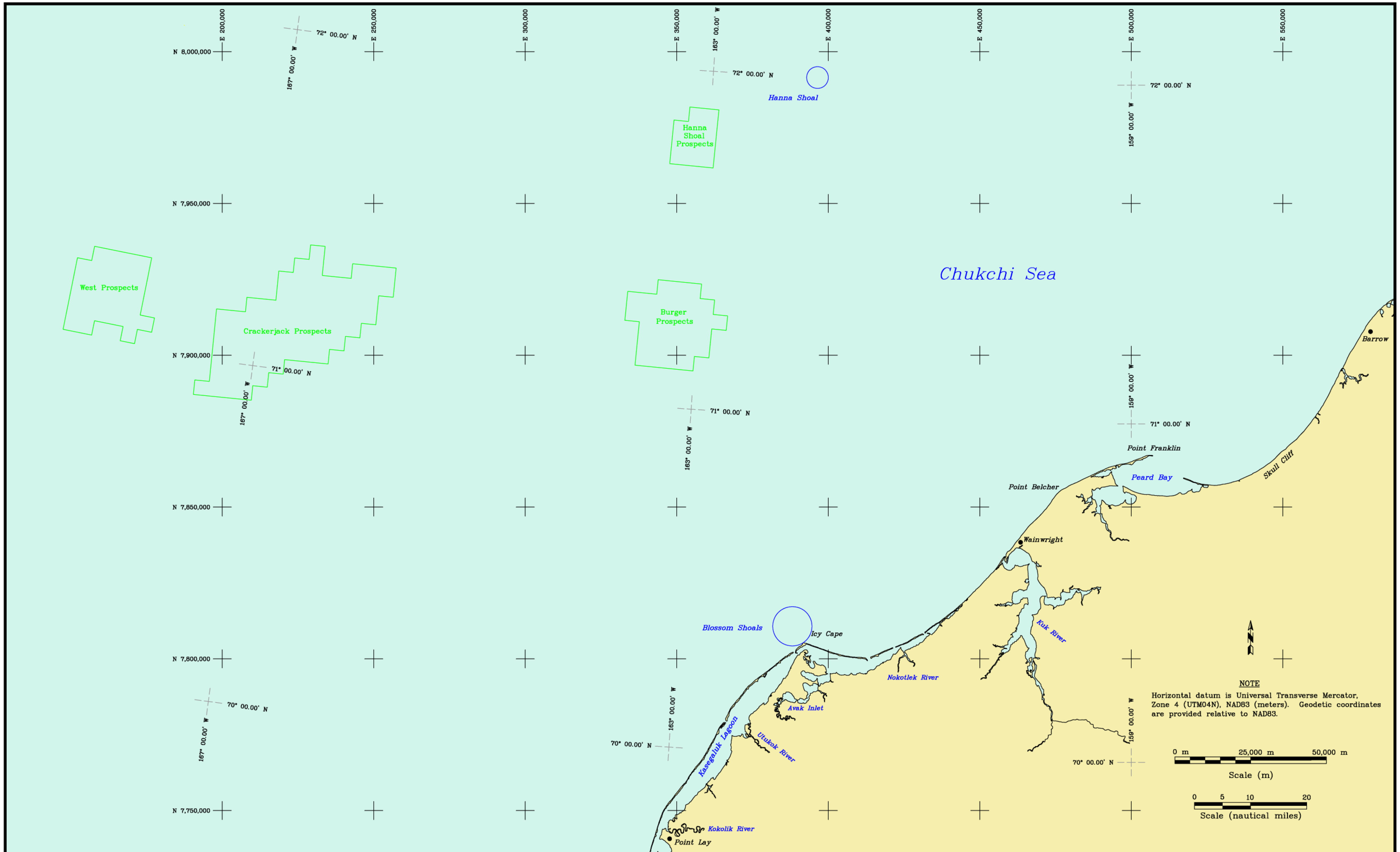


Figure 4. Geographic Points of Interest in Chukchi Sea

2. PRIOR STUDIES

As indicated in Section 1, six annual freeze-up studies were conducted as joint industry programs from 1980-81 through 1985-86 (Vaudrey, 1981; 1982; 1983; 1984; 1985; 1986). In addition, a joint industry freeze-up study was undertaken in 2009-10 (Coastal Frontiers and Vaudrey, 2010).

The findings of the 1980s freeze-up studies were made available to the present project through the courtesy of Shell (Reece, 2009). The primary objectives of each study were twofold: (1) observe and record major ice movement events and their effects on man-made islands and structures, and (2) document the size and distribution of multi-year floes, the locations of major first-year ridges and rubble fields, and the zonation of the nearshore ice. Each study included a series of aerial surveys conducted at two- to three-week intervals from early October until early December to monitor the progression of freeze-up.

The first three studies (1980-81 through 1982-83) were limited to the central Beaufort Sea, from Cape Halkett on the west to Flaxman Island on the east. The last three studies (1983-84 through 1985-86) were expanded significantly to include the entire region between Icy Cape in the Chukchi Sea and Barter Island in the Beaufort Sea. Occasionally, the eastern boundary of the reconnaissance flights was extended to points east of Barter Island, sometimes going as far as the Canadian border. Each of the three studies commencing in 1983, 1984 and 1985 included an additional trip at the end of January to record late freeze-up ice movements caused by storms occurring after the early December visit. Meteorological data, including wind speed and direction as well as air temperature, were acquired from coastal or near-coastal reporting stations at Deadhorse airport, the NOAA facility at Barrow, and the Barter Island DEW station.

Based on the observations made during the reconnaissance flights, the chronology of each freeze-up season was established. Areas of emphasis included the first occurrence of sea ice, the ice growth, and the various ice types (first-year, second-year, and multi-year) present during each stage of the freeze-up process. Ice pile-up events on man-made structures and islands and on natural barrier islands and the mainland shore were noted and described. The storms that created these events were identified and quantified in terms of their intensity, duration, and direction. The progress of the freeze-up season was documented by reporting the ice conditions observed during each successive survey trip.

Key findings from the freeze-up studies conducted in the 1980s are presented below:

Beaufort Sea: 1980s

- **Initiation of Freeze-Up:** Freeze-up occurred in the nearshore Beaufort Sea between late September and early October, generally coinciding with the accumulation of 40 to 50 FDD. Warming trends in October retarded initial ice growth by 7 to 10 days in 1983 and 1985 and by almost three weeks in 1984.
- **Landfast Ice and Shear Zone Development:** Persistent easterly winds in the Beaufort Sea were found to create a grounded shear zone that provided stability for the landfast ice. In contrast, intermittent westerly winds during freeze-up maintained the dynamics of the ice cover and prevented landfast ice stability. Freeze-up seasons without westerlies tended to have a well-established shear zone and stable landfast ice.
- **Ice Pile-Ups and Rubble Pile Formation:** The potential for significant ice pile-up on natural shorelines and man-made facilities was found to increase during storm reversals, especially during the first two months after freeze-up. Two such ice movement sequences occurred during the six-year study period. The first, in November, 1981, was caused by a westerly that loosened the landfast ice followed by an easterly that drove the sheet ice back into the shoreline. The second, in mid-October, 1982, resulted from an easterly that created a lead offshore of the temporary fast ice followed by a strong westerly that dislodged the fast ice and drove it up the slopes of man-made drilling islands and onto their work surfaces.

  The severity of ice pile-up events, in terms of pile-up height and encroachment distance, was found to correlate primarily with the loss of confinement and secondarily with the intensity and duration of the storm.

  The storm reversals that caused shoreline pile-ups often created significant rubble piles offshore, especially on Stamukhi Shoal and Weller Bank. Several large rubble piles were observed in 10 to 12 m of water, 10 to 15 nm (19 to 28 km) northwest of Seal Exploration Island (the current location of Northstar Production Island), during a strong southwesterly in late December, 1983.
- **Multi-Year Ice:** Multi-year ice was present in varying concentrations in the nearshore zone of the central Beaufort Sea during each of the six freeze-up seasons studied. The most extensive multi-year ice invasion occurred in late September, 1980, with a 3- to 5-tenths concentration located 2 to 3 nm (4 to 6 km) offshore of the barrier islands from Cross to Flaxman. Multi-year ice presence in 1981, 1982 and 1984 was limited to localized belts and patches of small floes and isolated ridge fragments grounded in the shear zone. During the summer of 1983, mild winds and cold air temperatures produced a significant concentration of second-

year ice in the nearshore region in early October. Two years later, in October, 1985, most of the multi-year ice lay north of a line that roughly paralleled the coast 15 to 20 nm (28 to 37 km) offshore.

Chukchi Sea: 1980s

- **Initiation of Freeze-Up:** In 1983, freeze-up near Barrow occurred around October 1. This early date appears to have resulted, at least in part, from the cooling and stabilizing influence of old ice present in the region. In 1984 and 1985, the nearshore waters of the Chukchi remained ice free until late October and mid-October, respectively.
- **Landfast Ice and Shear Zone Development:** Landfast ice development along the Chukchi coast was found to be very limited in extent due to the predominant easterly winds. These winds repeatedly opened a coastal flaw lead which, in turn, promoted ice production when refreezing occurred in the lead.
- **Ice Pile-Ups:** As in the Beaufort Sea, it was noted that storm reversals during the freeze-up season can lead to shoreline pile-ups along the Chukchi coast, especially near the village of Barrow and near Point Belcher (Figure 4). However, an absence of strong winds in 1983 and a lack of storm reversals in both 1984 and 1985 minimized the number of pile-ups observed on the Chukchi coast.
- **Multi-Year Ice:** Cold air temperatures and a lack of strong winds during the summer of 1983 produced a significant concentration of second-year ice north of the 71°N parallel in the Chukchi Sea in early October. In November 1984, a 2- to 3-tenths concentration of multi-year ice in the western Beaufort Sea was advected into the northern Chukchi. It remained north of the 71°N parallel through late January 1985, and was located well offshore of the prevailing 10- to 20-nm (19- to 37-km) wide coastal flaw lead. The multi-year floes typically ranged from 300 to 600 m in diameter, with a maximum value of 4 km. In October 1985, the concentration of multi-year ice in the Chukchi exceeded that in the Beaufort, and the ice was located closer to the coast.

Significant findings from last year's 2009-10 freeze-up study include the following:

Beaufort Sea: 2009-10

- **Initiation of Freeze-Up:** Freeze-up in the nearshore portion of Beaufort Sea occurred during the third week in October.

- **Landfast Ice and Shear Zone Development:** An intense easterly storm in late December created a grounded shear zone to the west of Prudhoe Bay that remained intact through midwinter. In contrast, westerly winds in January 2010 removed much of the landfast ice off the barrier islands to the east of Prudhoe Bay, and the ice remained dynamic through mid-February.
- **Ice Pile-Ups:** Ice pile-ups were observed on or adjacent to six natural barrier islands and one man-made island during the reconnaissance flights conducted in early February. The estimated pile-up heights ranged from 1 to 16 m. The largest pile-up exceeded 2 km in length.
- **Multi-Year Ice:** For the first time since 2001-02, multi-year ice floes invaded the nearshore waters of the Alaskan Beaufort Sea. The floes remained 10 to 20 nm (19 to 37 km) offshore as they migrated toward the west and ultimately entered the Chukchi Sea.

Chukchi Sea: 2009-10

- **Initiation of Freeze-Up:** Freeze-up proceeded more slowly than in the Beaufort, with the ice edge advancing to the south and west during the month of November. By the end of the month, ice covered the Chukchi Sea north of Cape Lisburne and east of 1`69°W.
- **Landfast Ice and Shear Zone Development:** Alternating periods of easterly and westerly winds repeatedly dislodged the nearshore ice between Barrow and Point Lay, causing the freeze-up process to start anew. As a result, most of the coast lacked a shear zone with sufficient grounding to stabilize the offshore boundary of the landfast ice, and the ice remained susceptible to removal during easterly storms.
- **Ice Pile-Ups:** Nineteen ice pile-ups were observed on the Chukchi Sea coast during the February reconnaissance flight, including three that encroached substantial distances onto the beach. The most significant pile-up extended 150 m alongshore and attained a maximum height of 15 m. The maximum heights of the other pile-ups ranged from 4 to 10 m.
- **Multi-Year Ice:** The multi-year ice that entered the northern Chukchi Sea from the western Beaufort split into two separate branches that persisted throughout the winter: (1) a northern branch that remained above the 71.5°N parallel in the eastern and central Chukchi before dipping south, and (2) a southern branch that extended southwest from Barrow to the vicinity of the 70°N parallel.

3. DATA ACQUISITION AND ANALYSIS

As indicated at the outset, the 2010-11 Freeze-Up Study was conducted using a combination of remotely-sensed data and on-site observations. This section describes the various sources of data and the methods of analysis. The discussion is subdivided into the following five categories: meteorological data (Section 3.1), ice charts (Section 3.2), satellite imagery (Section 3.3), telemetry buoy data (Section 3.4), and the aerial reconnaissance missions (Section 3.5). Digital files containing the data are provided on the CD that constitutes Appendix B.

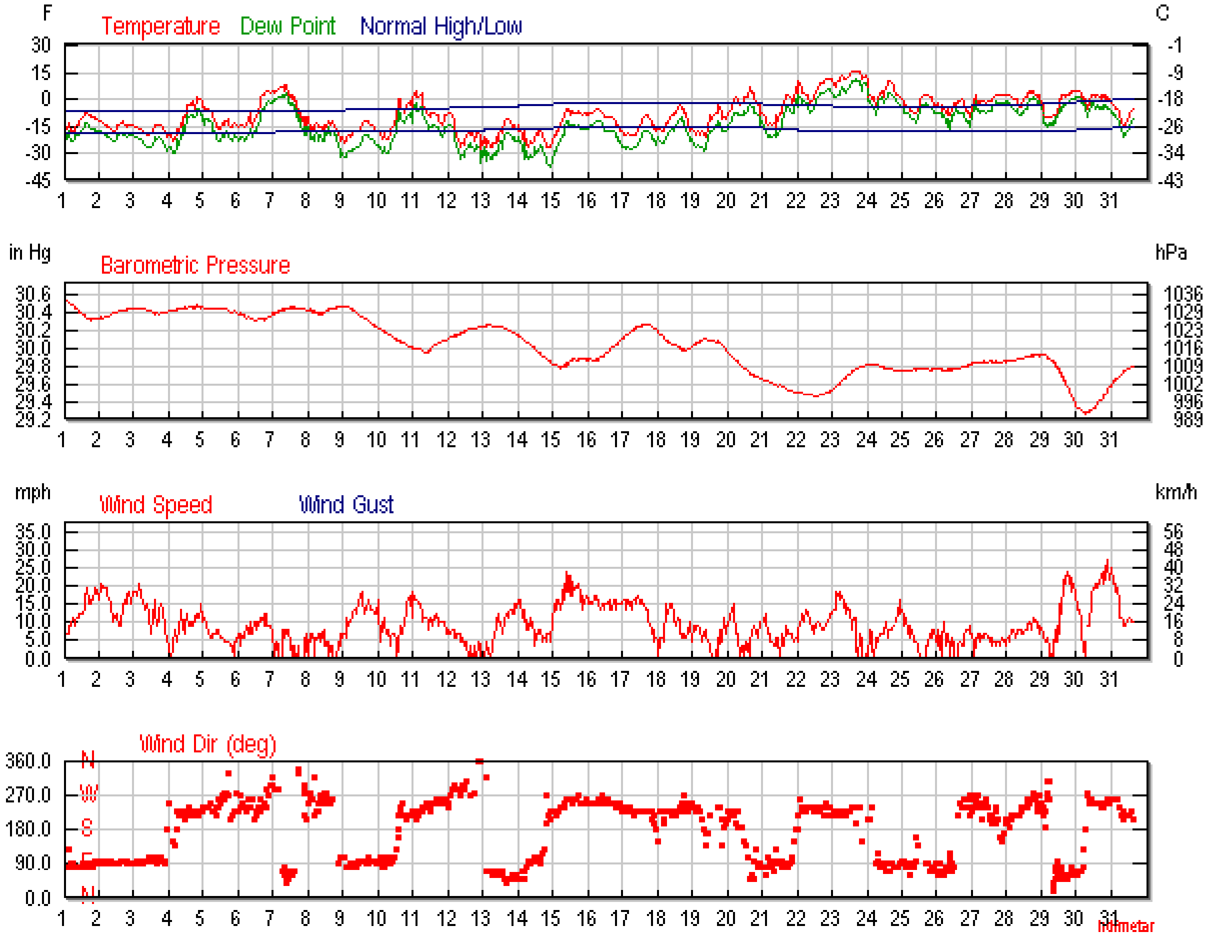
3.1 Meteorological Data

Meteorological data were obtained from two publicly-available sources: the Weather Underground (2011) and the National Ocean Service (2011). The following data were downloaded from the Weather Underground website for the Barrow and Deadhorse Airports covering the eight-month period from October 2010 through May 2011:

- Monthly plots of air temperature, barometric pressure, wind speed, and wind direction (included as *.gif files in Appendix B, with a representative example shown in Figure 5);
- Monthly tabulations of daily wind, temperature, barometric pressure, dew point, humidity, visibility, and precipitation data (compiled in an Excel spreadsheet in Appendix B).

The wind data were used to identify storm events and changes in wind direction that initiated significant ice movements. Although the monthly plots developed by the Weather Underground provide a useful overview of the wind conditions (*e.g.*, Figure 5), the tabulated values of sustained wind speed and wind direction were replotted to obtain better resolution while also displaying the wind speeds in knots rather than miles per hour. These plots appear in the assessments of meteorological conditions that are presented in Sections 4 and 5.

The air temperature data were used to derive freezing degree days (FDD), which were computed for each day as the difference between the freezing point of seawater (29°F) and the mean air temperature. The daily values were accumulated over the nine-month period from September 2010 through May 2011, with “negative” freezing-degree days (when the mean daily air temperature exceeded 29°F) subtracted from the total. The results for both Barrow and Deadhorse are shown in Table 1.



Source: Weather Underground, 2011

Figure 5. Meteorological Data Recorded at Deadhorse Airport in March 2011

Table 1. Cumulative Freezing-Degree Days (<29°F) at Barrow and Deadhorse in 2010-11

Site	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Barrow	7	199	739	1925	3121	4113	5216	6117	6388
Deadhorse	24	292	848	2220	3523	4535	5710	6662	6950

To supplement the data obtained from the Weather Underground, monthly plots of air temperature, sea water temperature, barometric pressure, wind speed, and wind direction measured at the Prudhoe Bay West Dock Seawater Treatment Plant were downloaded from the National Weather Service website for the period from October 2010 through March 2011. The plots are included as PNG files in Appendix B.

3.2 Ice Charts

Ice charts were downloaded from two publicly-available sources: the Canadian Ice Service ("CIS"; 2011) and the National Ice Center ("NIC"; 2011). Although the charts from both organizations provide similar information, the CIS products tend to incorporate greater detail. However, coverage is limited to the Beaufort Sea and extreme northeast portion of the Chukchi. The NIC produces separate charts for the Beaufort and the entire Chukchi.

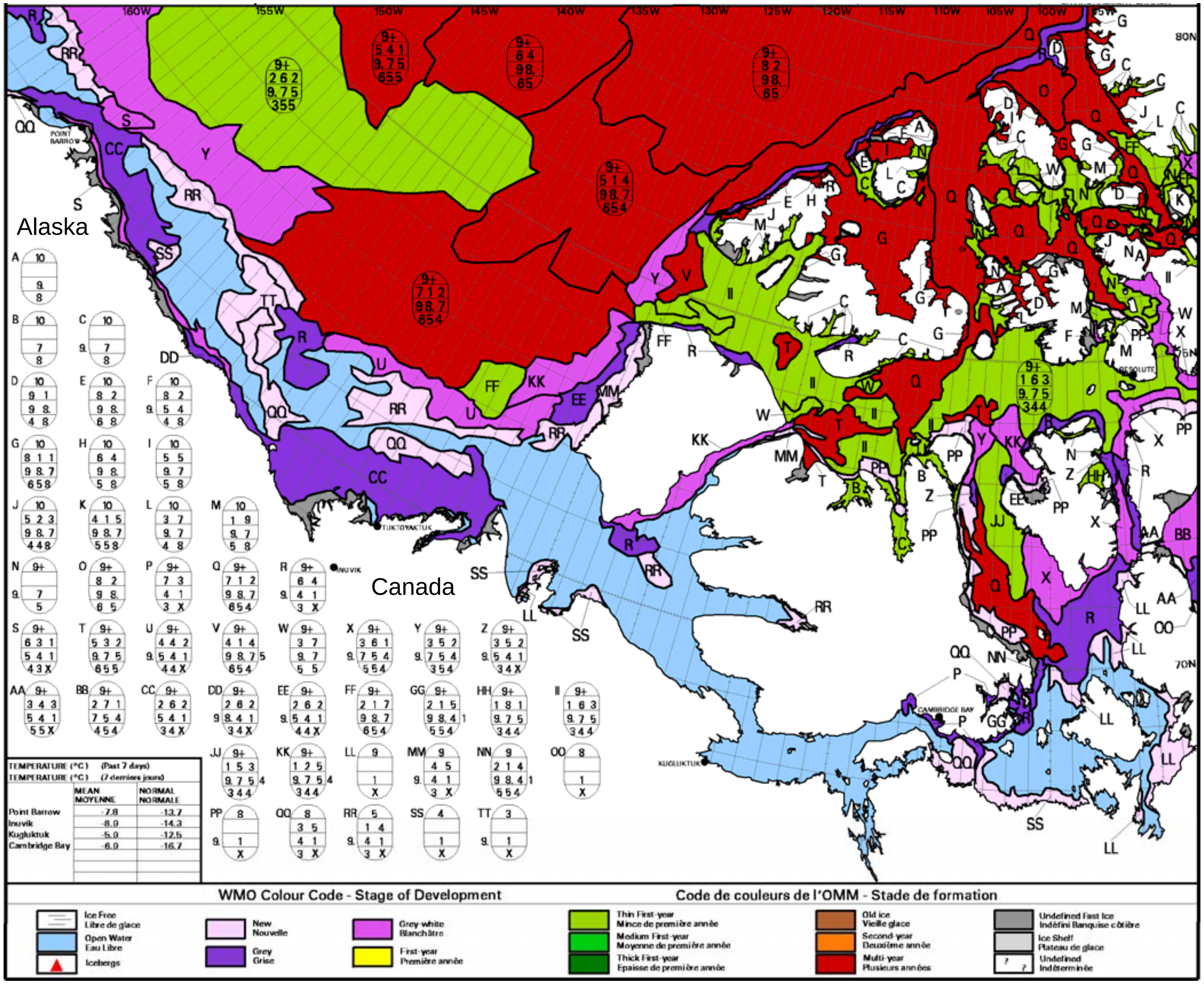
Twenty pairs of ice charts showing concentration and stage of development were obtained from the CIS for the period from October 4, 2010, through March 28, 2011. The charts, which were issued on a weekly basis through December and bi-weekly thereafter, are provided as GIF files in Appendix B. A sample Stage-of-Development chart for November 1st, immediately prior to complete freeze-up in the Alaskan Beaufort Sea, is included as Figure 6.

Sixty three ice concentration charts covering the period from October 4, 2010, through March 28, 2011 were obtained from the NIC, consisting of thirty Beaufort Sea charts and thirty three Chukchi Sea charts. The charts typically were issued twice per week in October and November, and once per week thereafter. A representative example that displays the Chukchi Sea on November 22nd, prior to complete freeze-up, is provided as Figure 7. PDF files of all of the NIC charts are included in Appendix B.

The ice charts from both organizations were used to track the evolution of freeze-up on a coarse scale, particularly during the early stages of the process. They were not sufficiently detailed to support the investigation of fine-scale features such as individual ice floes and ice movement lines.

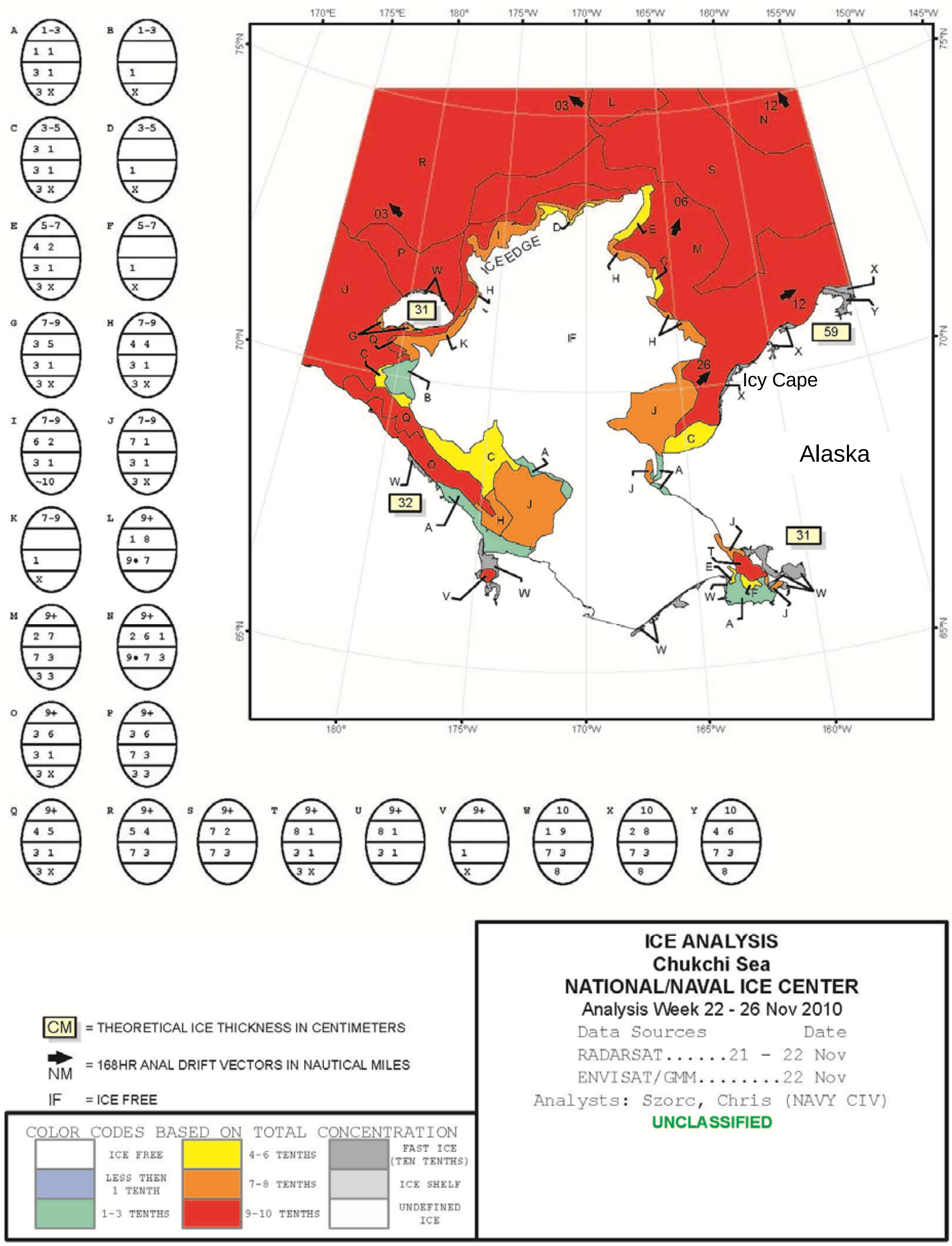
3.3 Satellite Imagery

Three different types of satellite imagery were used to study the ice conditions that prevailed during the 2010-11 freeze-up season: RADARSAT-2, AVHRR (Advanced Very High Resolution Radiometer), and MODIS (Moderate Resolution Imaging Spectro-radiometer). The RADARSAT imagery served as the primary source of ice data, while the AVHRR and MODIS imagery were used in supplemental roles.



After: Canadian Ice Service, 2011

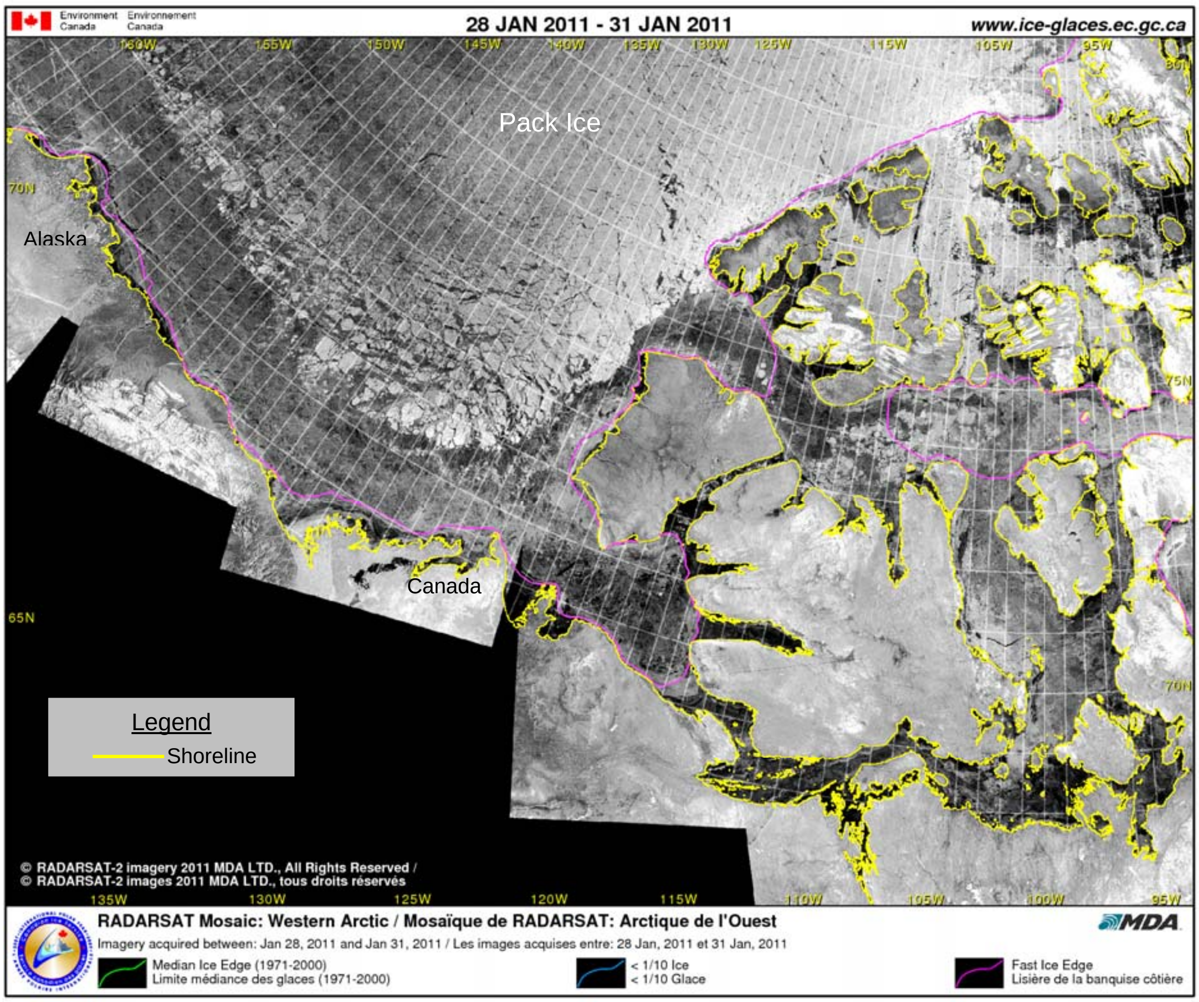
Figure 6. CIS Ice Chart of Beaufort Sea for November 1, 2010



After: National Ice Center, 2011

Figure 7. NIC Ice Chart of Chukchi Sea for November 22, 2010

General information about the progress of freeze-up was obtained from twenty publicly-available RADARSAT mosaics compiled by the CIS (2011) for the period from October 4, 2010 until March 28, 2011. The mosaics, which were produced on a weekly basis from October through December and bi-weekly thereafter, are provided as GIF files in Appendix B. Although the resolution was inadequate to support detailed analysis, the composite images provided useful information on synoptic-scale ice conditions. A representative example that illustrates the considerable separation between the perennial pack ice and the Alaskan coast at the end of January 2011 is shown in Figure 8.



After: Canadian Ice Service, 2011

Figure 8. CIS RADARSAT Image of Beaufort Sea for January 28-31, 2011

The most useful RADARSAT-2 images were provided by Shell, which supplied seventeen high-resolution, geo-referenced scenes of the Beaufort and nineteen of the Chukchi. The former were acquired between October 3, 2010, and February 13, 2011 while the latter were acquired between October 7th and February 12th. Each image was obtained using the ScanSAR Wide beam mode, which provides a nominal resolution of 100 m over a nominal area of 270 x 270 nm (500 x 500 km; MacDonald, Dettweiler and Associates Ltd., 2009). These characteristics were sufficient not only to track the general evolution of the ice conditions during freeze-up and early winter, but also to support detailed investigations of specific features and phenomena that included the landfast ice edge, multi-year ice floes, and ice movement over extended periods of time.

The licensing agreement for the RADARSAT-2 images prohibits the distribution of the original geo-referenced TIF images. Accordingly, each scene is provided in Appendix B in JPG format. A representative example showing the Chukchi Sea on December 8th, immediately after freeze-up, is provided in Figure 9.

Numerous AVHRR images were downloaded from the National Weather Service Alaska Region Headquarters (2011) for the primary purpose of bridging the chronological gaps between RADARSAT scenes. These images, which were obtained on an as-needed basis from October 2010 through March 2011, are provided as JPG files in Appendix B. A sample scene in Figure 10 shows a narrow strip of temporary fast ice in the Chukchi Sea with a large expanse of broken ice offshore. In the Beaufort, a lobe of temporary landfast ice off Harrison Bay tapers to an extremely narrow strip off the barrier islands that lie to the east of Prudhoe Bay.

The utility of the AVHRR imagery was limited by the sensor's 1-km resolution and inability to penetrate cloud cover. Notwithstanding these limitations, the availability of multiple scenes per day allowed large-scale changes in the ice canopy to be tracked on a short-term basis.

MODIS imagery, like AVHRR imagery, was acquired to supplement the RADARSAT scenes. Unfortunately, the sensor's maximum resolution of 250 m was outweighed by its inability to penetrate cloud cover, its dependence on light in the visible spectrum, and its inability to image the region north of the 72°N parallel. As a result, limited numbers of useful scenes were acquired prior to the onset of darkness in early November and subsequent to the return of daylight in mid-February. The images, downloaded from the MODIS Rapid Response website (NASA, 2011), are provided as JPG files in Appendix B. Figure 11 presents an image acquired on March 3rd, at which time a flaw lead was evident off the northern Chukchi coast.

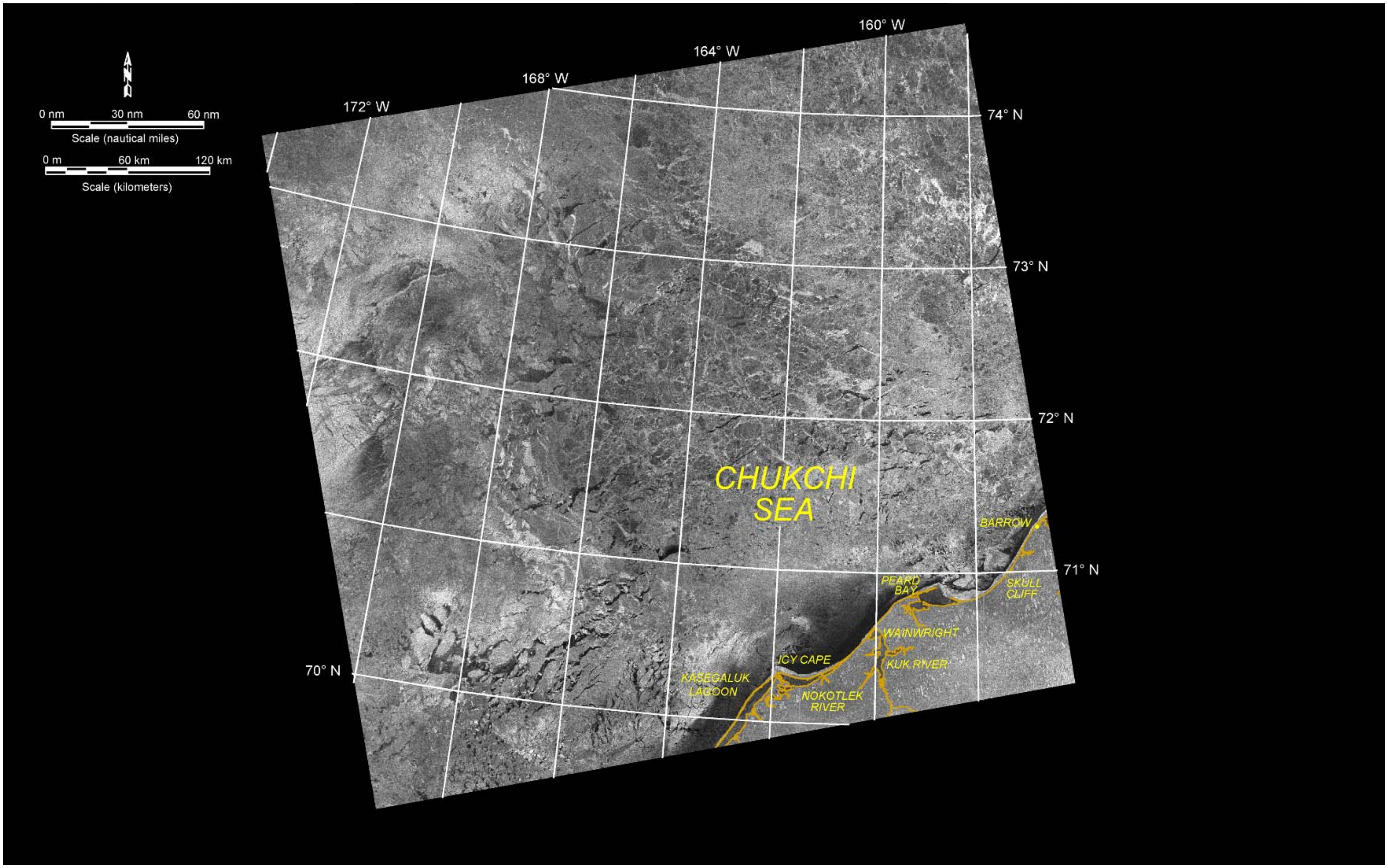
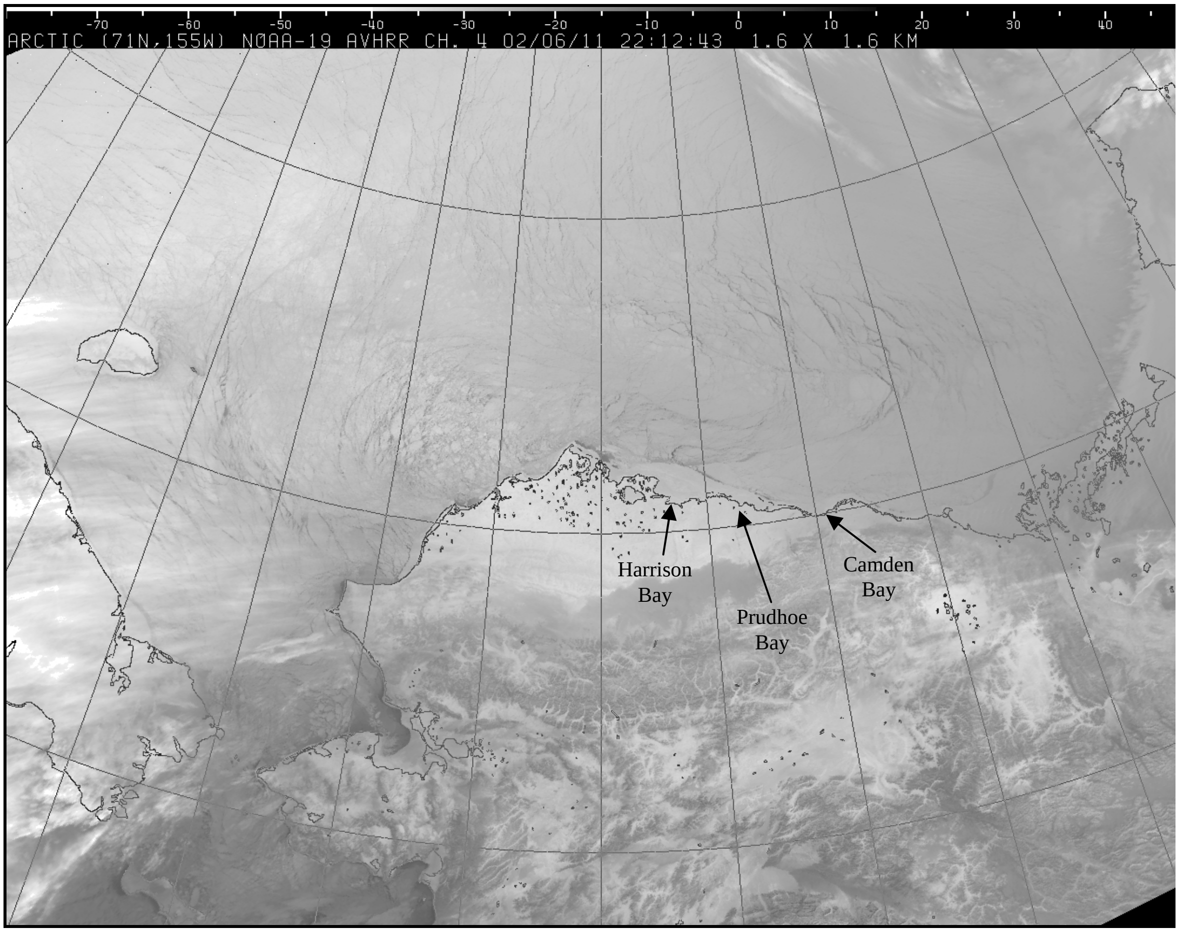


Figure 9. RADARSAT-2 Image of Chukchi Sea Acquired on December 8, 2010



Source: National Weather Service, 2011

Figure 10. AVHRR Image of Beaufort and Chukchi Seas on February 6, 2011

3.4 Iridium Telemetry Buoys

On January 26, 2011, Shell installed seven Iridium telemetry buoys in the Beaufort Sea to document ice movement. Four of these buoys were located off Flaxman Island on the west side of Camden Bay, while three were located off Spy Island on the east side of Harrison Bay. The buoy positions were transmitted hourly via satellite and compiled on a proprietary website. Shell contributed the data to this project in the interest of developing a more complete understanding of ice dynamics during the early-winter period (Hansen, 2010). The information proved to be extremely useful both in correlating storm events with ice movements and in defining the boundary between stationary landfast ice and mobile pack ice.

As shown in Figure 12, all seven buoys tended to follow coast-parallel trajectories at varying rates of speed from the time of deployment in January through the end this study's

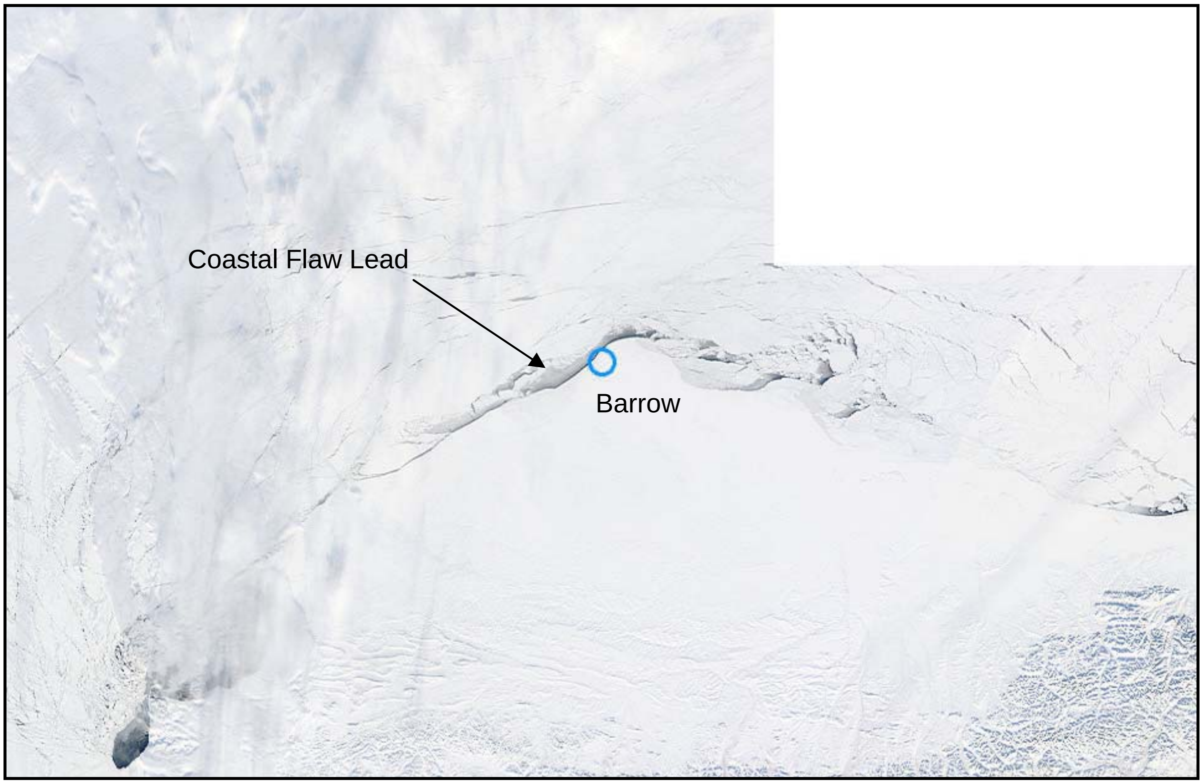
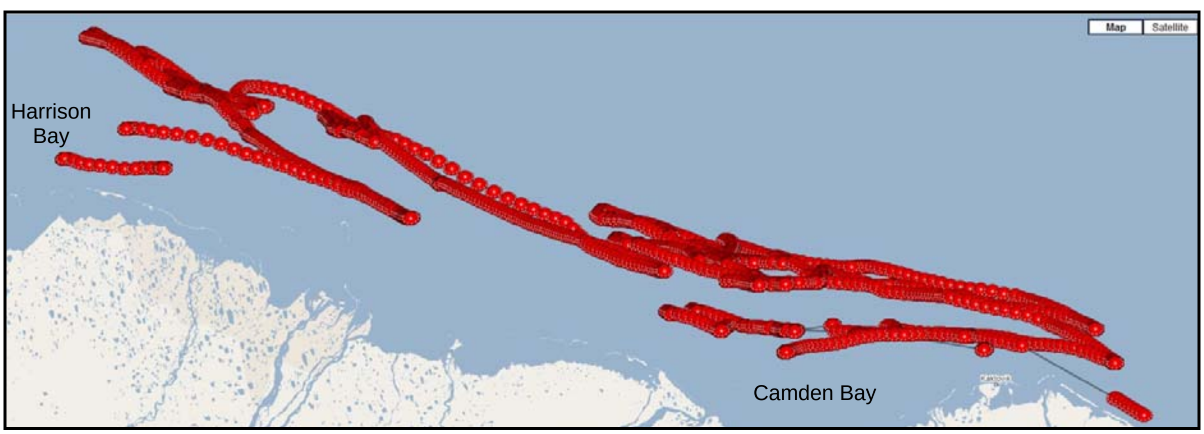


Figure 11. MODIS Image of Beaufort and Chukchi Seas on March 3, 2011

monitoring period on March 31st. Because many of the buoys had moved away from Shell's areas of interest, two replacements were installed in the Camden Bay area and three in the Harrison Bay area on March 16th. Figure 13 illustrates that all five replacement buoys remained stationary or moved only short distances through March 31st. The hourly position data for all twelve iridium buoys are tabulated in an Excel spreadsheet that appears in Appendix B.



Source: Joubeh Technologies; © Joubeh Technologies, 2008 – All Rights Reserved

Figure 12. Trajectories of 7 Original Iridium Buoys, February 4 – March 31, 2011

Source: Joubeh Technologies; © Joubeh Technologies, 2008 – All Rights Reserved

Figure 13. Trajectories of 5 Replacement Iridium Buoys, March 17 – 31, 2011

3.5 Aerial Reconnaissance Missions

Five aerial reconnaissance missions were conducted in early February 2011 with the intent of acquiring on-site information to supplement the remotely-sensed data obtained from other sources. The specific objectives were as follows:

- Obtain ground truth information to confirm and expand upon the conclusions drawn from satellite imagery;
- Investigate major features identified in the satellite imagery, such as leads and well-developed shear lines;
- Detect, investigate, and document small-scale ice features and characteristics that were beneath the resolution of the satellite imagery, including shoreline pile-ups, offshore rubble piles and ridges, and the stability of the landfast ice.

Four of the missions were conducted using a de Havilland Twin Otter (Plate 2). This fixed-wing aircraft offered the benefits of an extended range, an ability to fly at relatively slow speeds, a high wing that permitted unobstructed views of the ice below, and a moderate cost per flight hour. The fifth mission was conducted using a Bell 212 helicopter, which provided invaluable opportunities to land at features of interest (Plate 3). The primary disadvantages of the helicopter were its limited range and high cost per flight hour.

Each flight path was mapped using either a Garmin GPSMAP 78sc or Trimble Pathfinder Pro XR receiver placed in one of the aircraft's bubble windows. To improve the accuracy of the position data, differential corrections broadcast in real time via satellite by the U.S. Government's Wide Area Augmentation System (WAAS) were received by the GPS unit when available. Static position checks conducted at North Slope survey

Plate 2. de Havilland Twin Otter at Barrow

Plate 3. Bell 212 Helicopter on Sea Ice in Mikkelsen Bay

monuments in the past have indicated that the accuracy attainable with WAAS is about 1 m. When operated in the stand-alone mode, the GPS accuracy typically is on the order of 10 m.

The GPS position data were displayed on a base map of the study area in real time using a laptop computer and Hypack survey software. This arrangement allowed the field crew both to direct the aircraft to locations of interest identified in advance from the satellite imagery and to record the locations of small-scale features noted during the flight.

The five flight paths are shown in Drawings CFC-835-01-001, -002, and -003 (Appendix A). The drawings display the locations of ice features observed during the flights as well as those of photographs taken during the flights. Each photo has been assigned a unique identification number such as "C1-18". The first portion, "C1" indicates the image was obtained during the first flight in the Chukchi Sea ("B" indicates Beaufort; "C" indicates Chukchi); the second portion, "18", indicates the image represents the 18th obtained during that flight. The photographs are provided in digital form in Appendix B, with the file names corresponding to the identification numbers shown on the drawing. The ice features observed during the flights are denoted on the drawings using the abbreviations listed in Table 2.

Table 2. Abbreviations for Ice Features

Ice Feature	Abbreviation
Active Shear Line	ASL
Broken Ice	BKN
Grounded Ice Blocks (height, m)	GIB (_m)
Inactive Shear Line	ISL
Landfast Ice	LFI
Lead	LD
Pile-Up (height, encroachment, m)	P/U (_,_m)
Refrozen Lead	RFL
Ridge (height, m)	RDG (_m)
Rubble (height, m)	RBL (_m)
Thermal Crack	TCK
Undeformed Ice	UDI

The objective and path of each flight are summarized below:

Beaufort Sea Flight No. 1 ("B1" on Drawing CFC-835-01-001)

Beaufort Sea Flight No. 1 was undertaken with the Twin Otter on February 2nd to observe the ice conditions in the central portion of the Alaskan Beaufort Sea. The flight originated in Deadhorse, proceeded north to Reindeer and Cross Islands, and then southeast along the barrier islands to Flaxman Island. Following a clockwise loop to observe the Point Thomson Central Pad and the prospective pipeline route of the Sivulliq Development, the aircraft headed east across Camden Bay to Barter Island. From Barter Island, it flew 7 nm (13 km) north before heading back across Camden Bay and continuing northwest over the first-year pack ice to Stamukhi Shoal. The remainder of the flight consisted of a leg to the south southeast over the eastern portion of Shell's Harrison Bay Prospects, a leg to the east southeast to visit Northstar Production Island, and a leg to the south southeast to return to Deadhorse. The total flight time was 3.1 hr.

Beaufort Sea Flight No. 2 ("B2" on Drawing CFC-835-01-001)

Beaufort Sea Flight No. 2, the sole helicopter mission, was undertaken on February 3rd. The intent was to investigate features of interest noted during Beaufort Sea Flight No. 1 to the extent permitted by the limited range of the helicopter. The flight originated in Deadhorse and proceeded northeast to the Sagavanirktok River Delta and the Endicott Project before heading southeast through Stefansson Sound and east into Mikkelsen Bay. The helicopter landed in Mikkelsen Bay at a site that appeared to contain undisturbed first-year ice, and the field crew measured the ice thickness using a portable drill motor and a 5-cm diameter, stainless steel ice auger (Plate 3). Although identical measurements of 122 cm were obtained in two holes located approximately 2 m apart, this thickness exceeded both the predicted value of 105 cm that was based on 3,583 cumulative FDD at Deadhorse Airport, and actual measurements of 94 to 113 cm that were obtained by others during the first week in February between West Dock and Reindeer Island (St. Lawrence, 2011). A possible explanation for this discrepancy is modest rafting of the ice in Mikkelsen Bay that occurred during the early stages of freeze-up.

After departing from the ice measurement site, the helicopter continued east along the mainland shore to the Point Thomson Central Pad before describing a clockwise loop around the Sivulliq pipeline route. It then headed east to investigate a large rubble pile off Mary Sachs Island before reversing course to follow the barrier island chain to Cross Island. Large, grounded ice blocks were observed on the seaward shorelines of all of the islands, with the largest blocks located on Cross (Plate 4). To gain a greater understanding of the nature and size of the blocks, the field crew landed on Cross Island. The ice comprising the blocks was found to be well-consolidated while the blocks themselves tended to be rounded, suggesting that they represented fragments of old ice rather than first-year rubble. The largest blocks, which were grounded on the north corner of the island, were found to be up to 5.5 m thick when measured with a hypsometer (Plate 5).

From Cross Island, the helicopter proceeded west to Northstar Production Island and then south southeast to Deadhorse. The total flight time (excluding stops) was 2.2 hr.

Beaufort Sea Flight No. 3 ("B3" on Drawing CFC-835-01-002)

Beaufort Sea Flight No.3 took place on February 4th, with the objective of documenting the ice conditions in the western Beaufort Sea between Deadhorse and Barrow. After flying north from Deadhorse to Stump Island, the Twin Otter followed the barrier island chain west to Spy Island. It then headed south along the Nikaitchuq Development flowline route to Oliktok Point, southwest along the shoreline of Harrison Bay, and northwest along the Oooguruk Development flowline route to the Oooguruk Offshore Drillsite. The aircraft proceeded northeast to a large rubble field offshore of Thetis Island before turning west to investigate an area in central Harrison Bay where two bright spots that conceivably could represent multi-year floes had been noted on the January 17th RADARSAT image (Spring, 2011). When neither multi-year ice nor other extraordinary features were found, the Otter flew east and then north through Shell's Harrison Bay Prospects until a substantial lead was encountered approximately 20 nm (37 km) off Oliktok Point. At that point, the aircraft turned to the west northwest to Weller Bank and continued to Point Barrow on a coast-parallel course located 15 to 20 nm (28 to 37 km) offshore. To the west of Weller Bank, the flight path coincided with the location of a huge refreezing lead (Plate 6) for a distance of more than 50 nm (93 km). The flight duration was 2.6 hr.

Chukchi Sea Flight No. 1 ("C1" on Drawing CFC-835-01-003)

Chukchi Sea Flight No.1 was conducted on February 5th to observe nearshore ice conditions and shoreline pile-ups between Barrow and Point Lay, a region where pipelines from the offshore prospects conceivably could make landfall. Although the original intent was to proceed southwest from Barrow while remaining 10 nm (19 km) offshore, head onshore to the coast at Point Lay, and then return to Barrow along the coast, intermittent areas of fog caused the aircraft to fly offshore from Barrow to

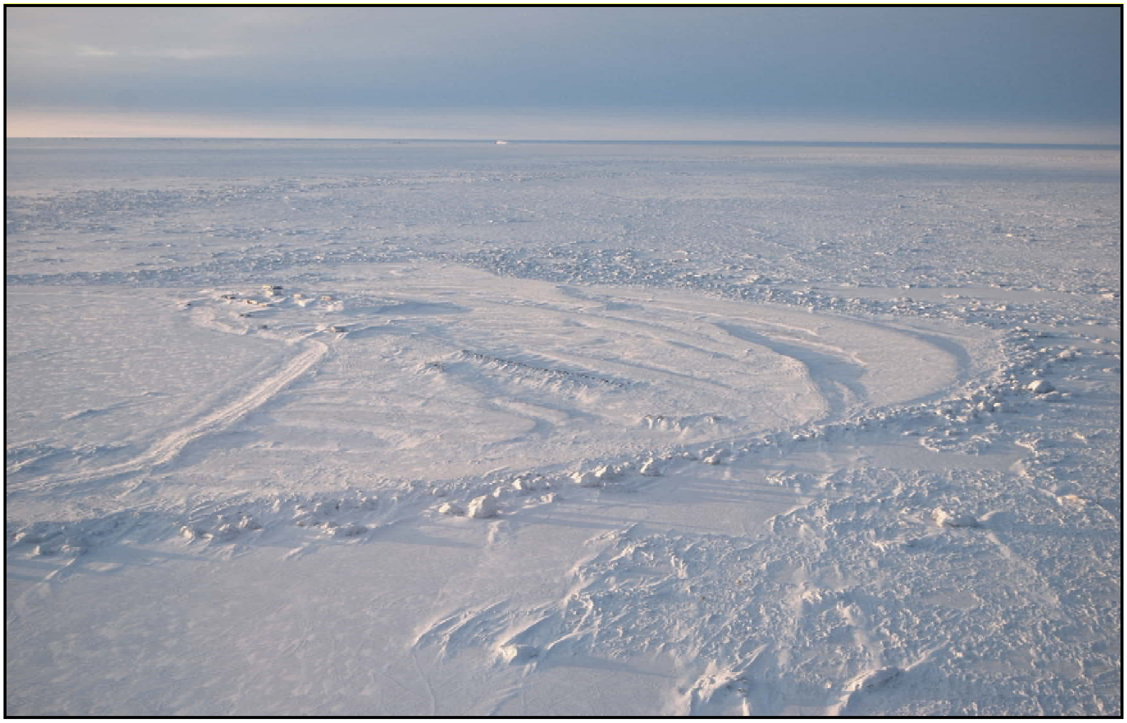


Plate 4. Grounded Ice Blocks on Northeast and Northwest Sides of Cross Island

Plate 5. 5.5-m Thick Grounded Ice Block at North Corner of Cross Island

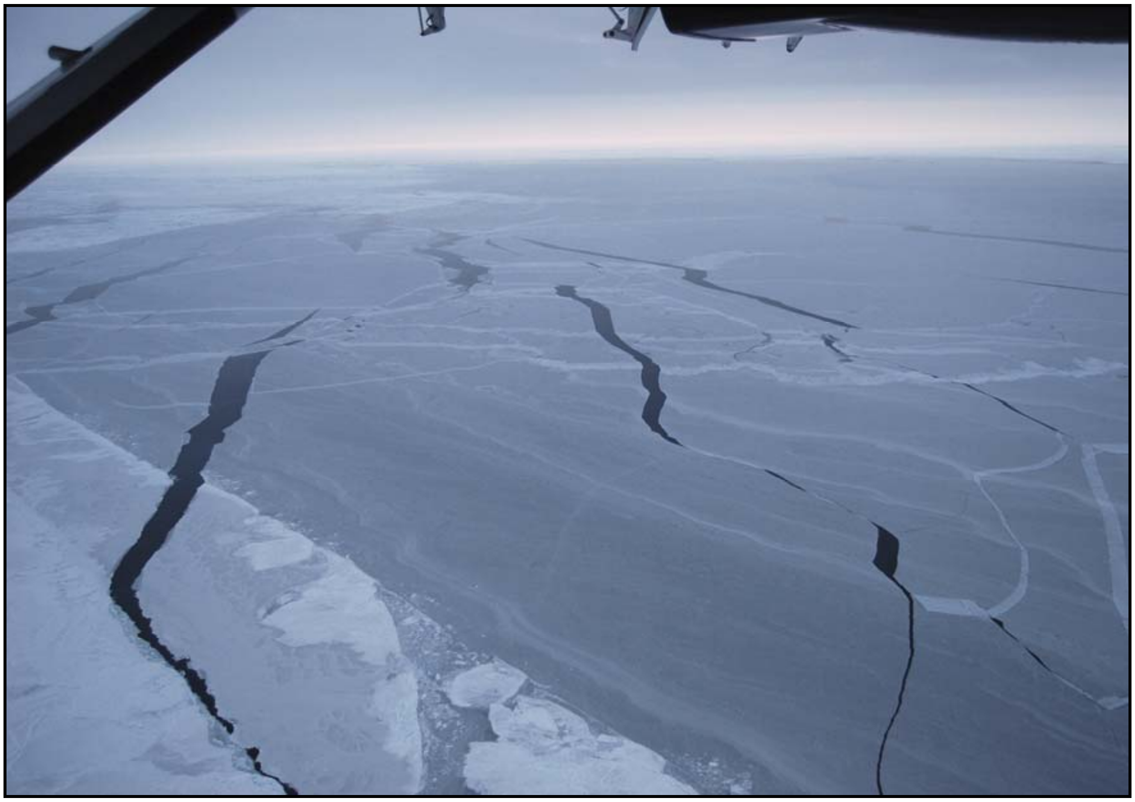


Plate 6. Huge Refreezing Lead off Pitt Point

Wainwright, onshore from Wainwright to Point Lay, offshore from Point Lay back to Wainwright, and onshore from Wainwright to Barrow with a number of smaller deviations along the way. Numerous ice pile-ups were noted along the shoreline, particularly in the region between Point Belcher and Wainwright. The flight duration was 3.4 hr.

Chukchi Sea Flight No. 2 ("C2" on Drawing CFC-835-01-003)

The final aerial reconnaissance mission, Chukchi Sea Flight No. 2, occurred on February 6th. The objective of this wide-ranging flight was to observe the ice conditions in the northern portion of the Chukchi Sea, with emphasis on Shell's Burger, Crackerjack, Hanna Shoal, and West Prospects. The Twin Otter flew from Barrow to Hanna Shoal, where a significant accumulation of rubble was noted at the site of Katie's Floeberg (Barrett and Stringer, 1978). The aircraft then headed southwest through the Hanna Shoal Prospects and west southwest to the West Prospects. After looping through the West Prospects, the flight proceeded northeast through the Crackerjack Prospects, east to circle the Burger Prospects, and east again to return to Barrow. The total flight time was 4 hr.

As in the case of the 2009-10 freeze-up study (Coastal Frontiers and Vaudrey, 2010), the reconnaissance flights conducted in support of the 2010 Study provided invaluable opportunities to confirm and refine the findings derived from satellite imagery, and to expand upon those findings with respect to small-scale features and processes. The primary operational lessons learned from the two studies are as follows:

1. In the Beaufort Sea, where distances offshore are comparatively small, the relatively high cost of chartering a helicopter is warranted by the ability to land at features of interest. Without this capability, it is likely that the field crew would not have been able to distinguish the fragments of old ice that were grounded on the barrier islands from newly-formed rubble or pile-ups.

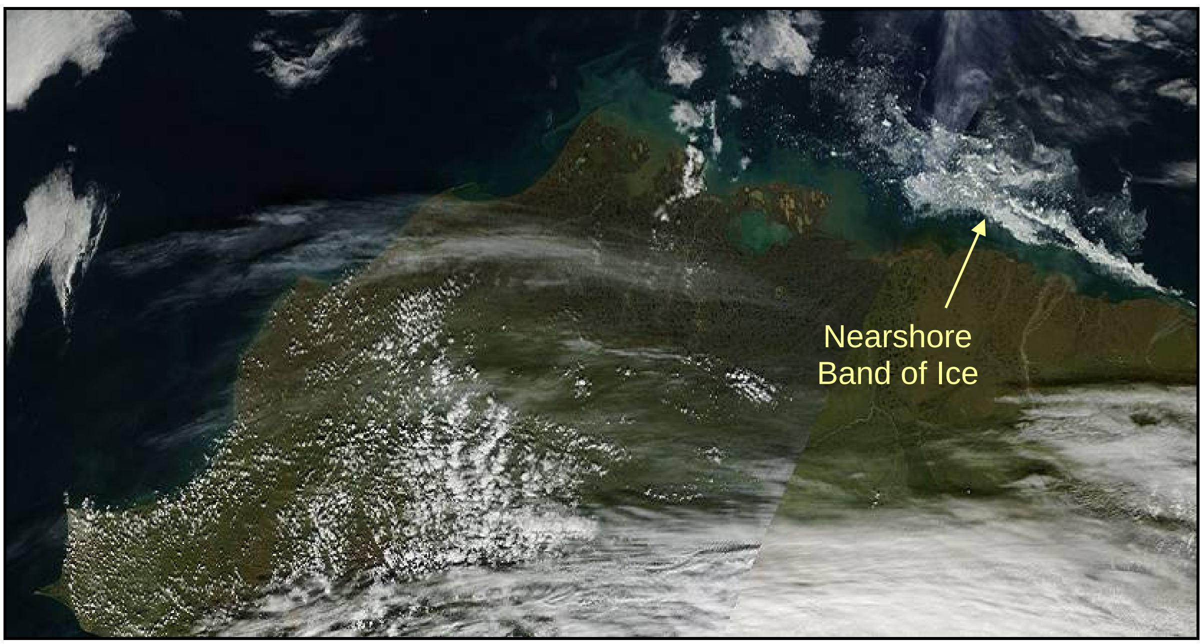
2. In the Chukchi Sea, where the distances offshore tend to be large, the cost of chartering a helicopter capable of visiting sites of interest (other than those along the coast) likely would be prohibitive.

3. If studies of this nature continue in the future, and if budgetary constraints permit, a second set of aerial reconnaissance missions conducted in late November or early December would greatly enhance the ability to interpret the early-season satellite imagery and investigate phenomena such as pile-ups that occur when the ice cover is mobile.

4. BEAUFORT SEA FREEZE-UP

4.1. Late Summer 2010

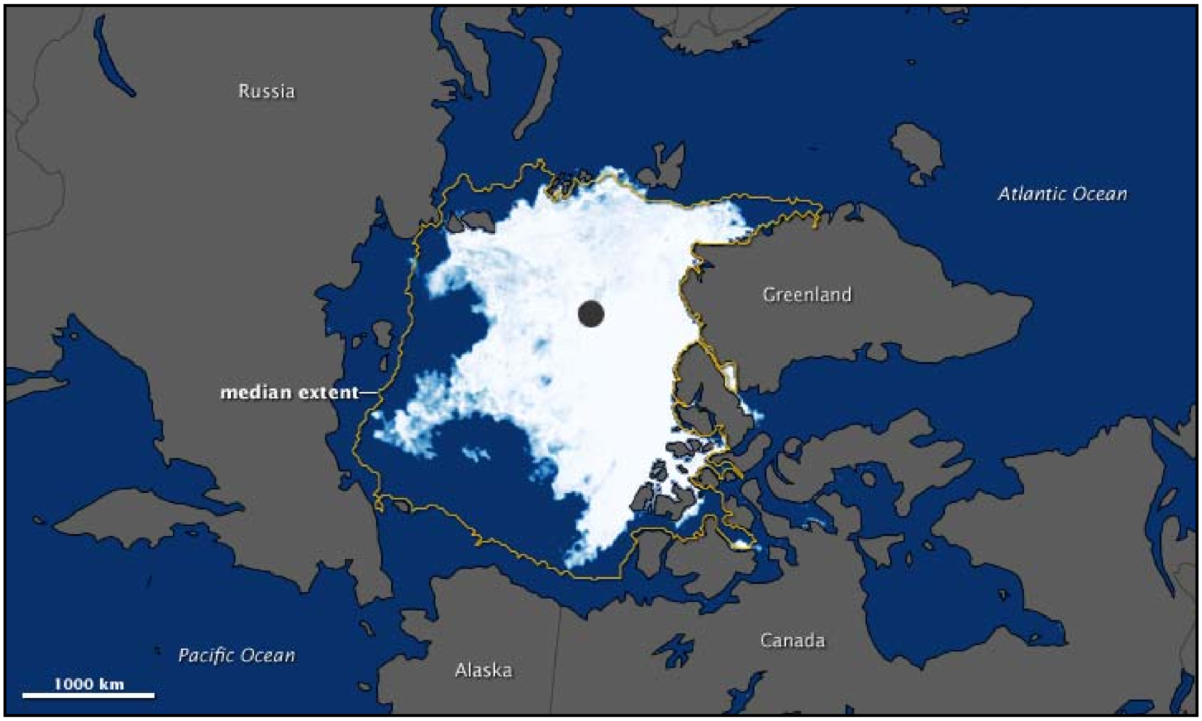
The ice cover in the Beaufort Sea diminished gradually in August 2010, with open water in the offshore area spreading from east to west. At the end of the month, the edge of the pack ice ranged from 120 to 140 nm (220 to 260 km) off the Alaskan coast. However, a band of ice persisted in the nearshore area from Flaxman Island to Smith Bay (Figure 14). The width of this feature increased from near zero at the eastern end to as much as 50 nm (93 km) off Harrison Bay. Although the band grew smaller in September, the NIC ice charts (2011) indicate that some of the ice persisted in the nearshore zone through the initiation of freeze-up in October.



Source: National Ice Center, 2011

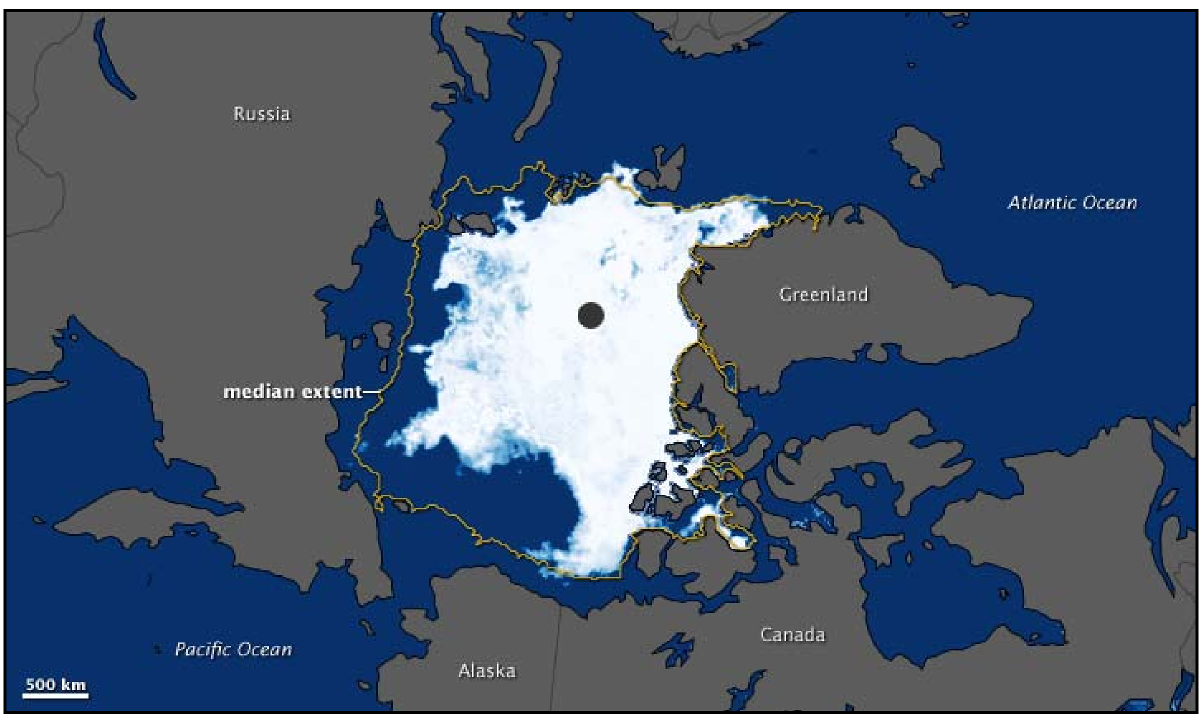
Figure 14. MODIS Image Showing Nearshore Band of Ice on August 14, 2010

The minimum summer extent of the pack ice (Figure 15) occurred on September 19th, a week later than in 2009. The total area, 4.60 million km^2, was the third lowest since satellite imagery became available in 1979 (National Snow and Ice Data Center, 2010). Lower values were recorded in 2007 and 2008, while the area in 2009 (Figure 16) was slightly higher. As shown in Figure 17, the average extent of the Arctic sea ice in September has declined substantially (at a rate of 11.2% per decade) since record-keeping began in 1979.



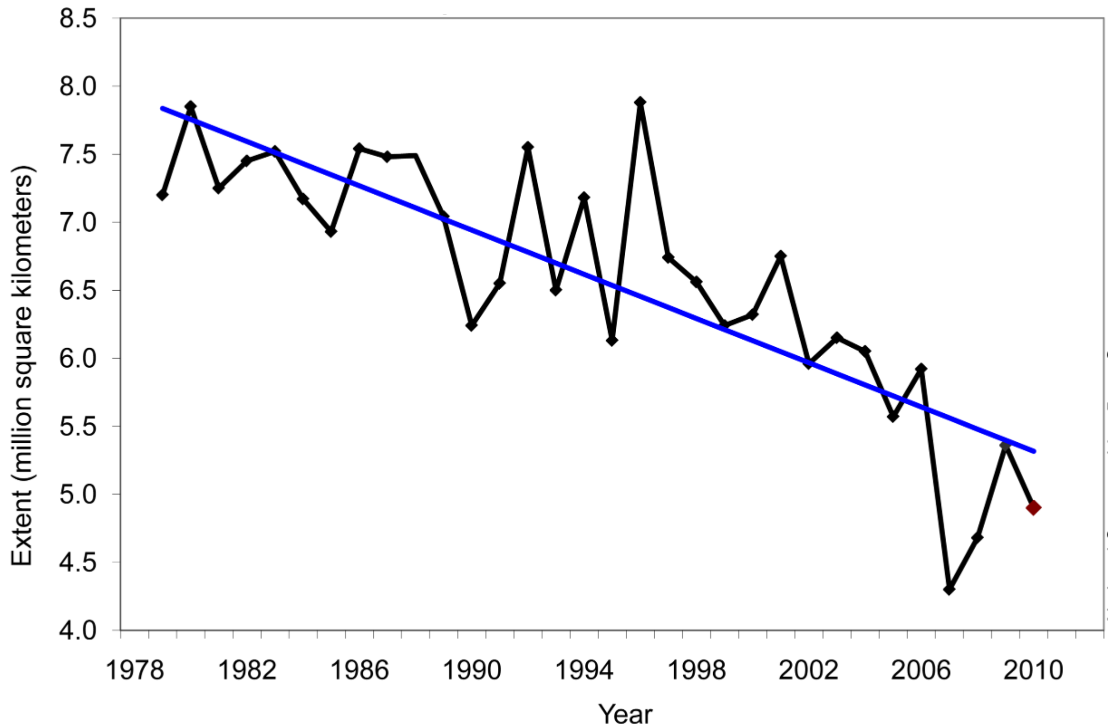
Source: National Snow and Ice Data Center, 2010

Figure 15. Sea Ice Minimum Extent on September 19, 2010



Source: NASA, 2009

Figure 16. Sea Ice Minimum Extent on September 12, 2009



Source: National Snow and Ice Data Center, 2010

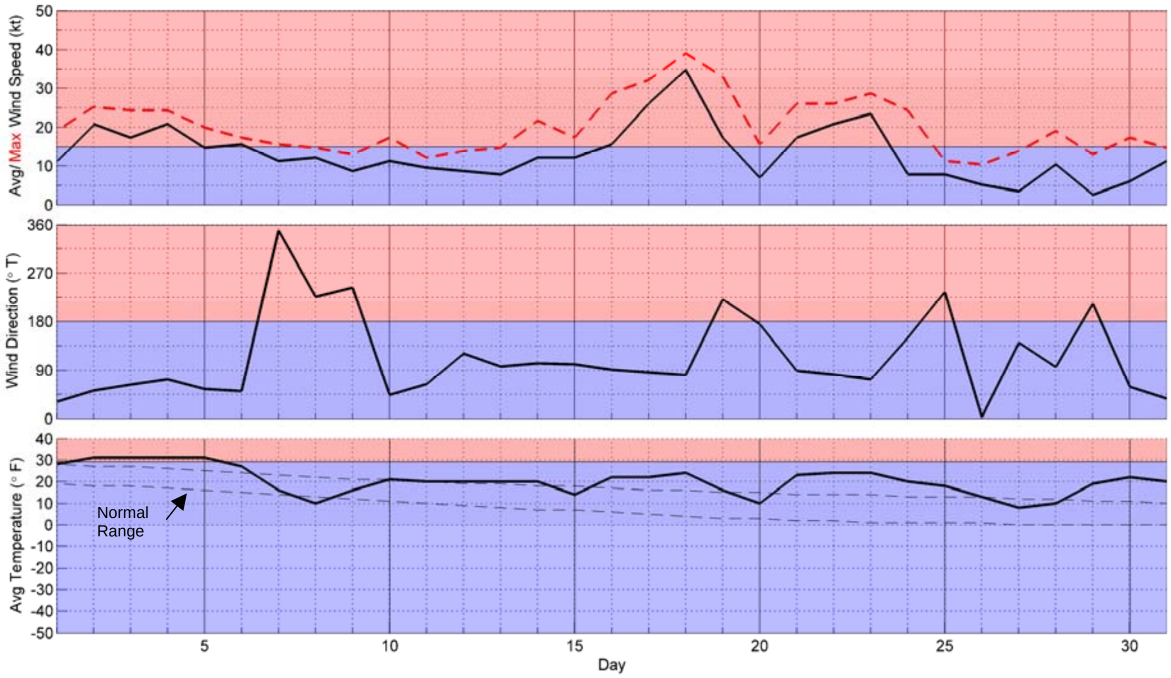
Figure 17. Average Sea Ice Extent in September, 1979-2010

Figure 15 illustrates the substantial disparity that existed between the ice edge on September 19, 2010 and median minimum value for the period from 1979 through 2000. The shortfall was particularly large off Alaska and eastern Siberia (NASA, 2010). In the case of Alaska, the NIC ice charts indicate that the distance between the ice edge and the coast ranged from about 120 nm (222 km) off Barter Island to more than 200 nm (370 km) off Point Barrow during the third week in September. By month-end, the distance had decreased to 100 nm (185 km) off Barter Island but remained nearly constant at 200 nm (370 km) off Point Barrow.

4.2. Freeze-Up

4.2.1. October 2010

Meteorological Conditions: The daily values of average and maximum sustained wind speed, average wind direction, and average air temperature at Deadhorse Airport are shown in Figure 18 along with the normal range of air temperatures defined by the long-term average values of the daily highs and lows. The significance of the red and blue color bands in this and all subsequent meteorological plots is indicated in Table 3. Unless stated otherwise, the wind speeds discussed in the text refer to the daily average values of the sustained wind speed (rather than the daily maximum values).



Source: Weather Underground, 2011

Figure 18. Meteorological Conditions at Deadhorse Airport in October 2010

Table 3. Significance of Color Bands in Plots of Meteorological Conditions

Parameter	Band Color	
	Blue	Red
Wind Speed	≤ 15 kt	> 15kt (Storm)
Wind Direction	Easterly	Westerly
Air Temperature	≤ 29°F (Freezing Point of Seawater)	>29°F

The air temperatures remained higher than normal for most of the month. Easterly winds predominated, with easterly storm events occurring on October 2nd through 6th, 16th through 19th, and 21st through 23rd. The second event was the most energetic of the entire freeze-up season, with the wind peaking at 35 kt (18 m/s) on October 18th before the direction switched from east to south and the speed dropped to 17 kt (9 m/s) on the following day. The characteristics of this and all other storms with a daily average sustained wind speed exceeding 15 kt (8 m/s) at Deadhorse Airport are presented in Table 4 for the six-month period from October 2010 through March 2011.

Table 4. Beaufort Sea Storm Characteristics, October 2010 – March 2011[1]

Month	Day	Duration (days)	Maximum Wind Speed (kt)[2]	
			Easterly	Westerly
October	2-6	5[3]	21	
	16-19	4	35	
	21-23	3	23	
November	3-4	2	28	
	9-10	2		16
	15-18	4		28
	21	1	18	
	24	1	16	
December	4	1	23	
	14	1		18
	21-22	2		20
January	2-3	2	30	
	7	1		16
	17-18	2		23
February	6	1		16
	10	1		17
	13-14	2		23
	22-26	5		34
March	15	1		16
Total Number of Events			**8**	**11**

Notes:

1. Table 4 includes all storm events with a daily average sustained wind speed exceeding 15 kt at Deadhorse Airport.
2. "Maximum Wind Speed" refers to highest daily average sustained wind speed that occurred during each storm event.
3. Daily average wind speed decreased to 15 kt on October 5 but freshened to 16 kt on October 6.

Ice Cover: Freeze-up in the Alaskan Beaufort Sea began during the first week in October, when ice began to form in the brackish waters off river deltas and in shallow bays and lagoons. Based on the NIC ice charts (2011), the nearshore region became ice-covered on or about October 11th, after about 80 freezing degree days (FDD) had accumulated at Deadhorse Airport. (Note: for the purpose of establishing a date for freeze-up, the "nearshore region" is defined as the area that typically becomes covered with landfast ice.) The ice cover that was present on the east side of Prudhoe Bay West Dock on October 20th (nine days later) is shown in Plate 7. As the month progressed, the nearshore ice spread seaward while the edge of the pack ice moved south. Progress was slowed, however, by the combined effects of the aforementioned warm air temperatures and easterly storm events. At month-end, a band of open water averaging 60 nm (111 km) in width persisted from Admiralty Bay to the Canadian border.

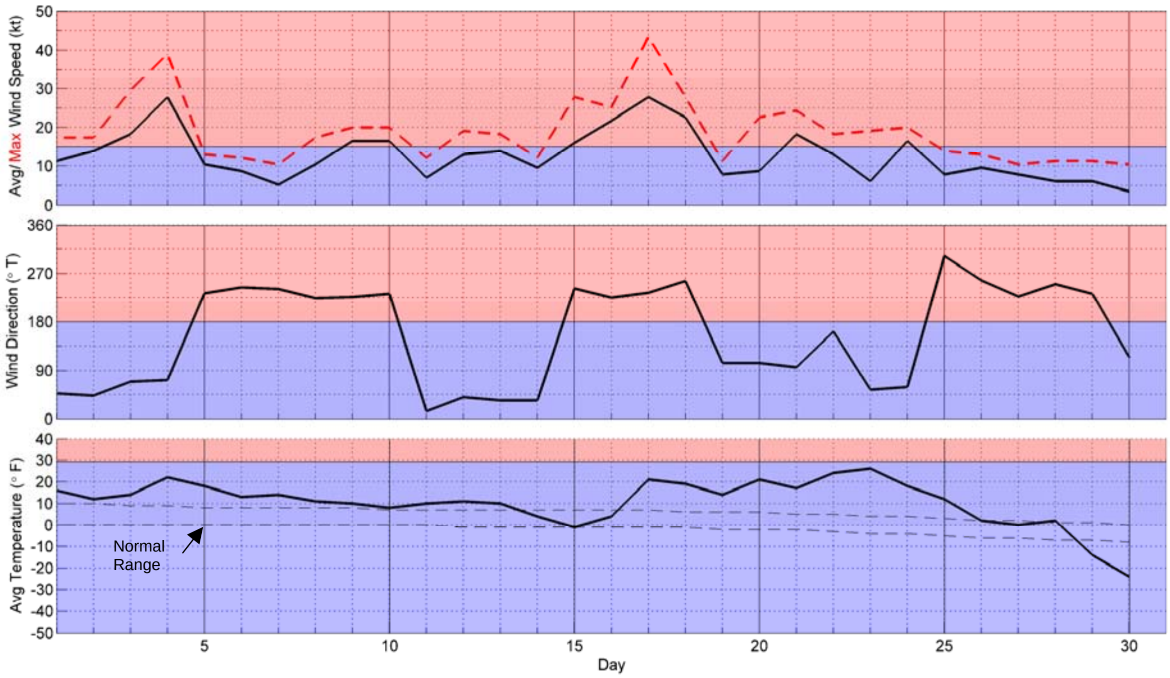
Plate 7. Ice Cover on East Side of Prudhoe Bay West Dock, October 20, 2011

<u>Ice Thickness</u>: The thickness of undisturbed first-year ice at the end of October is estimated to be 25 cm, based on the relationship of Bilello (1960) with an accumulated total of 292 FDD at Deadhorse Airport (Table 1).

<u>Ice Pile-Up</u>: As discussed in more detail in Section 4.3, a substantial ice pile-up composed of what appeared to be 10- to 15-cm thick plates was noted on the south side of the Oooguruk Offshore Drillsite in Harrison Bay during the flight over the western Beaufort Sea conducted in early February. This feature probably resulted when the winds veered to the southwest after the easterly storm of October 2nd through 6th.

4.2.2. November 2010

Meteorological Conditions: The meteorological conditions that prevailed at Deadhorse Airport in November are shown in Figure 19. The air temperatures tended to be normal or above normal until the last two days of the month, when they dropped substantially. The wind direction alternated between easterly and westerly, with changes in direction typically occurring once or twice per week.



Source: Weather Underground, 2011

Figure 19. Meteorological Conditions at Deadhorse Airport in November 2010

November was punctuated by five storm events of moderate duration and intensity (Table 4). The first was a two-day easterly that peaked on the 4th with a wind speed of 28 kt (14 m/s). Two westerlies followed, a two-day storm on the 9th and 10th with a maximum speed of 16 kt (8 m/s) and a four-day storm from the 15th through 18th with a maximum speed of 28 kt (14 m/s). The final two storm events of the month were one-day easterlies that occurred on the 21st and 24th with wind speeds of 18 and 16 kt (9 and 8 m/s), respectively.

Ice Cover: Based on ice charts from the NIC and CIS that show a band containing open water or less than one tenth ice cover on November 1st, and a RADARSAT-2 image that shows uninterrupted ice cover on the 3rd, complete freeze-up in the Alaskan Beaufort Sea occurred on or about November 2nd. The temperature data recorded at Deadhorse Airport prior to this date produced an accumulated total of 305 FDD.

The nascent ice canopy was disturbed during the first half of November by the three storm events that occurred between the 3rd and 18th. The NIC ice charts indicate that the ice concentration decreased to as little as one to three tenths between November 4th and 8th from Harrison Bay to the Canadian border, presumably in response to the easterly storm on November 3rd and 4th.

Ice Thickness: The calculated thickness of undisturbed first-year ice increased from 25 cm at the beginning of the month to 47 cm at the end. The calculation is based on an accumulated total of 848 FDD at Deadhorse Airport (Table 1), including 556 FDD in November.

Landfast Ice: The successive locations of the landfast ice edge as interpreted from RADARSAT-2 images obtained on November 3rd, 10th, 17th, 23rd, and 30th are shown in Figure 20. Although ice movement lines are evident in these images, a well-defined shear zone with significant grounded rubble is conspicuously absent. This situation appears to have arisen in part from the two westerly storms in mid-month (which tended to push the ice offshore before it became grounded), and in part from the modest ice thicknesses that prevailed throughout the month (which impeded the development of rubble with sufficient mass and strength to become firmly grounded).

The most striking aspect of Figure 20 is the failure of the landfast ice to expand offshore as the month progressed. In Camden Bay, the landfast ice edge remained close to shore, in water depths less than 6 m. Between Camden and Harrison Bays, the landfast ice zone was limited to the protected waters behind the barrier islands for the entire month-long period. In Harrison Bay, the edge of the landfast ice retreated from the 11-m contour on November 3rd to the 5.5-m contour at month-end.

Leads: Leads running north northeast – south southwest and located offshore of the region bounded by Pitt Point and Cape Halkett are evident in the November 3rd RADARSAT image. The leads were up to 6 nm long and 1 nm wide (11 km long and 2 km wide). A week later, on November 10th, leads of similar size and orientation were present off the barrier islands between Thetis and Flaxman Islands. These features closed prior to the November 17th image. On November 30th, substantial leads trending north northeast – south southwest with lengths to 20 nm (37 km) reappeared north of the barrier islands between Cross and Flaxman (Figure 21).

Multi-Year Ice: Large multi-year ice floes as indicated by bright returns on the RADARSAT-2 images remained absent from the nearshore zone of the Beaufort Sea throughout the month of November. Farther offshore, isolated floes began arriving from the

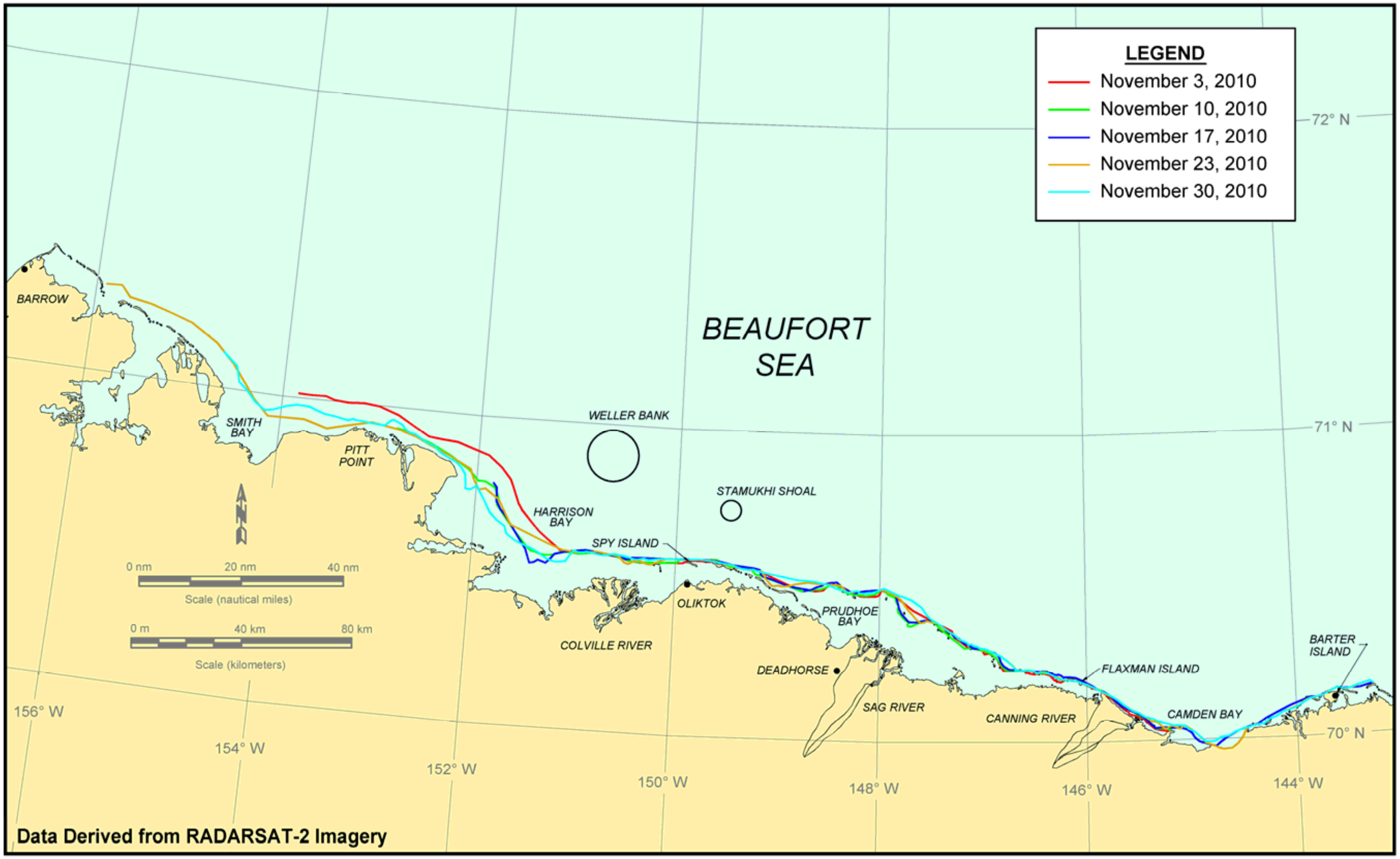


Figure 20. Beaufort Sea Landfast Ice Edge in November 2010

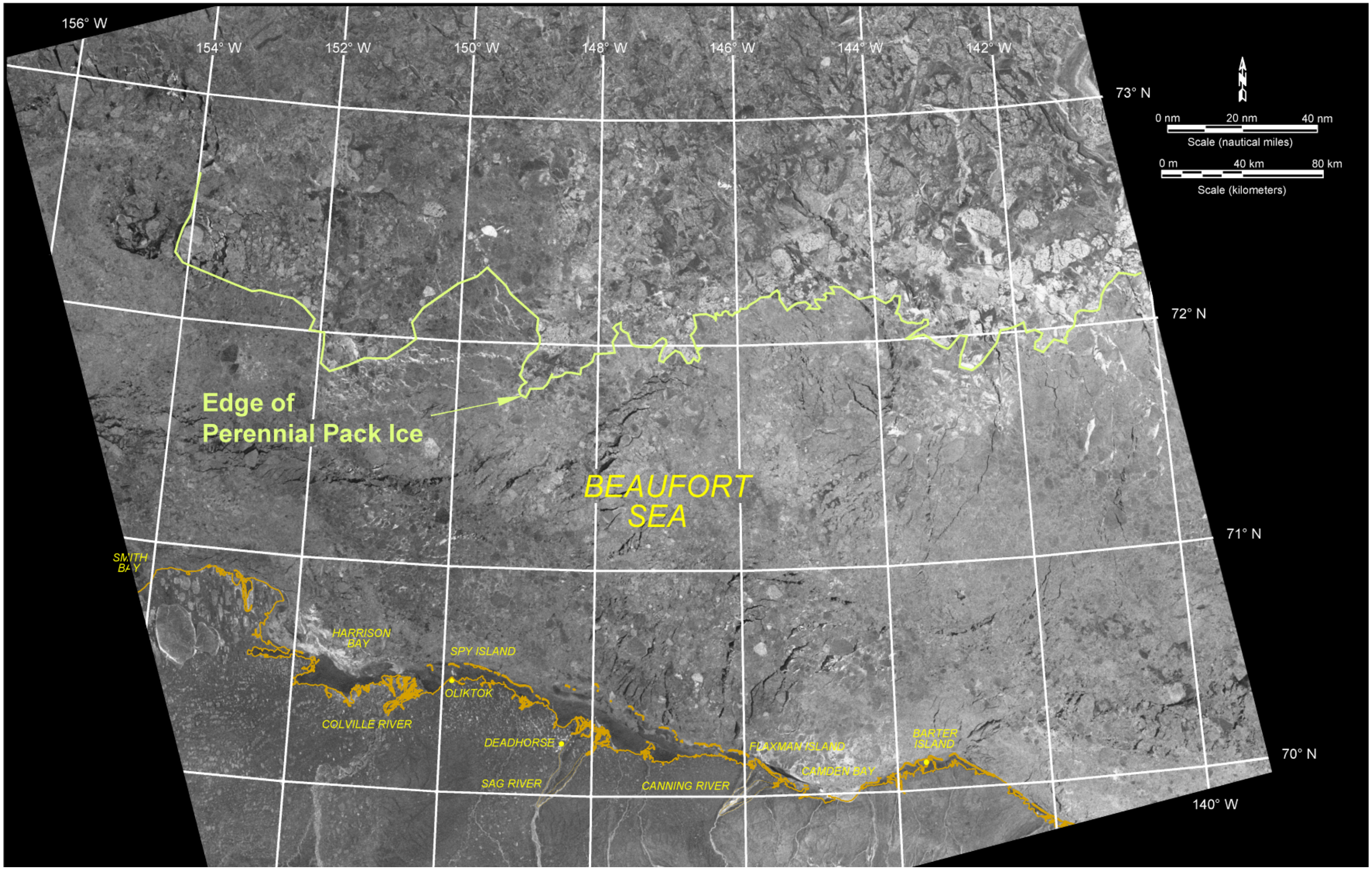


Figure 21. RADARSAT-2 Image of Beaufort Sea Acquired on November 30, 2010

Canadian Beaufort during the second week of the month. The floes marched steadily toward the west, ending the month to the north of Harrison Bay in the vicinity of the 151°W meridian. As shown in Figure 21, a denser concentration of multi-year floes followed the widely-spaced leaders as the month progressed. The southern boundary of the multi-year ice (the edge of the perennial pack ice) tended to remain between 71.5° and 72°N.

Ice Movement: Ice movement rates at the south edge of the pack ice were quantified by tracking the progress of selected multi-year floes in successive RADARSAT-2 images. As shown in Figure 22, Floe A was identified in the November 10th, 17th, 23rd, and 30th images while Floes B, C, and D were identified starting with the November 17th image. The diameters of these floes ranged from 5 to 15 km.

All four floes moved steadily toward the west at speeds that ranged from 7.2 to 11.8 nm/day (13 to 22 km/day) between successive RADARSAT images. The highest rates, 11.8 nm/day (22 km/day) between November 10th and 17th for Floe A and 11.2 nm/day (21 km/day) between November 23rd and 30th for Floe D, occurred when these floes were located at the southern edge of the multi-year ice and therefore less constrained by other large floes. Strong, sustained easterlies were absent from the wind record at Deadhorse Airport during both of these periods (Figure 19), suggesting that the conditions offshore (approximately 150 nm or 278 km away) may have differed appreciably from those in Deadhorse.

When speeds were computed from the first and last positions recorded for each floe in November ("monthly speeds"), the values of westerly drift were found to range from 7.7 to 9.9 nm/day (14 to 18 km/day). The average monthly speed, 8.3 nm/day (15 km/day), represents the highest value recorded during the study period (November 2010–February 2011).

4.2.3. December 2010

Meteorological Conditions: The wind and temperature data recorded at Deadhorse Airport in December 2010 are provided in Figure 23. Air temperatures tended to be slightly below normal until the last week of the month, when they dropped substantially. On the 27th, 28th, and 29th, the average daily temperature remained at or below -40°F (-40°C).

As in November, easterly and westerly winds occurred with nearly equal frequency, with changes in wind direction typically occurring once or twice per week. Storm events were infrequent and relatively mild: a one-day easterly with a wind speed of 23 kt (12 m/s) on December 4th, a one-day westerly with a wind speed of 18 kt (9 m/s) on the 14th, and a

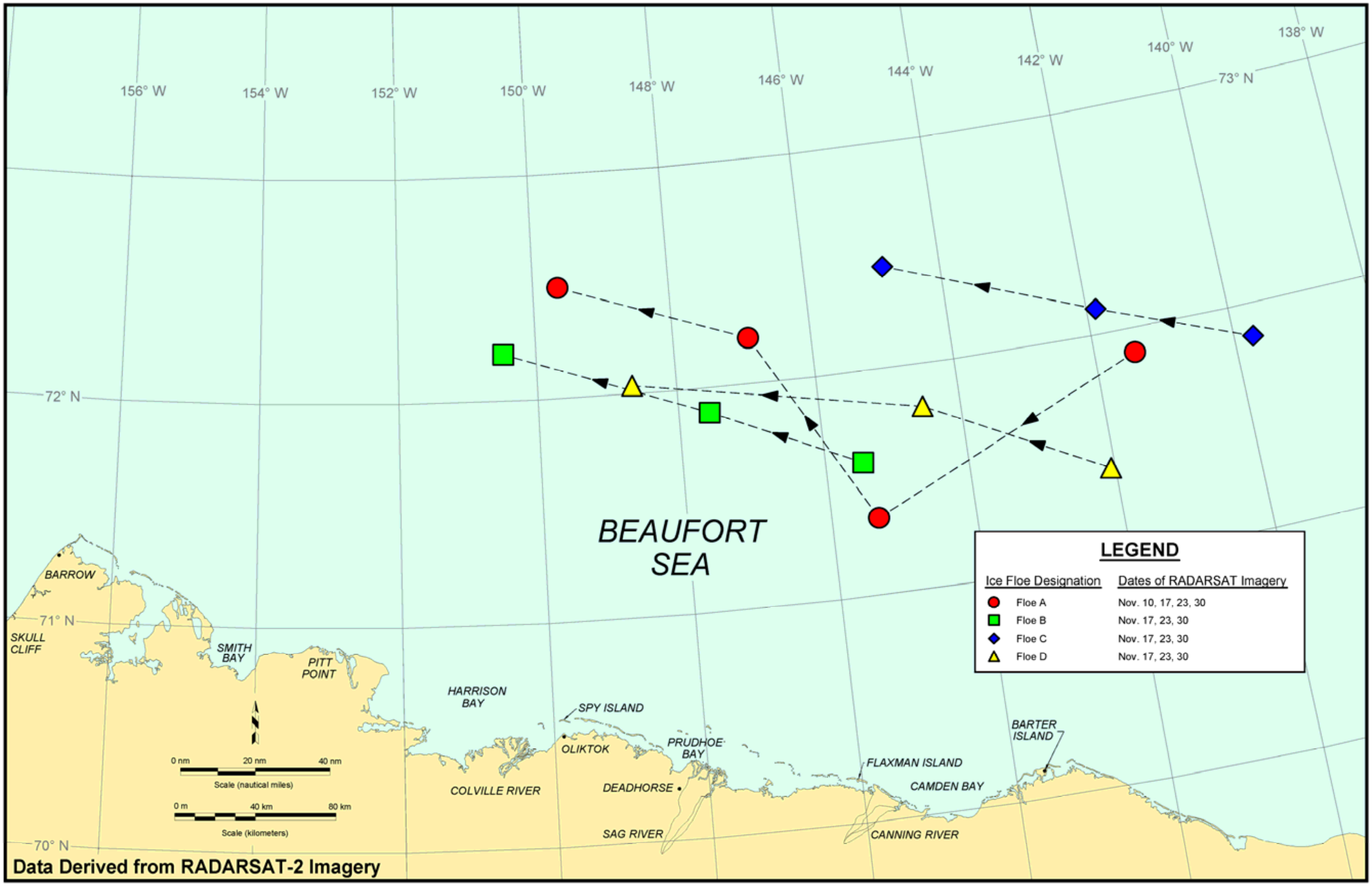
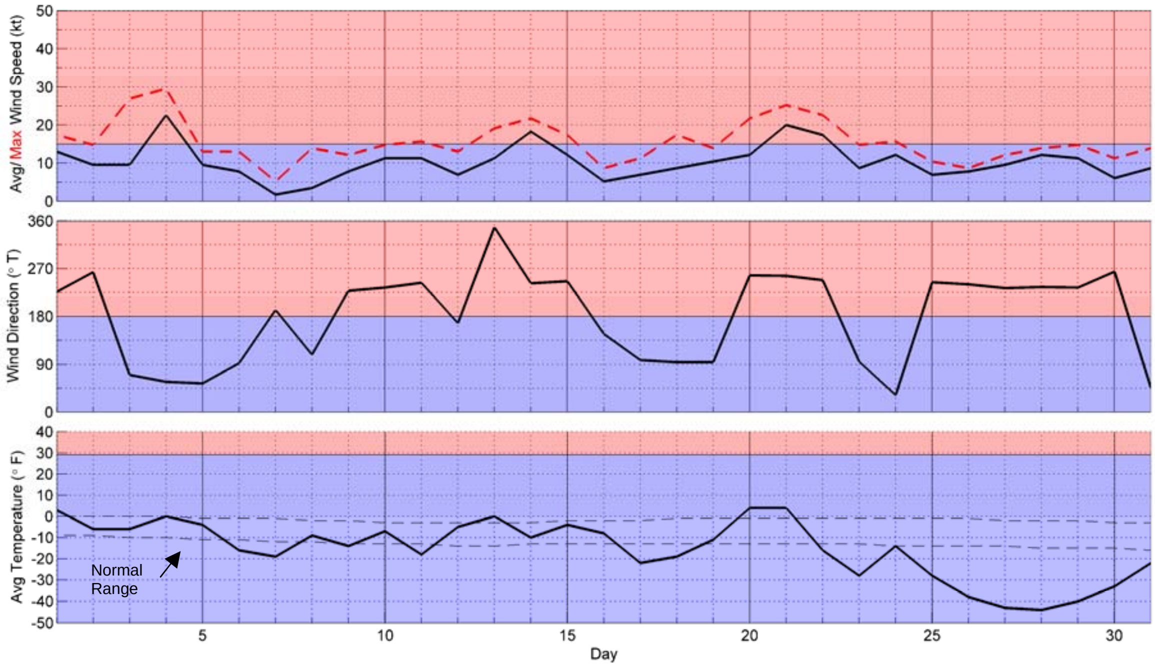


Figure 22. Beaufort Sea Multi-Year Ice Floe Displacements in November 2010



Source: Weather Underground, 2011

Figure 23. Meteorological Conditions at Deadhorse Airport in December 2010

two-day westerly with a wind speed of 20 kt (10 m/s) on the 21st and 22nd (Table 4). It is noteworthy that easterly winds seldom exceeded 10 kt (5 m/s) after the brief storm at the beginning of the month.

Ice Thickness: The calculated thickness of undisturbed first-year ice increased from 47 cm at the beginning of the month to 82 cm at the end, based on the addition of 1,372 FDD in December to produce an accumulated total of 2,220 FDD.

Landfast Ice: The locations of the landfast ice edge in December were estimated from RADARSAT-2 images obtained on the 7th, 14th, and 21st.. The results are presented in Figure 24 along with the prior location on November 30th.

Between November 30th and December 7th, the landfast ice edge remained close to the barrier islands to the east of Prudhoe Bay and close to shore in Camden Bay. In Harrison Bay, however, the landfast ice edge moved offshore as much as 16 nm (30 km) to Weller Bank. This substantial advance resulted from the 23-kt (12-m/s) easterly storm on December 4th (Table 4), which apparently caused rubble to ground on the shoal while creating a distinct shear line.

After a week of negligible change between December 7th and 14th, the landfast ice edge retreated in Harrison Bay but advanced offshore from Stamukhi Shoal on the west to

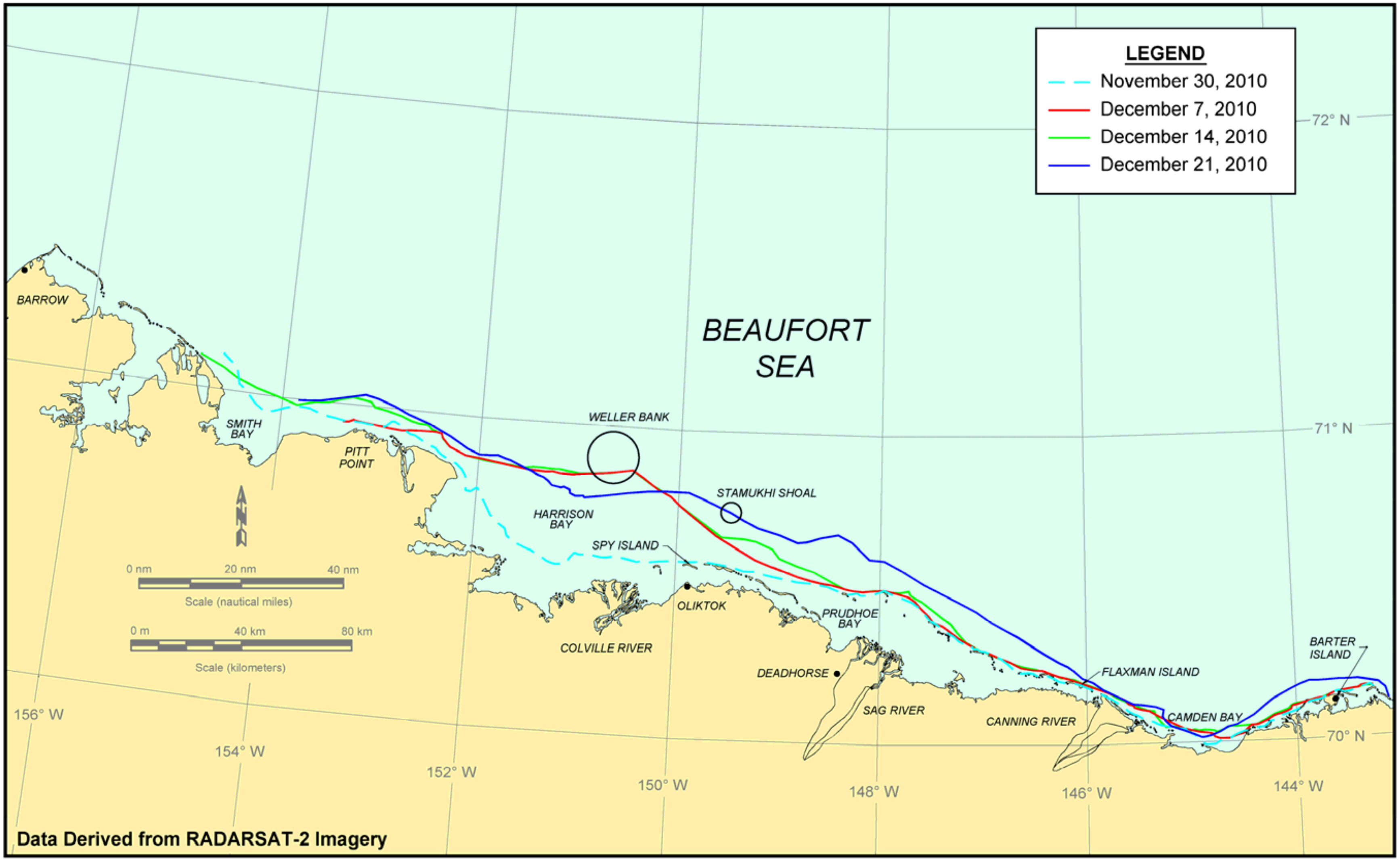


Figure 24. Beaufort Sea Landfast Ice Edge in December 2010

Flaxman Island on the east. These changes probably resulted from the sequence of a westerly storm on the 14th followed by a period of moderate easterly winds. The westerly storm caused the ice to lose confinement, after which the easterly winds pushed the ice back onshore. Ice rubble is evident on the north side of the landfast ice edge off Harrison Bay on December 21st, suggesting that the changes in wind direction caused substantial ice motion and deformation.

Leads: RADARSAT-2 images obtained on December 7th, 14th, and 21st indicate that very few leads were present in the ice canopy. On December 7th, the largest such feature was located adjacent to the landfast ice edge over a 15-nm (28 km) stretch to the west of Cross Island. Small leads trending northeast-southwest also were present in Camden Bay. Thereafter, on December 14th and 21st, significant leads were conspicuously absent (Figure 25).

Multi-Year Ice: The large multi-year ice floes that entered the Alaskan Beaufort Sea in November continued to march westward throughout December. As shown in Figure 25, the floes tended to remain north of the 72°N parallel as they crossed the Beaufort en route to the Chukchi Sea.

Ice Movement: Movement of the pack ice in December was quantified by comparing the positions of seven multi-year floes over various periods bracketed by RADARSAT-2 images obtained on November 30, 2010, and January 5, 2011. Four of the floes (A, B, C, and D) had been tracked in November, while three new floes were added in December (Floes E, F, and G with diameters ranging from 10 to 22 km). The tracking period for each floe was determined by the extent to which it could be identified in the November 30th and January 5th images as well as intermediate scenes obtained on December 7th, 14th, 15th and 23rd. In the case of Floes A and D, which moved into the Chukchi in mid-month, the tracking period was terminated on December 15th and 22nd, respectively. The results are presented in Figure 26.

As in November, each floe experienced a net displacement toward the west during each interval in which data were acquired. The highest rate, 9.6 nm/day (18 km/day), was attained by Floe D between November 30th and December 7th. Not surprisingly, this period included the December 4th easterly storm. The lowest rate of 5.0 nm/day (9 km/day) was recorded by Floe G between December 21st and January 5th, when westerly winds predominated.

Three or more positions spanning a period of at least two weeks were recorded for five of the seven floes tracked in December. The monthly speeds computed for these floes on

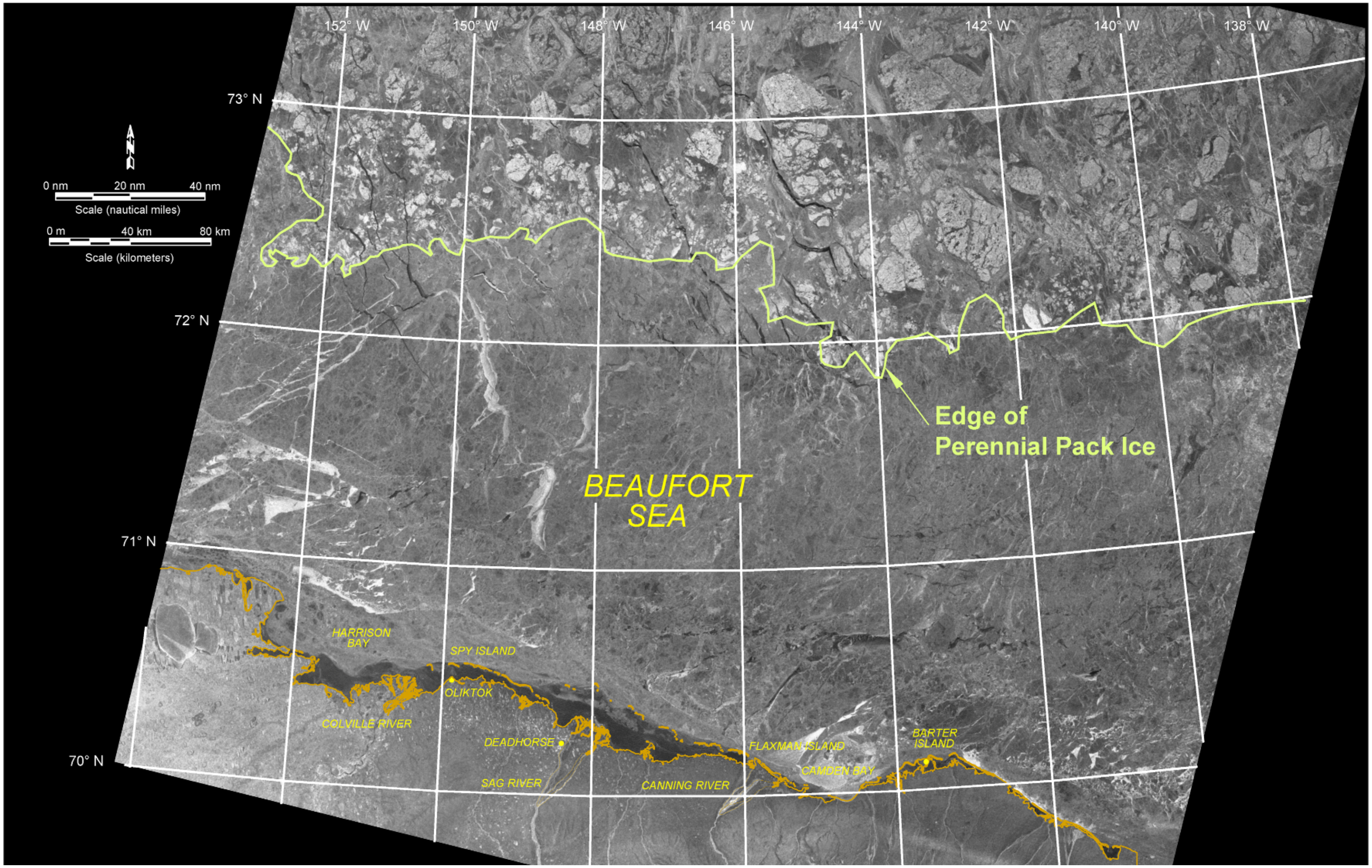


Figure 25. RADARSAT-2 Image of Beaufort Sea Acquired on December 21, 2010

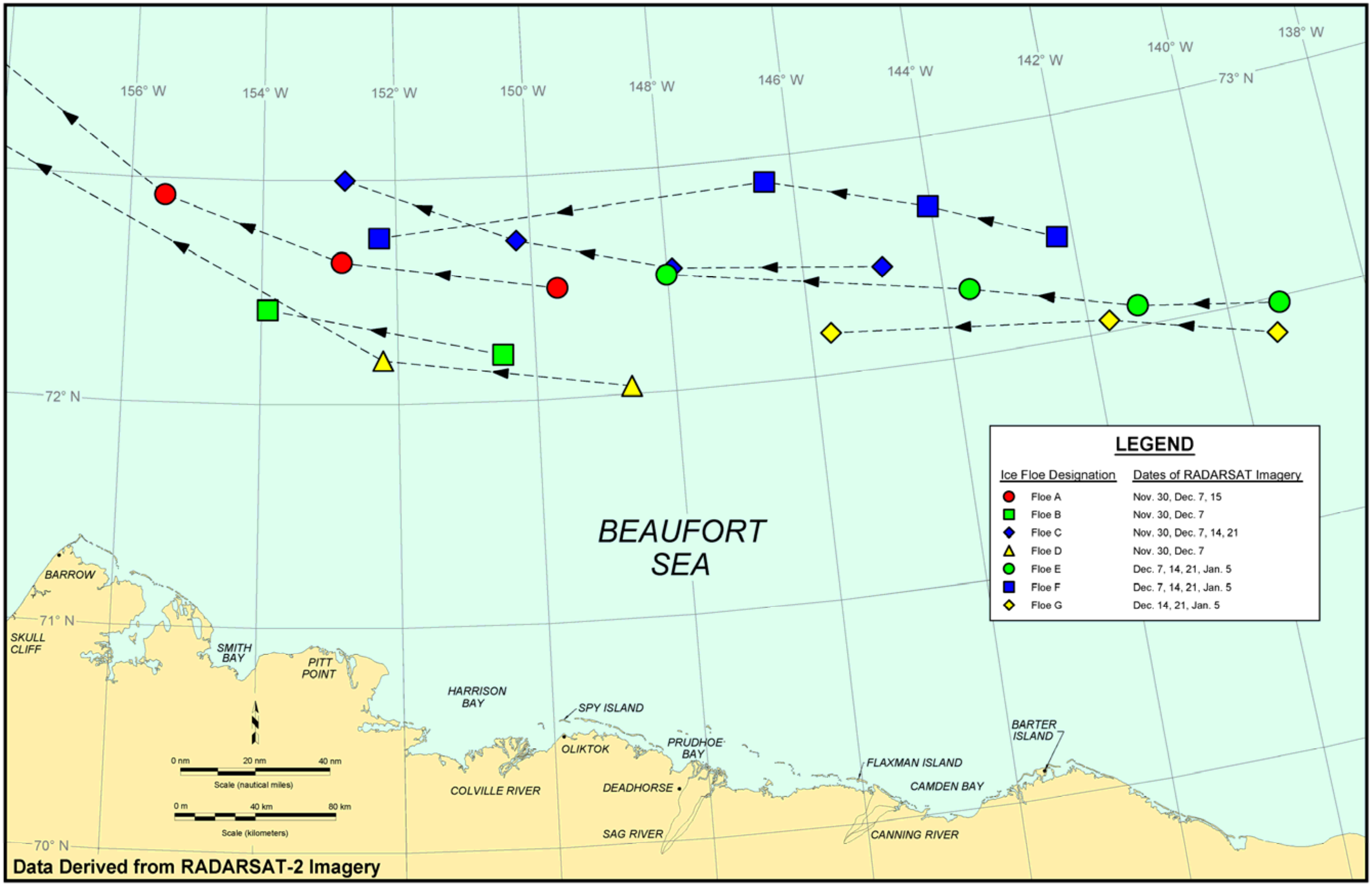
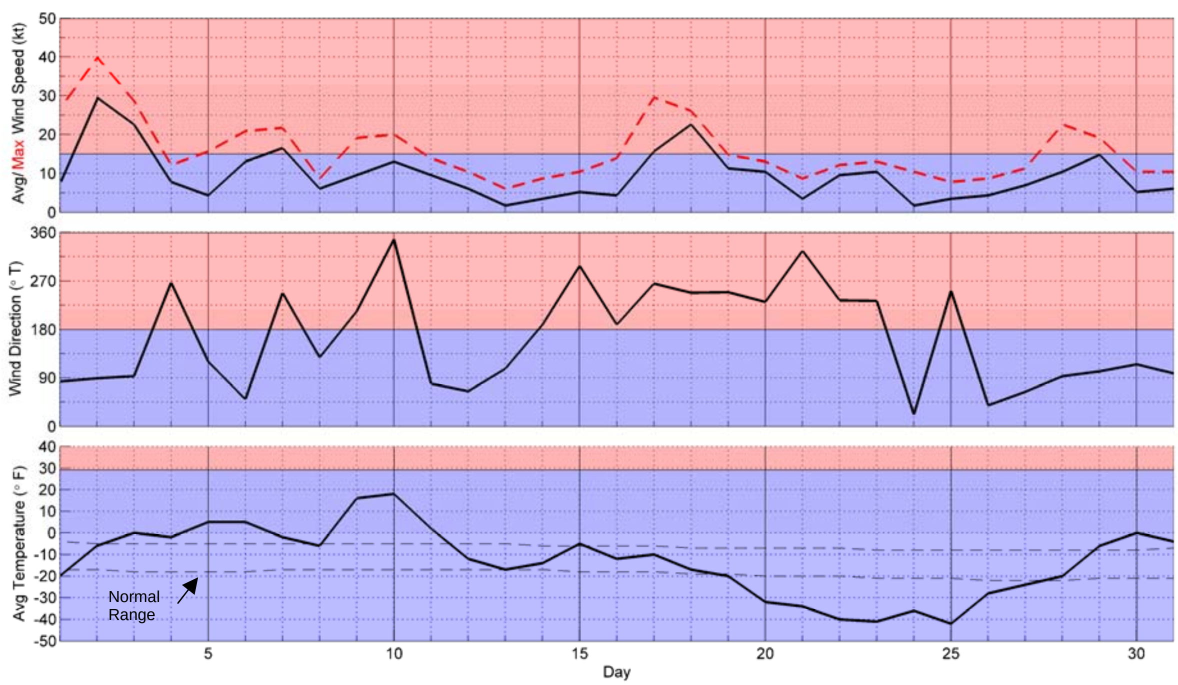


Figure 26. Beaufort Sea Multi-Year Ice Floe Tracks in December 2010

the basis of their first and last recorded positions between November 30th and January 5th ranged from 5.5 to 7.2 nm/day (10 to 13 km/day). The average monthly speed of 6.3 nm/day (12 km/day) was nearly 25% less than that in November, a finding that reflects the lack of sustained easterly winds and paucity of easterly storms in December. Floe speeds also were reduced by the increased confinement that resulted from a higher concentration of multi-year floes, thicker first-year ice between such floes, and a lack of large leads.

4.2.4. January 2011

Meteorological Conditions: Figure 27 presents the wind and temperature data recorded at Deadhorse Airport in January 2011. With the exception of a brief surge that raised the average daily temperature above 15°F (-9°C) on the 9th and 10th, the temperatures remained close to normal through January 19th. They then dropped below -25°F (-32°C) from the 20th through 26th before returning to normal at the end of the month.



Source: Weather Underground, 2011

Figure 27. Meteorological Conditions at Deadhorse Airport in January 2011

The wind regime in January was characterized by low to moderate speeds and frequent changes in direction, including ten swings between easterly and westerly. The storm pattern was similar to that in December, with an easterly storm at the outset and two westerlies later in the month (Table 4). The sole easterly event occurred on January 2nd and 3rd with a maximum wind speed of 30 kt (15 m/s). A one-day westerly with a maximum wind speed of 16 kt (8 m/s) followed soon thereafter on the 7th. The final storm of the month, a 23-kt (12 m/s) westerly, took place on the 17th and 18th.

Ice Thickness: One thousand, three hundred and three FDD accumulated at Deadhorse Airport in January, bringing the total to 3,523 FDD since the inception of freeze-up. The predicted ice thickness at the end of the month was 107 cm, representing an increase of 25 cm since the end of December.

Landfast Ice: Figure 28 illustrates the locations of the landfast ice edge derived from RADARSAT-2 images obtained on December 21st and January 5th, 10th, 17th, and 31st. During the two-week period between December 21st and January 5th, the extent of the landfast ice expanded in Camden Bay and to the west of Harrison Bay – two areas with minimal landfast ice at the outset. Conversely, the more extensive accumulation of landfast ice between Flaxman Island and central Harrison Bay retreated. These changes probably resulted from the combined effects of the westerly storm on December 21st and 22nd, which dislodged the weakly-consolidated landfast ice between Flaxman Island and Harrison Bay, and the easterly storm of January 2nd and 3rd, which caused rubble formation and landfast ice expansion in Camden Bay and west of Pitt Point.

Between January 5th and 17th, the winds were light to moderate while the landfast ice edge was essentially static. The situation changed between the 17th and 31st, however, with the ice edge retreating again in western Camden Bay and west of Pitt Point while advancing to Weller Bank off Harrison Bay. The losses presumably resulted from the week-long period of westerly winds that lasted from the 17th through 23rd (including a westerly storm on the 17th and 18th); the gain off Harrison Bay probably resulted from moderate easterly winds that began on the 26th.

The defining characteristic of the landfast ice in January was its transience. In the absence of sustained easterly winds that are necessary to cause rubble formation and secure grounding, the landfast ice edge remained unstable and subject to retreat throughout the month.

Leads: The RADARSAT-2 image from January 5th shows an intermittent lead extending along the landfast ice edge between Harrison Bay and Brownlow Point. The lead width varied from negligible in some areas to nearly 2 nm (3.5 km) off Pingok Island. A number of smaller leads trending northeast-southwest and extending as much as 16 nm (30 km) off the barrier island chain emanated from this prominent, shore-parallel feature.

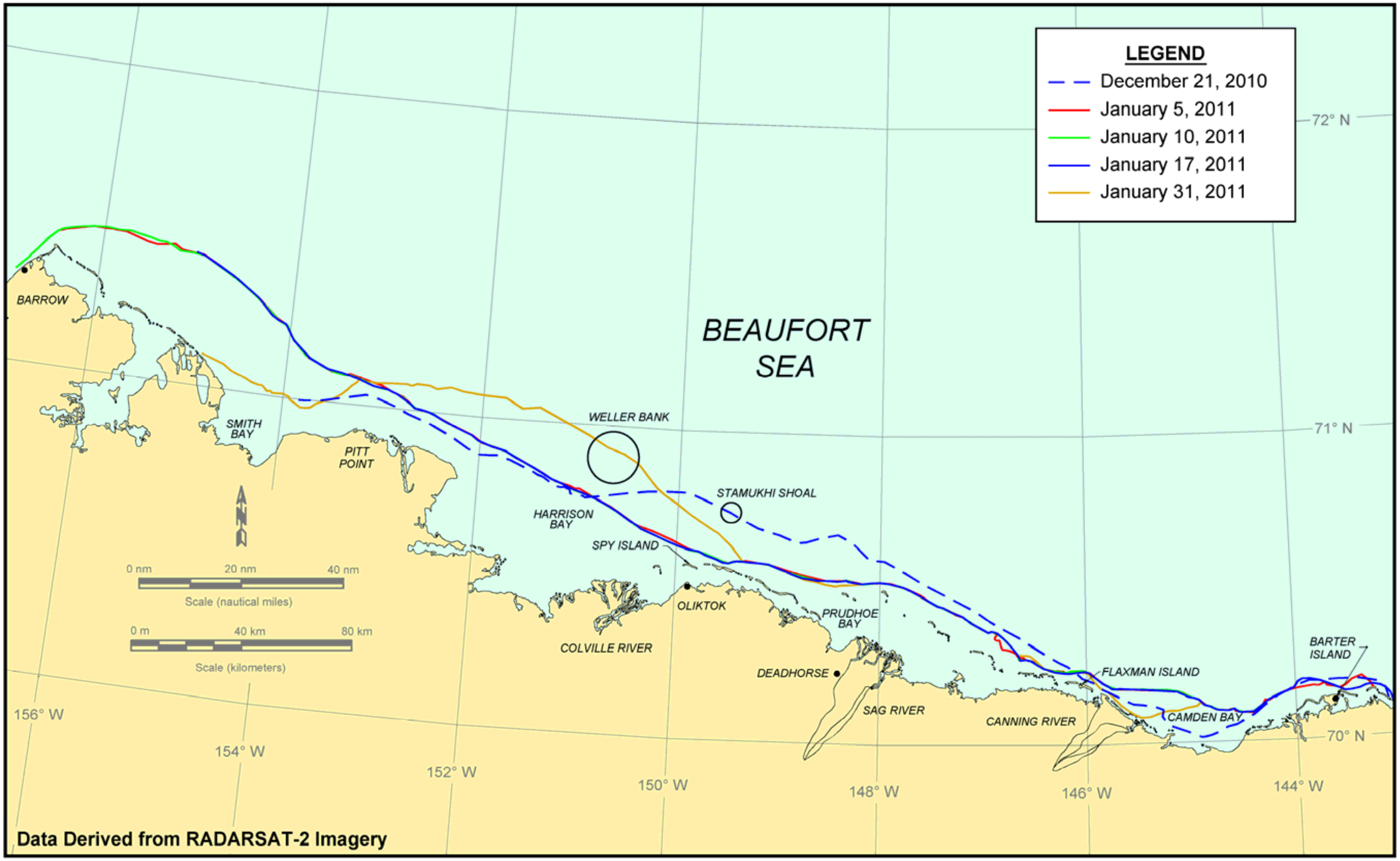


Figure 28. Beaufort Sea Landfast Ice Edge in January 2011

Farther east, a re-freezing polynya measuring about 30 nm (56 km) east-west by 15 nm (28 km) north-south occupied the central and eastern portion of Camden Bay.

Significant leads and polynyas were absent on January 10th and 17th, but the situation had changed dramatically when the last image of the month was acquired on January 31st. As shown in Figure 29, an extremely large lead measuring more than 250 nm (463 km) long and up to 5 nm (9 km) wide extended east from the vicinity of Smith Bay. A number of smaller but nevertheless substantial leads were present in Camden Bay, oriented northeast-southwest.

Multi-Year Ice: The multi-year ice floes that marked the southern edge of the perennial pack ice remained well offshore in January. On the 5th, the southern boundary was located in the vicinity of the 72°N parallel throughout the Alaskan Beaufort Sea. At month-end, the boundary trended west northwest from 71.2°N in the eastern portion to 72.6°N in the western portion (Figure 29).

Ice Movement: Six multi-year floes were used to investigate ice movement rates over various periods between RADARSAT-2 images obtained on January 5th, 10th, 17th, 22nd, 29th, and 31st. Three of the floes, E, F, and G, were carried over from December (Figure 26), while three new floes (H, I, and J with diameters from 12 to 16 km) were added in January. The trajectories of the six floes are shown in Figure 30.

In keeping with the southerly migration of the perennial pack ice that occurred in the eastern portion of the Alaskan Beaufort Sea, Floe J followed a southwesterly track. The other five floes, located in the central and western portions, experienced net displacements toward the northwest. The two westernmost floes, F and H, reversed direction and headed back to the southeast between January 17th and 22nd during a period of sustained westerly winds. These floes then resumed their travel to the northwest when moderate easterlies ensued from the 26th to the end of the month. Had it been possible to obtain positions for the other four floes on January 22nd, it is likely that their trajectories would have displayed similar reversals in direction.

The monthly speeds computed for Floes E through J on the basis of their first and last recorded positions between January 5th and 31st ranged from a minimum of 1.4 to a maximum of 2.9 nm/day (2.6 to 5.4 km/day). These relatively low values, along with the average of 2.3 nm/day (4.3 km/day), are consistent with the absence of sustained easterly winds and the reversals in floe direction noted above.

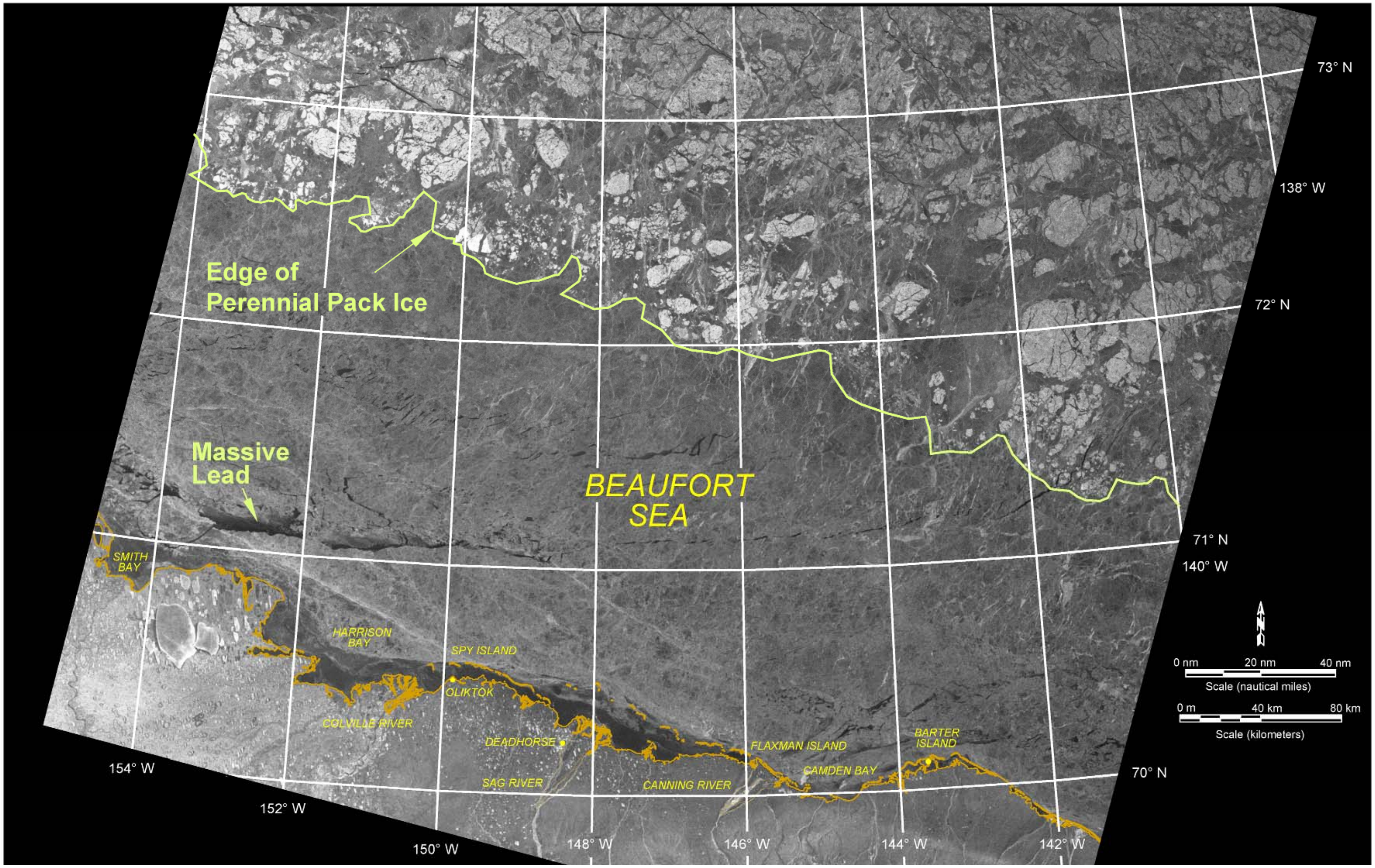


Figure 29. RADARSAT-2 Image of Beaufort Sea Acquired on January 31, 2011

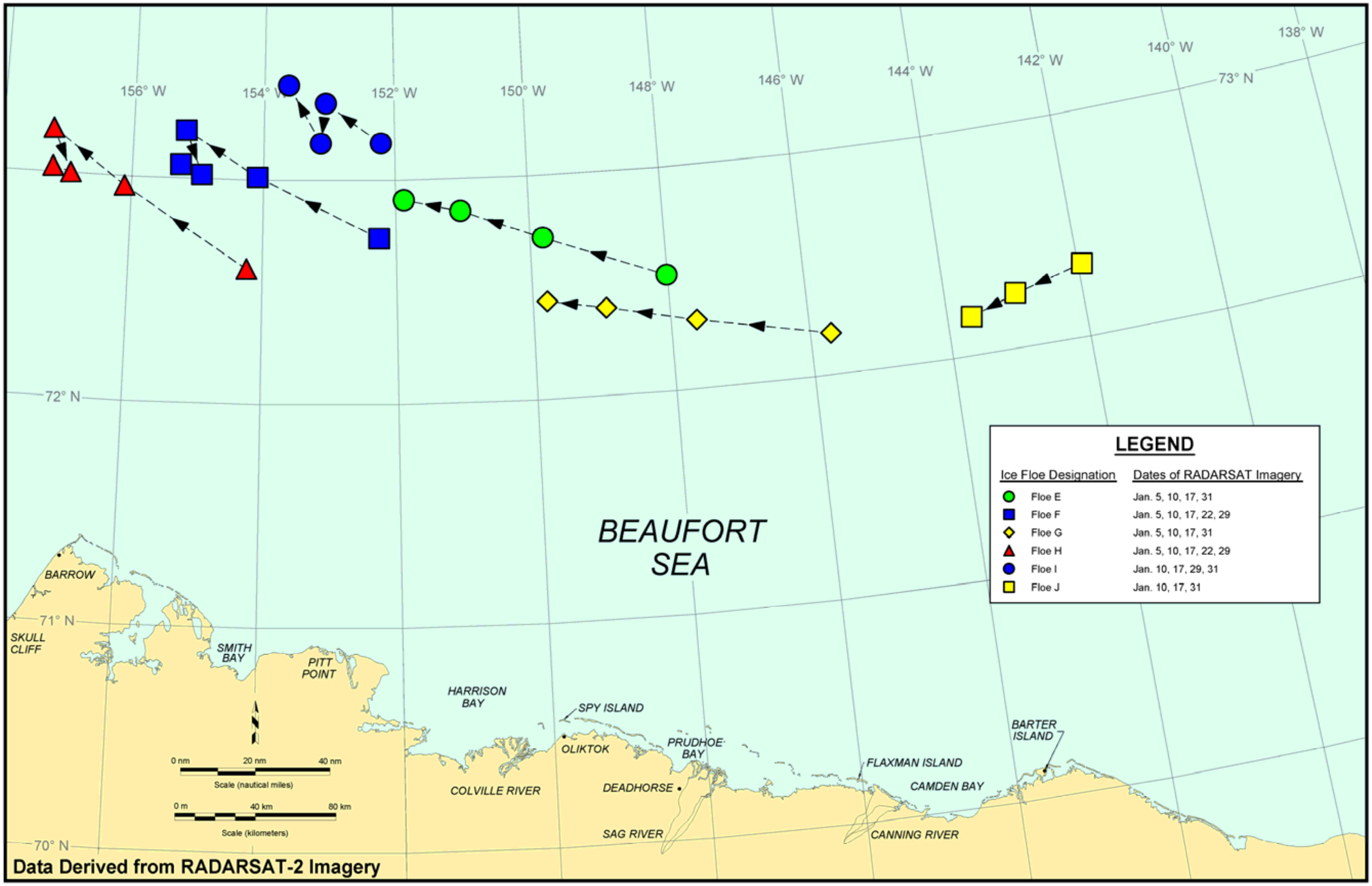


Figure 30. Beaufort Sea Multi-Year Ice Floe Tracks in January 2011

The highest speed recorded in January was 8.4 nm/day (15.6 km/day). It was attained by Floe I between the 29th and 31st during a period of moderate easterly winds. The lowest speed, 0.7 nm/day (1.3 km/day), was logged by Floe H between the 22nd and 29th (a period of light and variable winds).

Per Section 3.4, Shell installed four Iridium buoys off Flaxman Island (Buoys 1 through 4) and three such buoys off Spy Island (Buoys A, B, and C) on January 26, 2011, to document ice movement. As shown in Figure 31, which displays the position of each buoy at midnight of each day, Buoys A, B, and C remained stationary for the remainder of the month. The two nearshore buoys off Flaxman Island (1 and 2) moved minimally, while the two offshore buoys (3 and 4) moved significant distances to the west on January 28th and 29th under moderate easterly winds. Buoy 4 attained a maximum daily average speed of 0.4 kt (0.2 m/s or 10 nm/day) during this period, while Buoy 3 reached 0.2 kt (0.1 m/s or 5 nm/day). As the corresponding average daily wind speed was 15 kt (8 m/s; Figure 27), the buoys moved at 2.7 and 1.3% of the wind speed.

4.3. Field Observations

As discussed in Section 3.5, aerial reconnaissance missions were undertaken in the Beaufort Sea on February 2nd, 3rd, and 4th. Beaufort Sea Flight Nos. 1 and 2 (Flights "B1" and "B2" on Drawing CFC-835-01-001) focused on ice conditions in the central Beaufort, while Beaufort Sea Flight No. 3 (Flight "B3" on Drawing CFC-835-01-002) was used to observe ice conditions in the western Beaufort Sea.

Light westerly winds averaging about 10 kt (5 m/s) prevailed from February 1st through 4th. As a result, the ice conditions observed during the three flights were found to resemble those depicted in the RADARSAT-2 image obtained on January 31st (Figure 29). Because the large multi-year ice floes evident in this image were located more than 100 nm (185 km) north of Prudhoe Bay, they were not included in any of the flight itineraries.

4.3.1. Nearshore Ice

Despite the easterly storms that occurred from October 2nd through 6th, 16th through 19th, and 21st through 23rd, the nearshore ice in semi-protected areas that included Simpson Lagoon, Prudhoe Bay, Stefansson Sound, Mikkelsen Bay, and Leffingwell Lagoon remained stable after the initiation of freeze-up. With the exception of prominent thermal cracks in Stefansson Sound and Mikkelsen Bay, and a modest, 1-m high rubble field off Tigvariak Island, the ice in these regions was found to be flat and featureless at the time of the reconnaissance flights (Plate 8).

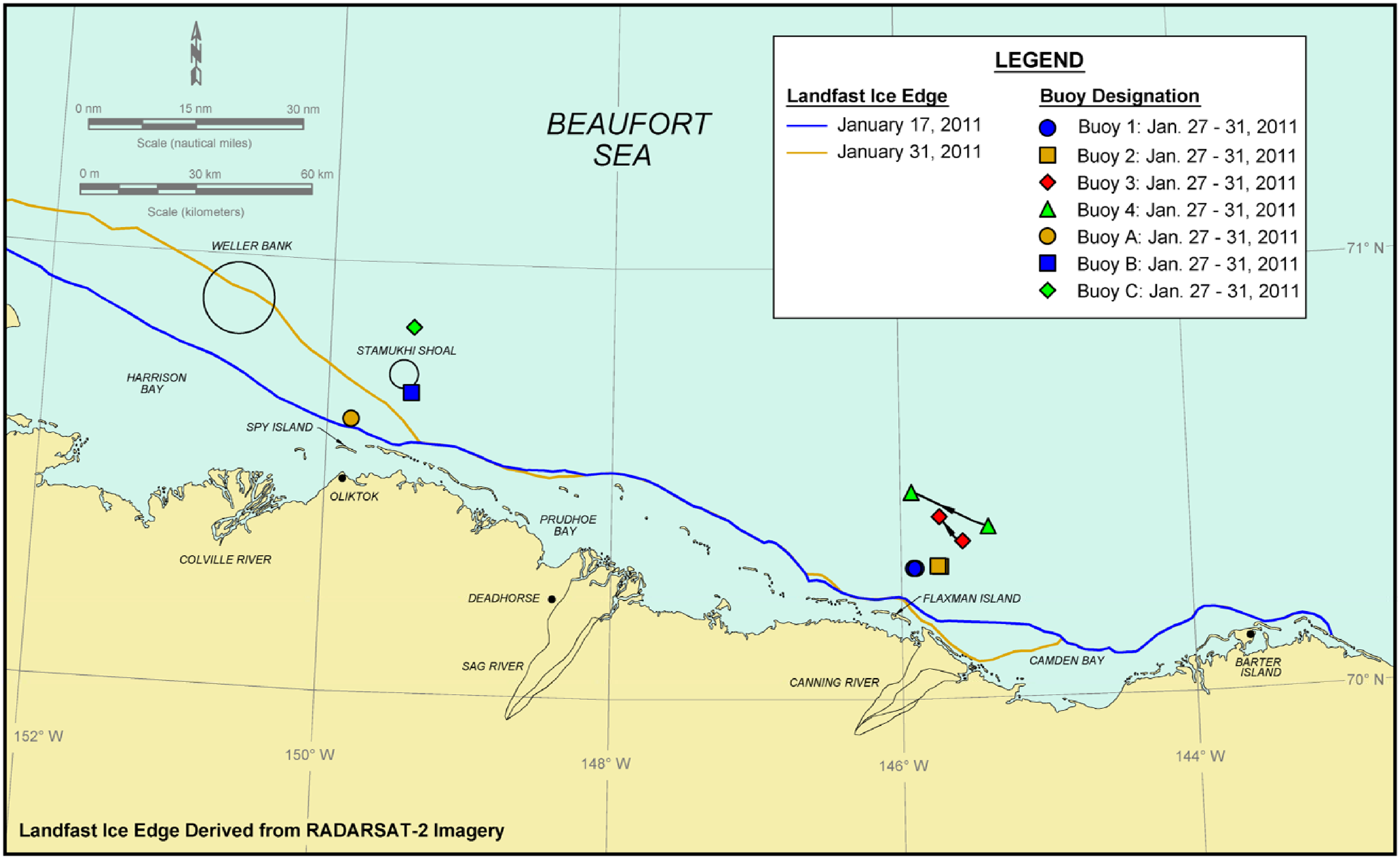


Figure 31. Beaufort Sea Iridium Buoy Tracks in January 2011

Plate 8. Flat Ice Cover Surrounding Endicott Main Production Island on February 3, 2011

As shown in Drawing CFC-835-01-001, the thermal cracks were located between the eastern edge of the Sagavanirktok River Delta and western edge of Leffingwell Lagoon. A representative example from Stefansson Sound is provided in Plate 9. Such features tend form when a rapid drop in air temperature is followed by a rapid rise. The drop causes contraction and cracking of the ice sheet, which are followed by refreezing and then compression and extrusion of the refrozen slush into a ridge as the temperature rises. Based on a review of the temperature data from Deadhorse Airport, the cracks and associated ridges noted during the aerial reconnaissance missions probably formed between November 28th and December 1st. During this four-day period, the average daily temperature dropped from +2 to -24°F (-17 to -31°C) before rebounding to +3°F (-16°C).

Similar cracks were observed in Stefansson Sound in 1982, at which time they disrupted ice road operations during the construction of Shell's Tern Island (Vaudrey, 1982a). Thermally-induced cracks also have been observed in Greenland (Kingery, 1962).

4.3.2. Landfast Ice and Shear Zone

The landfast ice zone observed during the 2011 reconnaissance flights resembled that which existed a year earlier to the extent that it was relatively wide in the western Beaufort off Harrison Bay, and narrower in the central Beaufort from Cross Island to Flaxman Island and throughout Camden Bay (Coastal Frontiers and Vaudrey, 2010). It differed, however,

Plate 9. Thermal Crack with Extruded Ridge in Stefansson Sound on February 3, 2011

Plate 10. Thermal Crack with Extruded Ridge in Stefansson Sound, February 1982

in that the ice edge was located closer to shore between Cross and Spy Islands, and also between Pitt Point and Point Barrow.

Whereas a well-developed, securely-grounded shear zone was observed between Cross Island and Point Barrow in 2010, the shear zone in this region was found to be less extensive and comparatively unstable in 2011. The contrast between the two years is evident in Plates 11 and 12, which show extensive rubble and clearly-defined shear lines on the east side of Weller Bank in February 2010 versus modest rubble and poorly-defined shear lines in February 2011. At Stamukhi Shoal, which lies to the southeast of Weller Bank and typically serves as another anchor point for the landfast ice, rubble generation had been insufficient to cause grounding at the time of the reconnaissance flights. As shown in Figure 28, the landfast ice edge lay well inshore of this location on January 31st.

The modest areal extent of the landfast ice and restrained development of the shear zone to the west of Cross Island reflected the paucity of both easterly storms and sustained easterly winds during the 2010-11 freeze-up season. Of particular note is the near-absence of easterly storms; only two such events occurred between December 1, 2010, and January 31, 2011, and both were of short duration. Although three easterly storm events occurred in November 2010, the ice was too thin and weak to become securely grounded at that time. Thereafter, when the ice became sufficiently thick to generate competent rubble, the easterly storms needed to energize the process failed to materialize.

To the east of Cross Island, the landfast ice edge was located in close proximity to the barrier islands and bounded by a refreezing lead (Drawing CFC-835-01-001). As shown in Plate 13, which displays a narrow band of landfast ice and a large lead on the seaward side of Pole Island in the Stockton Island chain, very modest amounts of rubble were present in the landfast ice. This situation prevailed throughout the barrier island chain except at the eastern end, where substantial but intermittent rubble piles up to 12 m high were located at the edge of the landfast ice off Mary Sachs and Flaxman Islands (Plate 14).

In the central portion of Camden Bay, about 10 nm (19 km) from shore, the ice cover was found to be extremely mobile with broken ice and refreezing leads. As illustrated in Plate 15, 2- to 3-m high ridges and rubble piles were noted but the ice was floating rather than grounded.

4.3.3. Fragments of Old Ice

Although large multi-year ice floes did not invade the nearshore waters of the Alaskan Beaufort Sea during the 2010-11 freeze-up season, grounded fragments of old ice were

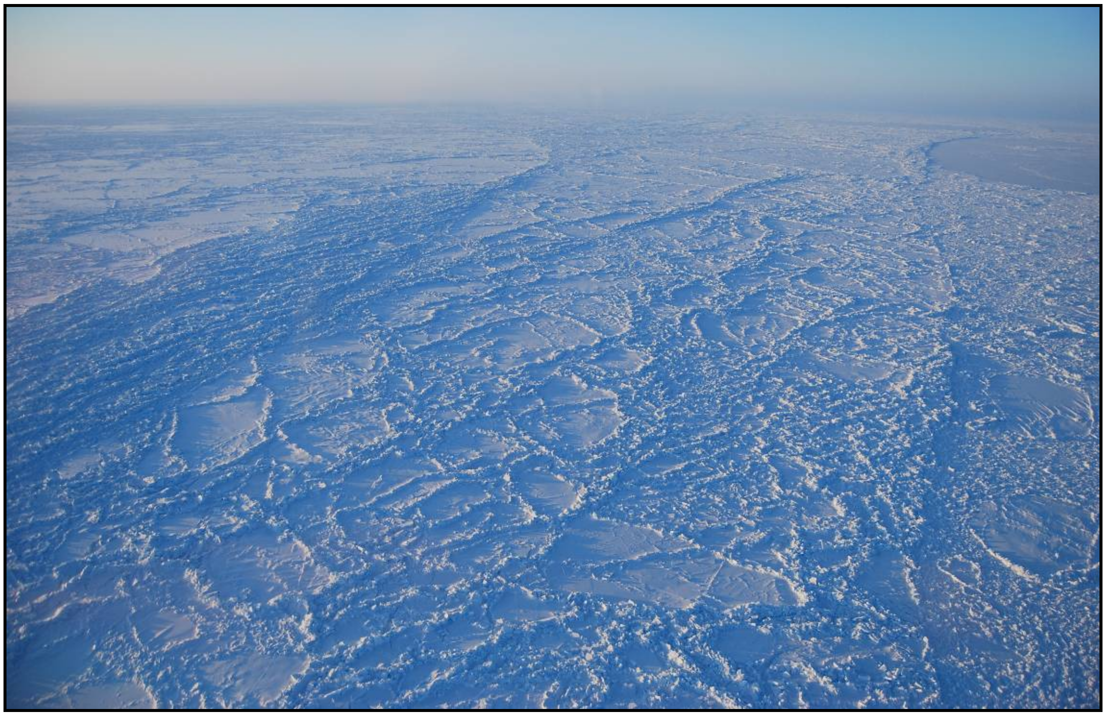


Plate 11. Well-Developed Shear Zone East of Weller Bank in February 2010 (Coastal Frontiers and Vaudrey, 2011)

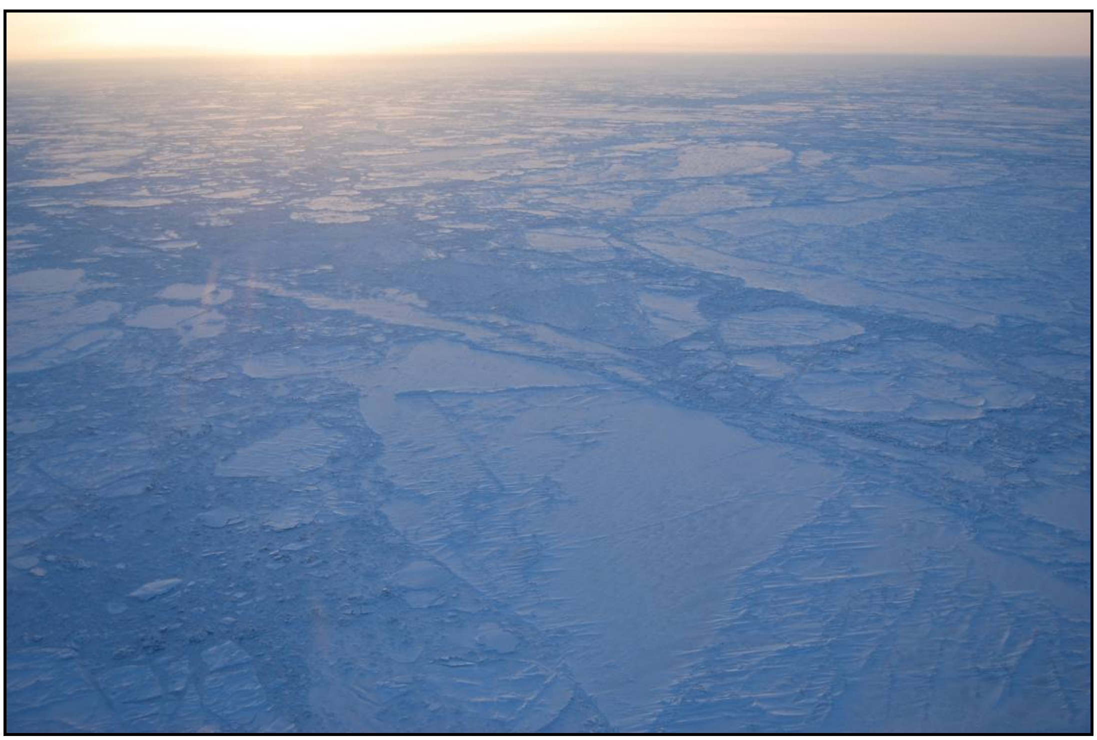


Plate 12. Poorly-Developed Shear Zone East of Weller Bank in February 2011

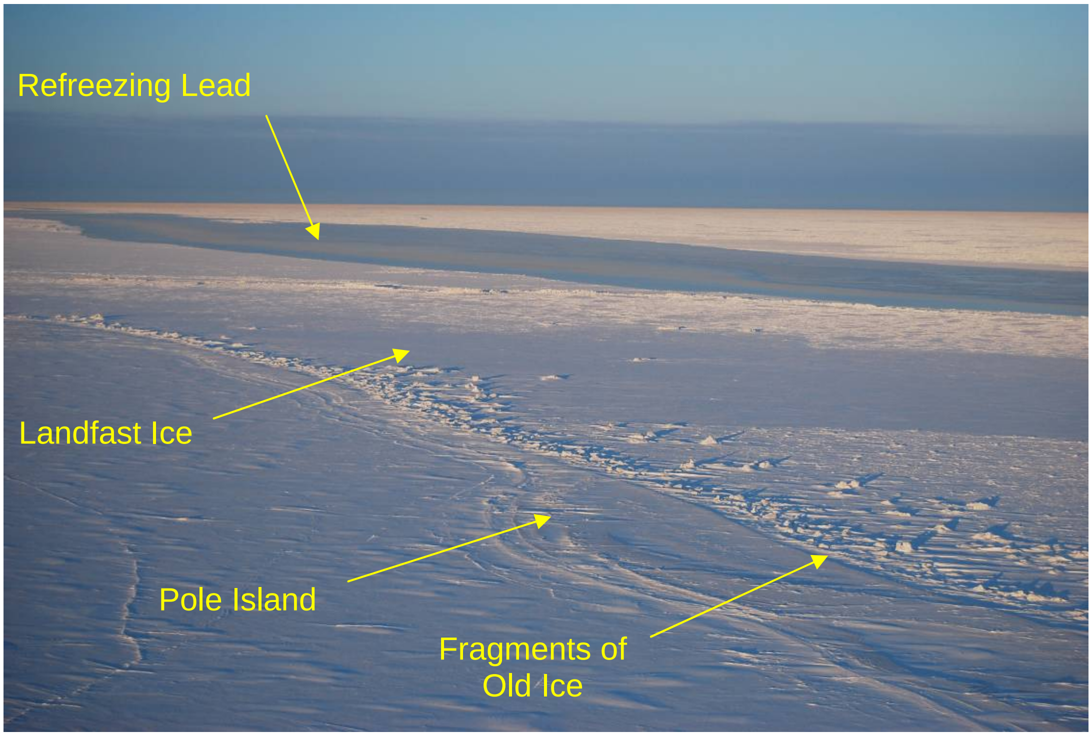


Plate 13. Narrow Band of Landfast Ice Adjoining Refreezing Lead off Pole Island on February 3, 2011

Plate 14. 12-m High Rubble Pile adjacent to Refreezing Lead off Mary Sachs Island on February 3, 2011

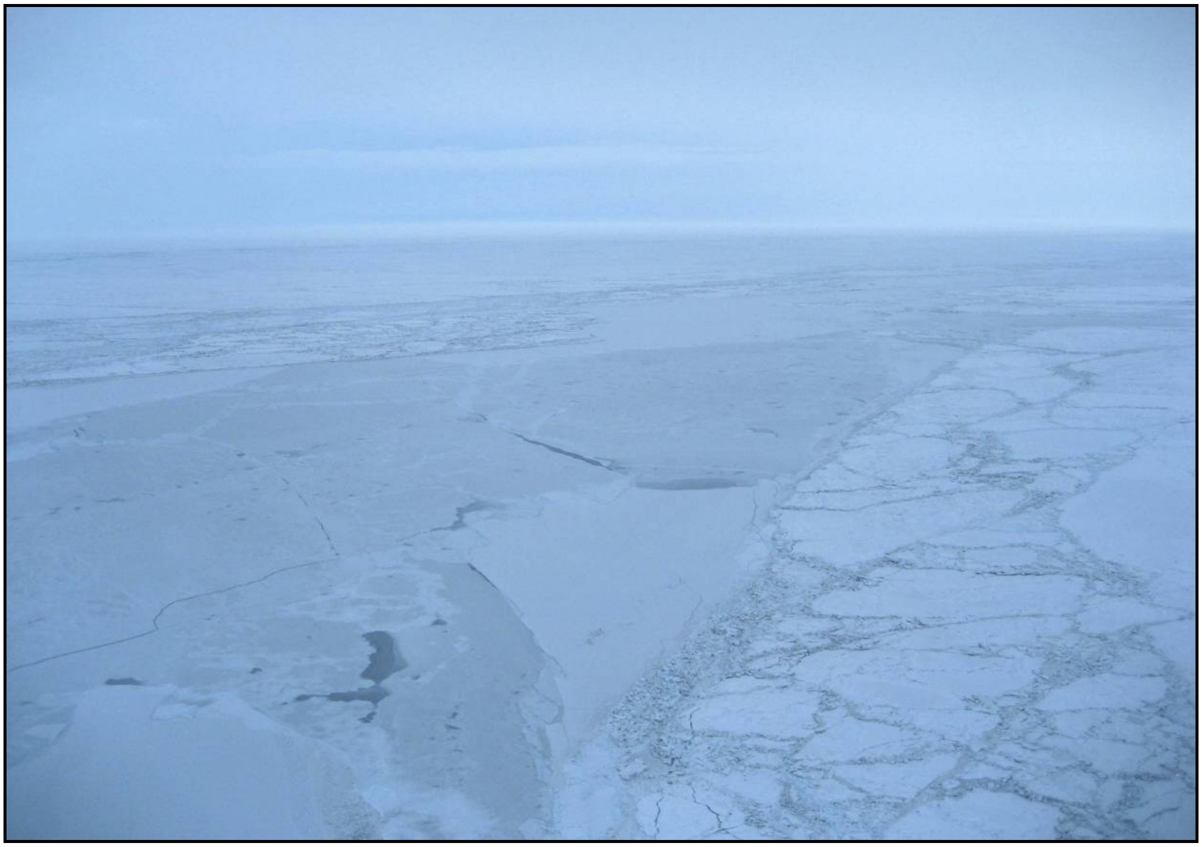


Plate 15. Refreezing Lead Bounded by 2- to 3-m High Rubble in Central Camden Bay on February 2, 2011

observed on the seaward shorelines of most of the barrier islands from Mary Sachs to Thetis. The fragments on the north side of Pole Island (in the Stockton chain) are evident in Plate 13, while smaller fragments noted on the West Dock Causeway on October 20 are shown in Plate 7. They also were noted in the first-year ice surrounding Northstar Island.

As discussed in Section 3.5, the fragments tended to be rounded, suggesting partial melting of old ice during the prior open-water season. The diameters ranged from 3 to 4 m to the east of Cross Island, and 1 m to the west. The largest blocks were located on Cross itself, where a maximum value of 5.5 m was measured with a hypsometer (Plates 4 and 5). The density of grounded blocks also peaked on Cross, where the shoreline coverage was nearly 100%. Values between 25 and 75% were estimated for the other barrier islands.

Similar accumulations of grounded, old ice were observed during the 1981 and 1982 freeze-up seasons by Vaudrey (1982; 1983). Plate 16 illustrates the fragments noted on Cross Island in mid-September 1981, while Plate 17 illustrates those on Narwhal Island in early October 1982.

Plate 16. Old Ice Fragments Grounded on Cross Island in September 1981

Plate 17. Old Ice Fragments Grounded on Narwhal Island in October 1982

The only plausible source for the grounded fragments in 2010-11 is the nearshore band of ice discussed in Section 4.1 and shown in Figure 14. Since the fragments arrived at West Dock Causeway prior to freeze-up in the nearshore region, they probably became dislodged during a westerly storm that engendered still water levels as high as 0.65 m above Mean Lower Low Water from September 27th through 29th (National Ocean Service, 2011). They then were driven aground by an easterly storm that began on October 2nd (Table 4).

4.3.4. Leads

As indicated above, prominent leads in various stages of refreezing were observed off the barrier islands to the east of Prudhoe Bay (Plate 13) and in Camden Bay (Plate 15). The most striking leads, however, were located in the western Beaufort between Harrison Bay and Point Barrow.

Plate 6 depicts the massive feature that can be seen trending east from the vicinity of Smith Bay in the January 31st RADARSAT-2 image (Figure 29) and that was still present during the flight on February 4th. Although refreezing was evident, the ice thickness was minimal. Farther south, between Stamukhi Shoal and Weller Bank, a large lead not evident in the RADARSAT image was encountered (Plate 18). The presence of open water and skim ice suggested that this feature had formed just prior to the flight, during a period of westerly winds that peaked with a maximum sustained speed of 20 kt (10 m/s) on February 3rd.

4.3.5. Ice Pile-Ups

Seven ice pile-ups were documented in the Alaskan Beaufort Sea during the reconnaissance flights conducted in February 2010, including a massive feature off the western end of Narwhal Island that stretched more than 1 nm (2 km) alongshore and attained a peak height of 16 m (Coastal Frontiers and Vaudrey, 2010). Six of the pile-ups were located on natural barrier islands, while the seventh was located on Northstar Production Island.

In contrast, only one pile-up was discovered during the 2011 flights. As discussed in Section 4.2.1, the feature was located on the Oooguruk Offshore Drillsite in the shallow waters of the Colville River Delta. It consisted of 10- to 15-cm thick plates that were stacked against the south corner and southwest side in multiple waves with heights of 3 m (Plate 19). Although some of the pile-up had been mechanically removed to accommodate on-ice activities prior to the reconnaissance flight, it appeared that the plates had not encroached beyond the waterline area of the island's gravel bag armor (Leidersdorf, *et al*., 2008). The probable cause of the pile-up was the combination of an easterly storm from October 2nd through 6th followed by an abrupt shift to westerly winds on the 7th.

Plate 18. Newly-Formed Lead near Stamukhi Shoal on February 4, 2011

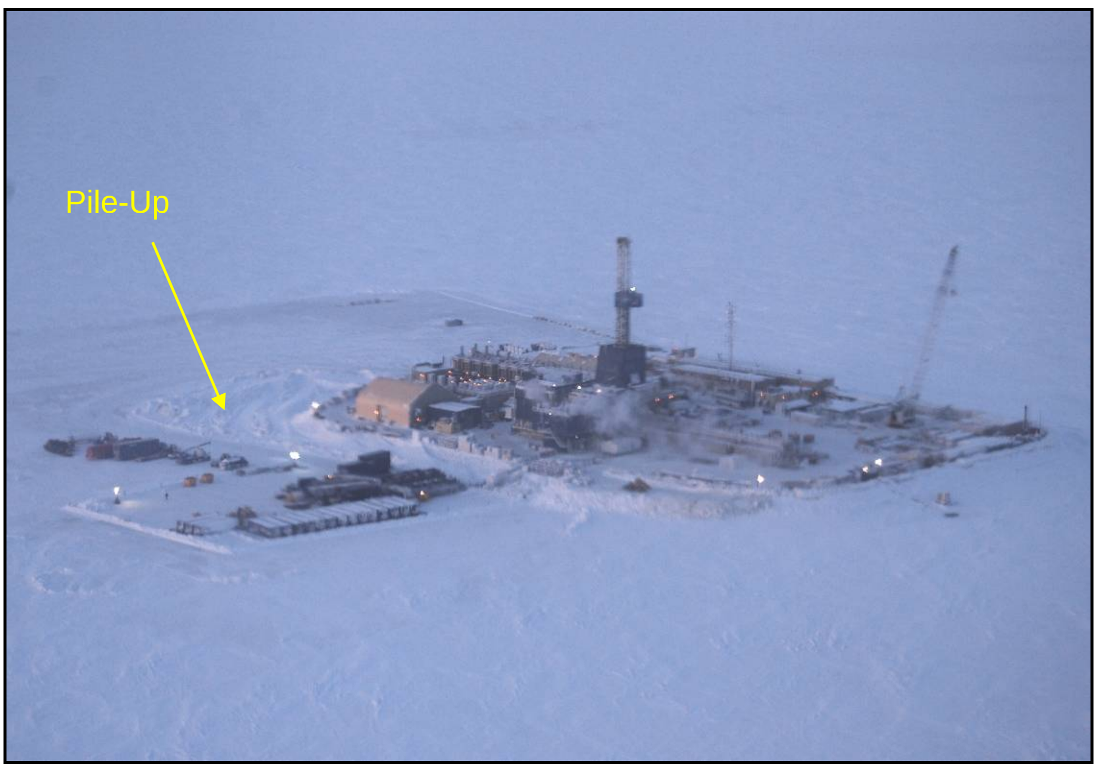


Plate 19. 3-m High Ice Pile-Up on Oooguruk Offshore Drillsite

4.3.6. Ice Conditions in Shell Prospects

When the prospective pipeline route for Shell's Sivulliq Development was inspected by helicopter on February 3rd, the transition between the landfast ice edge and the large refreezing lead that paralleled the barrier islands (Plate 14) was located approximately 0.5 nm (0.9 km) off Mary Sachs Entrance. A second lead with a similar orientation was located 2 nm (4 km) off the Entrance (Plate 20), after which extensive rubble fields and occasional ridges with heights of 3 to 4 m prevailed to the offshore end of the route (Plate 21). Inshore of the landfast ice edge, in the region that includes Mary Sachs Entrance and Leffingwell Lagoon, the ice was relatively flat and smooth with the exception of embedded fragments of old ice in the Entrance (Plate 22).

In summary, the ice on the Sivulliq pipeline route was found to be relatively stable inside the 6-m isobath and dynamic and unstable outside. This pattern is similar to that noted during the 2010-11 freeze-up study, except that the transition between stable and unstable ice occurred farther offshore, in the vicinity of the 12-m isobath, in February 2010 (Coastal Frontiers and Vaudrey, 2010).

Plate 20. Open Lead 2 nm off Mary Sachs Entrance on Sivulliq Pipeline Route on February 3, 2011

Plate 21. 3- to 4-m High Rubble and Ridge on Offshore Portion of Sivulliq Pipeline Route on February 3, 2011

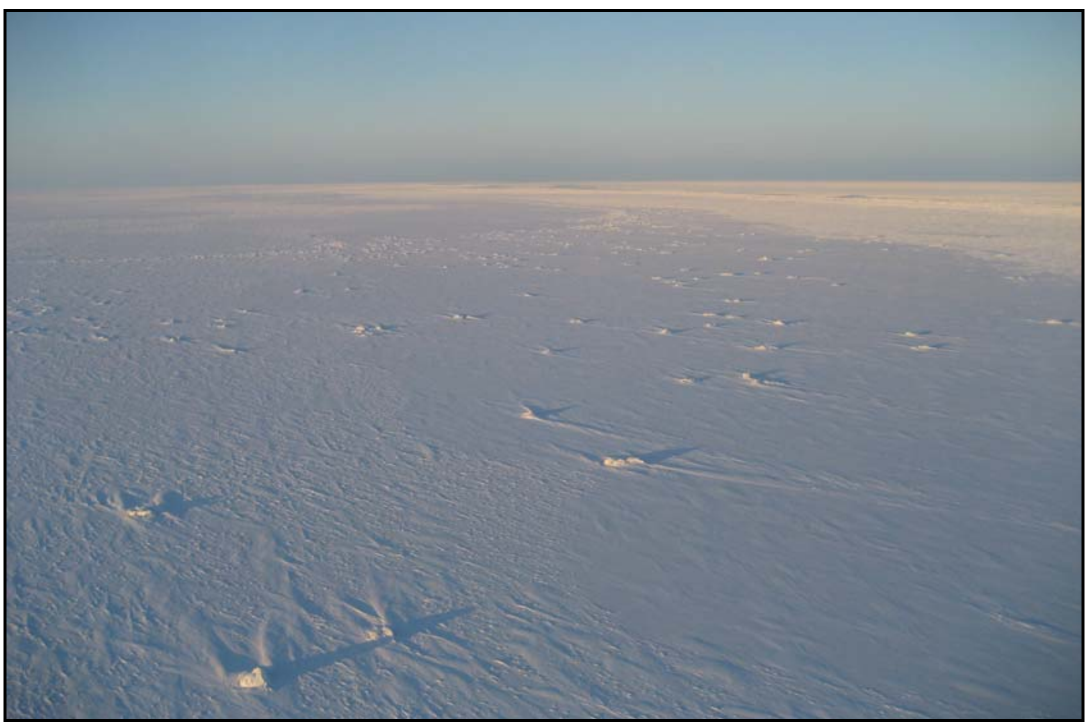


Plate 22. Flat, Stable Ice with Embedded Fragments of Old Ice in Mary Sachs Entrance on February 3, 2011

The northeastern portion of Shell's Harrison Bay Prospects, including Stamukhi Shoal, was covered by highly mobile ice that lay seaward of the landfast ice edge (the location of which appeared unchanged from that on January 31st; Figure 28). Four-meter high ridges and rubble were noted in this region along with the refreezing lead shown in Plate 23 and the open lead shown in Plate 18.

In the southwestern portion of the Harrison Bay Prospects, where the ice was landfast, inactive shear lines were surrounded by extensive rubble fields. A representative example is presented in Plate 24. At the southern edge of the prospects, ridges and rubble piles trending east-west and attaining heights of up to 10 m were noted in water depths of 10 to 12 m (Plate 25). These features corresponded to the location of the landfast ice edge in November (Figure 20), and probably resulted from the 2-day easterly storm of November 3rd and 4th.

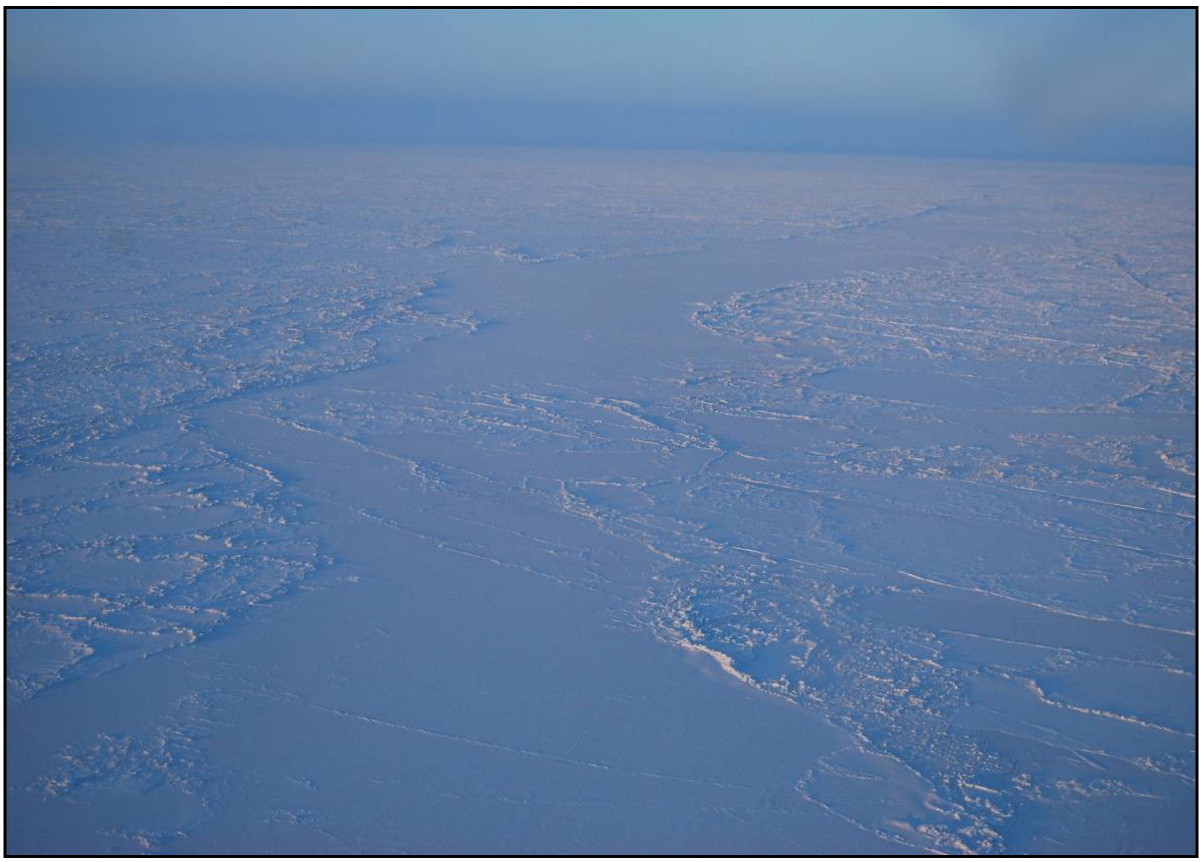


Plate 23. 4-m High Rubble and Refrozen Lead in Harrison Bay Prospects on February 4, 2011

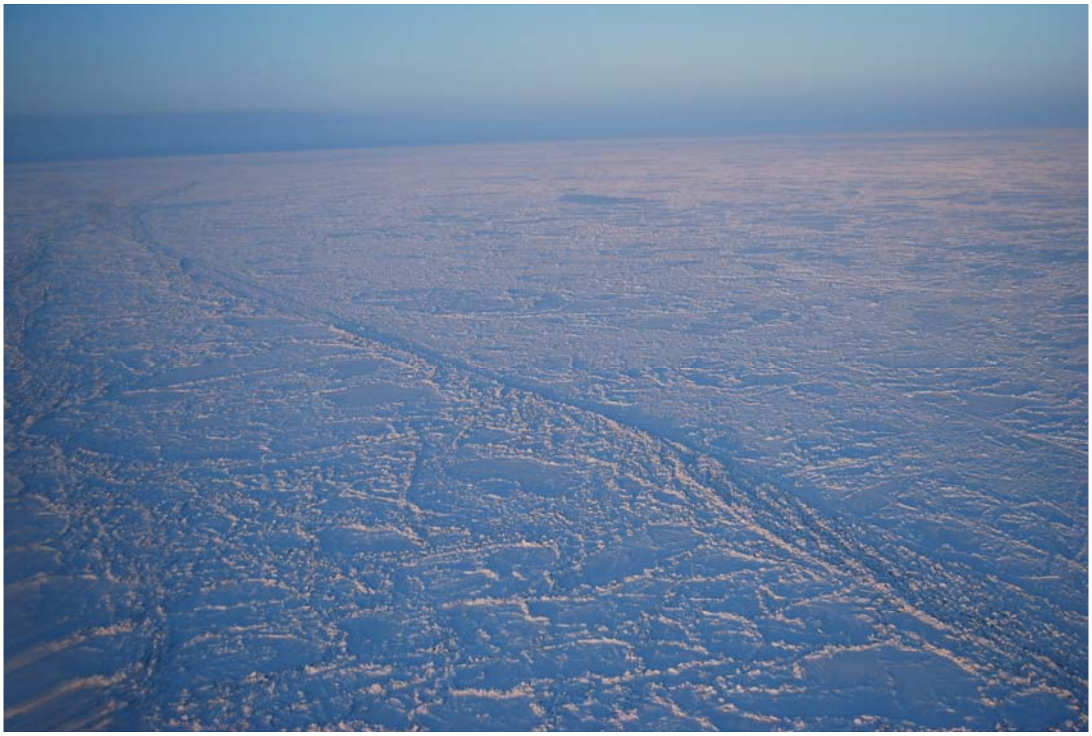


Plate 24. Inactive Shear Line Surrounded by Rubble in Harrison Bay Prospects on February 4, 2011

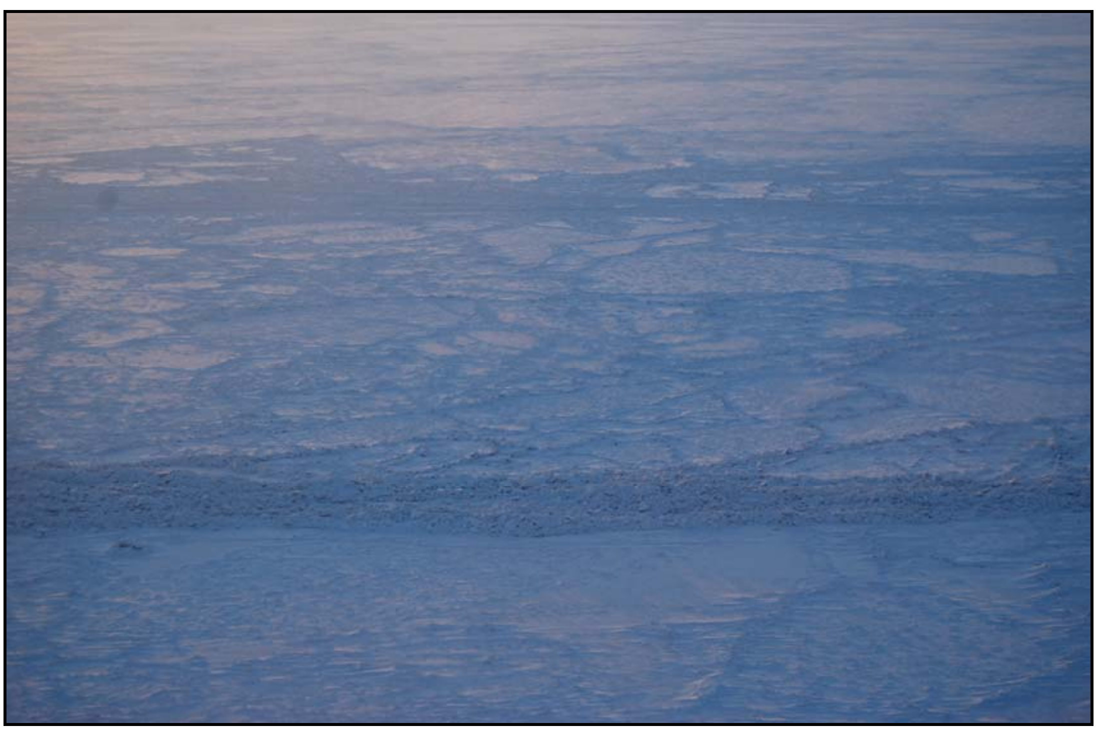
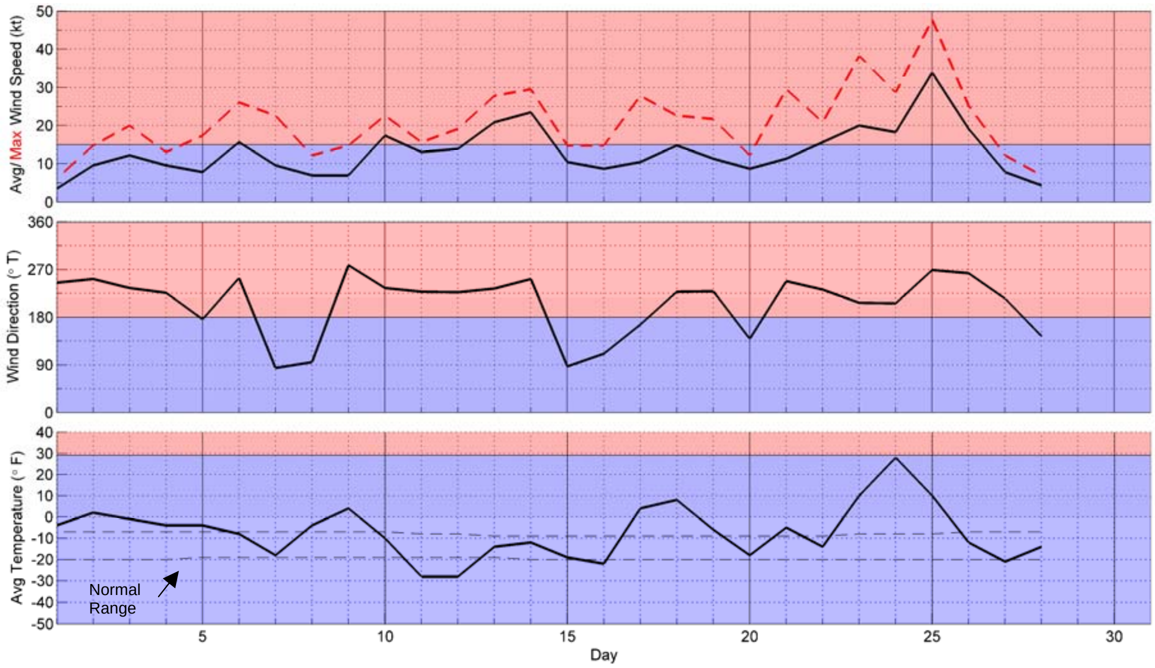


Plate 25. 10-m High Rubble Pile at Southern Edge of Harrison Bay Prospects on February 4, 2011

4.4. Mid-Winter

4.4.1. February 2011

Meteorological Conditions: The meteorological conditions recorded at Deadhorse Airport in February are displayed in Figure 32. The average daily temperatures tended to be higher than normal, including a maximum value of +28°F (-2°C) on the 24th. Westerly winds prevailed on most days, and the easterlies that did occur were of short duration and moderate speed.



Source: Weather Underground, 2011

Figure 32. Meteorological Conditions at Deadhorse Airport in February 2011

Westerly storm events occurred on four occasions: the 6th, 10th, 13th through 14th, and 22nd through 26th (Table 4). The first three were not particularly strong, with maximum wind speeds of 16, 17, and 23 kt (8, 9, and 12 m/s). The four-day storm at the end of the month was not only longer but also substantially more energetic, with a maximum speed of 34 kt (17 m/s).

Ice Thickness: The calculated thickness of undisturbed first-year ice increased from 107 cm at the beginning of the month to 124 cm at the end, based on the accumulation of 1,012 FDD in December and 4,535 FDD since the beginning of the freeze-up season.

Landfast Ice: Figure 33 presents the locations of the landfast ice edge derived from RADARSAT-2 images obtained on January 31st and February 13th (the last image available

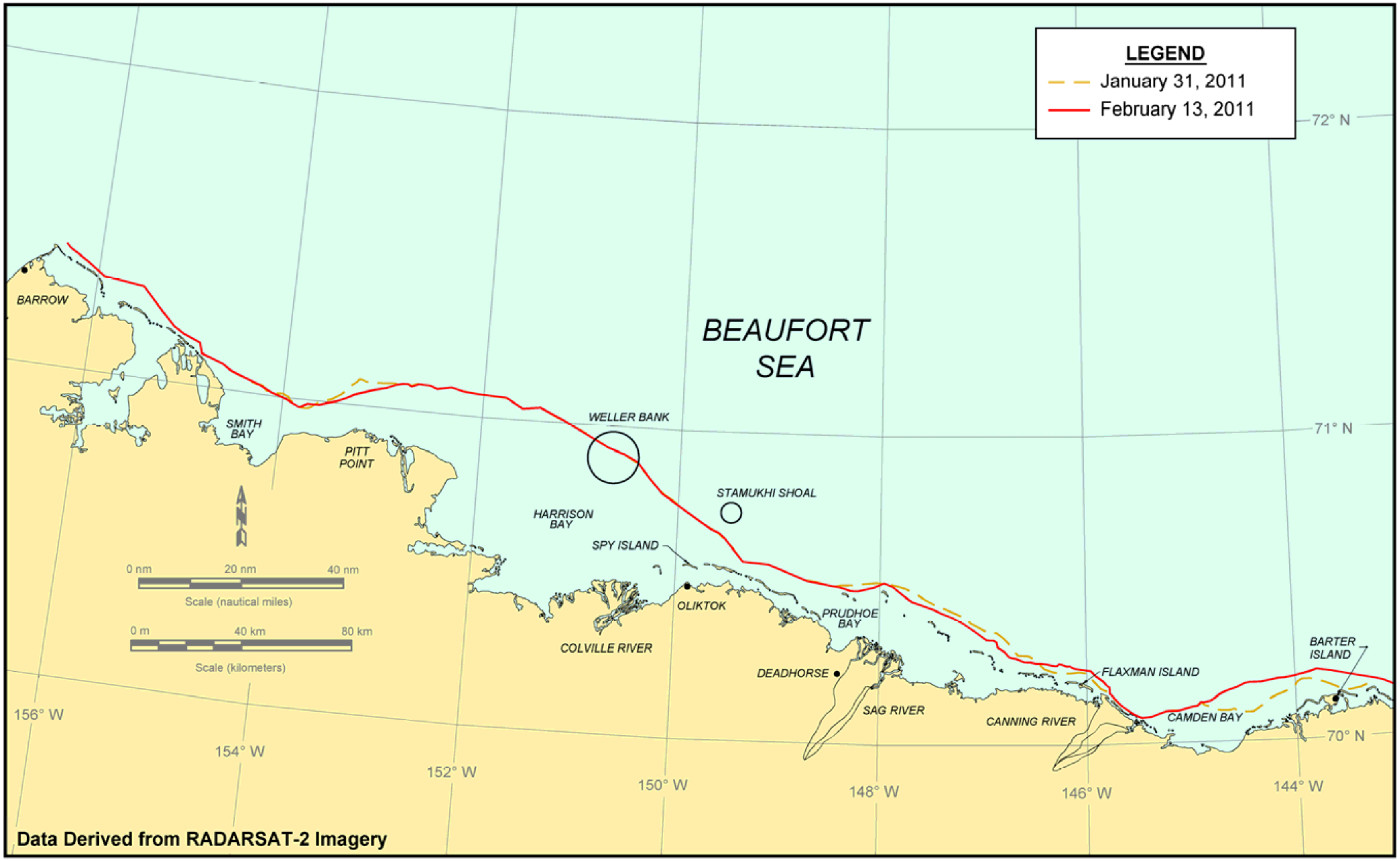


Figure 33. Beaufort Sea Landfast Ice Edge in February 2011

for analysis). During this two-week period, the ice edge remained virtually unchanged to the west of Prudhoe Bay, retreated slightly between Prudhoe Bay and Flaxman Island, and advanced modestly in the eastern portion of Camden Bay. The expansion of the landfast ice in Camden Bay is consistent with the accumulation of east-moving ice driven by westerly winds (Figure 32).

Leads: Significant leads and polynyas were absent from the RADARSAT-2 image obtained on February 13th (Figure 34).

Multi-Year Ice: The perennial pack ice continued to maintain substantial separation from the Alaskan Beaufort Sea coast through February 13th. As shown in Figure 34, the southern boundary was located slightly to the north of the 71°N parallel in the eastern portion, and slightly to the south of the 73°N parallel in the western portion.

Ice Movement: Ice movement rates in February were investigated using five multi-year floes (Floes E, F, G, I, and J) and seven Iridium buoys (Buoys 1 through 4 and A through C). The five floes, all of which had been followed in January, were identified in RADARSAT-2 images obtained on either January 29th or 31st , and February 12th or 13th. In the eastern Beaufort, Floe J moved to the west; in the western Beaufort, the other four floes moved to the northwest (Figure 35). The average floe speeds were extremely low: 1.4 to 3.0 nm/day (2.6 to 5.6 km/day) with an average of only 1.8 nm/day (3.3 km/day). These findings indicate that the east-to-west set of the Beaufort Gyre was nearly overcome by the persistent westerly winds evident in Figure 32.

The tracks described by the seven Iridium buoys during the month of February are displayed in Figure 36 (based on the positions reported at midnight on each day). Off Spy Island, Buoys A and B remained stationary until they were pushed to the east southeast by the westerly storm of February 22nd-26th. The displacement of Buoy A indicates that the landfast ice edge identified in the February 13th RADARSAT-2 image was breached during the storm, causing the zone of landfast ice in Harrison Bay to contract. Buoy C, located farther offshore, moved back and forth in a contour-parallel direction before moving 63 nm (117 km) to the east southeast during the month-end storm event.

The two inshore buoys off Flaxman Island, 1 and 2, moved east to the vicinity of Barter Island during the course of the month, with most of the translation occurring during westerly storm events. The two offshore buoys, 3 and 4, followed trajectories similar to that of Buoy C, with back-and-forth movement along the bathymetric contours before displacements of 44 and 46 nm (82 and 85 km) to the east southeast during the February 22nd–26th storm.

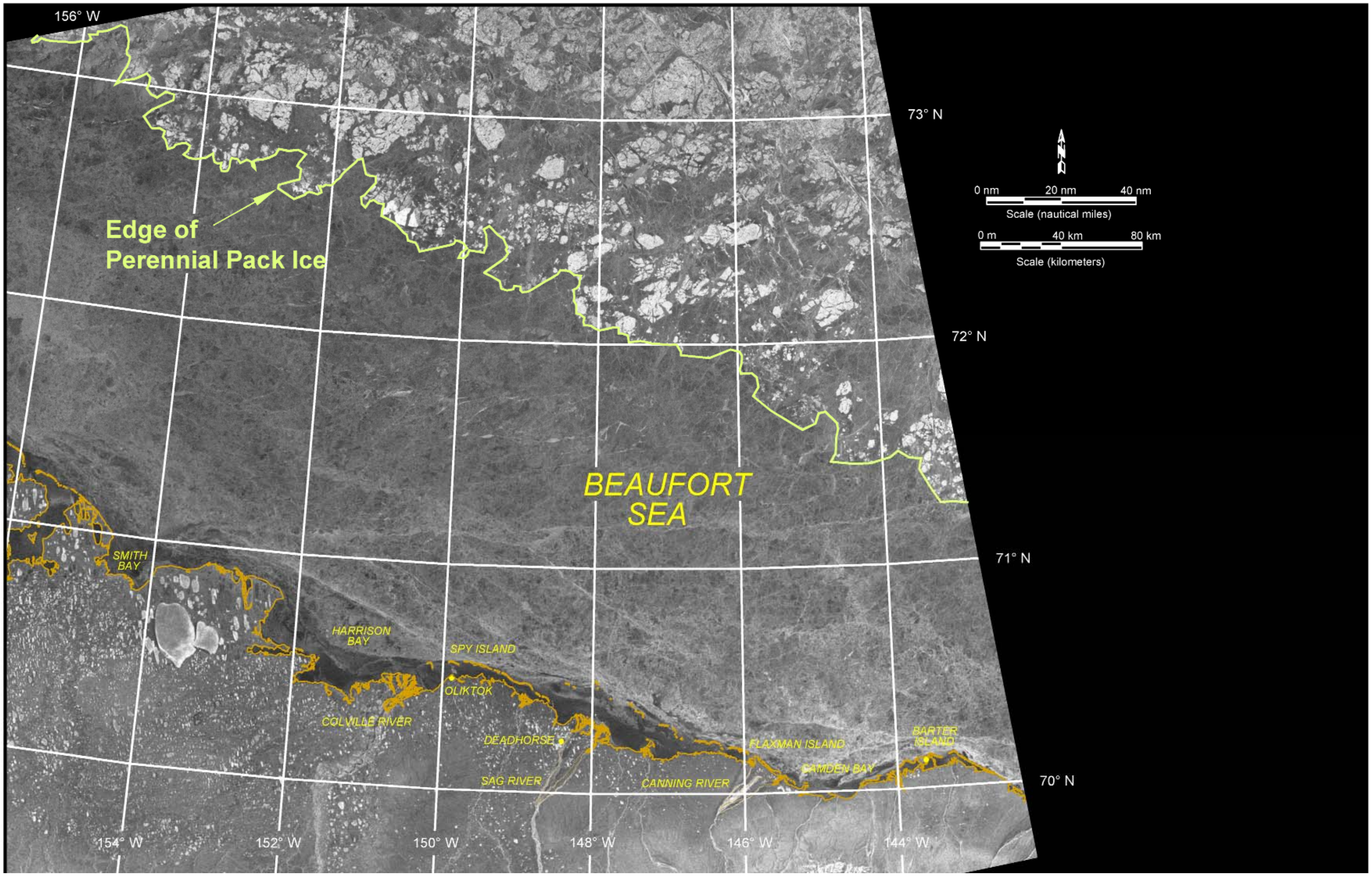


Figure 34. RADARSAT-2 Image of Beaufort Sea Acquired on February 13, 2011

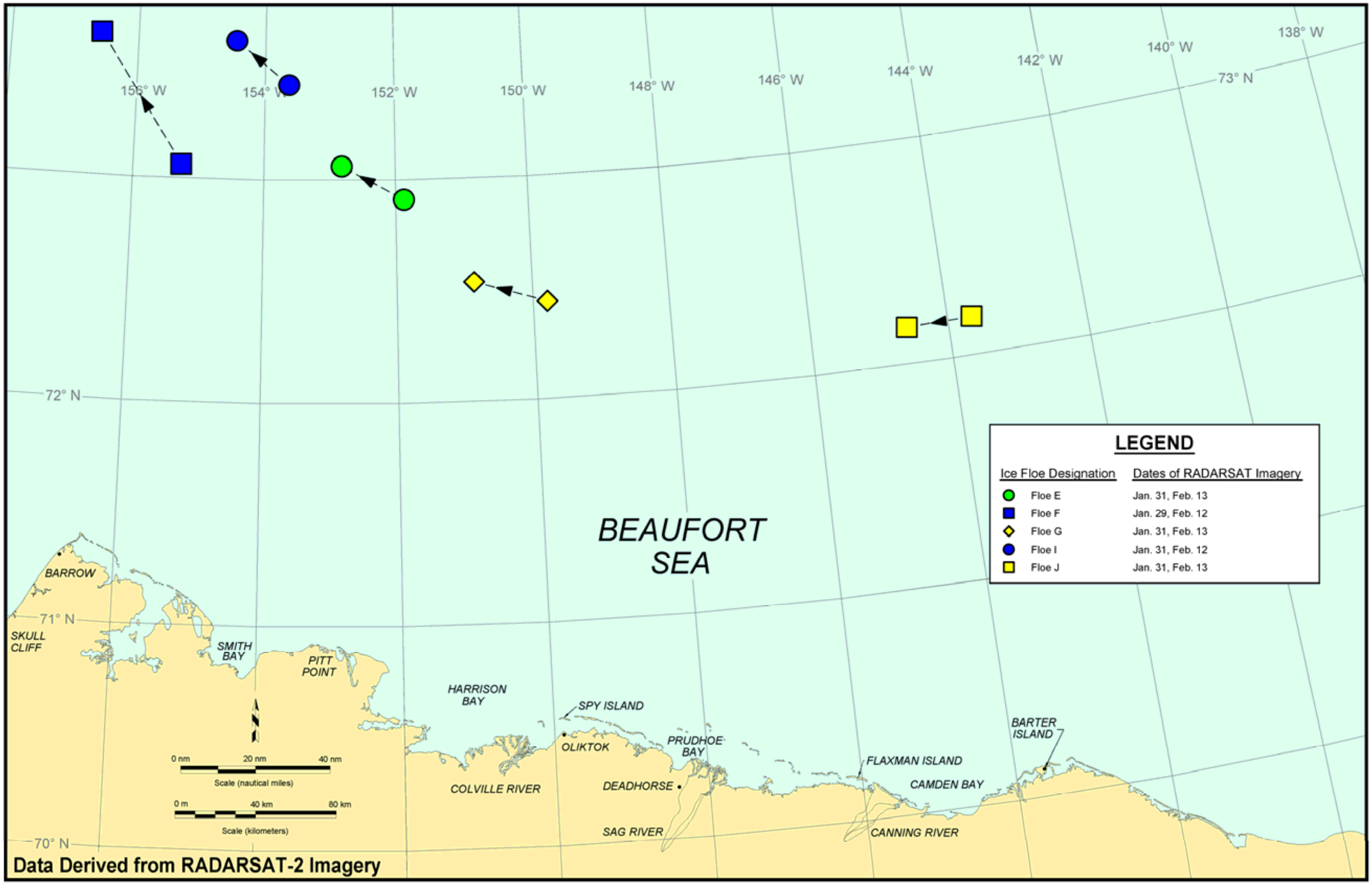


Figure 35. Beaufort Sea Multi-Year Ice Floe Tracks in February 2011

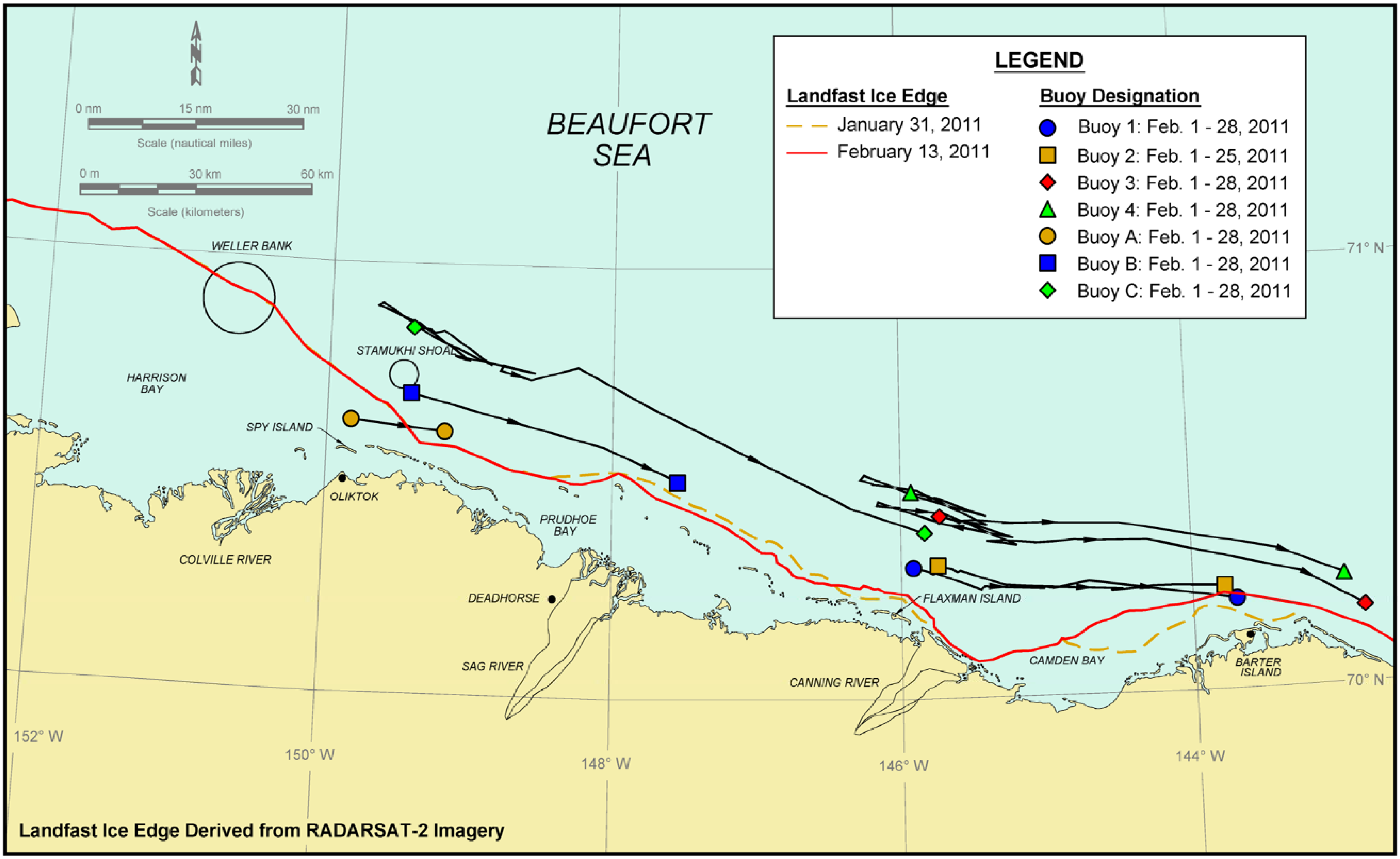


Figure 36. Beaufort Sea Iridium Buoy Tracks in February 2011

Figure 37 presents a time series of the average daily speed for each buoy computed from successive positions at midnight. The average daily wind speed and direction from Deadhorse Airport also are shown. With the exception of Buoy 2, which ceased continuous data transmission on February 25th and failed completely on the 26th, all of the buoys reached their maximum speeds on the 25th or 26th.

Table 5 summarizes the maximum value of the average daily speed attained by each buoy during each of the four westerly storms in February. The highest speed of 1.3 kt (0.7 m/s) was registered by Buoy C on February 25th. Table 5 also includes a "wind factor" for each storm computed as the ratio between the maximum daily buoy speed and maximum daily wind speed recorded at Deadhorse Airport during the storm. The highest wind factor, 3.8%, occurred during the February 22nd-26th storm, presumably because the ice lost confinement during this sustained, high-energy event. The computed wind factors should be regarded as approximate, in that the buoys were separated from the source of the wind data (Deadhorse Airport) by substantial distances.

Table 6 is analogous to Table 5 but presents the maximum hourly speed attained by each buoy rather than the maximum daily speed. The values shown were derived by computing the speed between each pair of successive hourly positions and then selecting the maximum value that occurred during each storm (after excluding obvious outliers). The wind factor shown for each storm was computed as the ratio between the maximum hourly buoy speed and maximum sustained wind speed recorded during the storm at Deadhorse Airport. As in the case of Table 5, the highest hourly speed (2.2 kt or 1.1 m/s) and highest wind factor (4.6%) were associated with the February 22nd–26th storm.

4.4.2. March 2011

<u>Meteorological Conditions</u>: Figure 38 presents the wind and temperature data recorded at Deadhorse Airport in March 2011. Despite occasional exceptions, the average daily temperatures tended to remain close to normal. The winds were exceptionally light, oscillating between easterly and westerly at an approximate frequency of twice per week. The most striking aspect of the wind regime, however, was a near-absence of storms: the sole event was a 16-knot westerly that occurred on March 15th. As a result, the Alaskan Beaufort Sea experienced only one easterly storm (January 2nd-3rd) during the first three months of 2011.

<u>Ice Thickness</u>: The calculated thickness of undisturbed first-year ice at the end of March was 142 cm, versus 124 cm at the outset. The calculation was based 5,710 FDD since the beginning of the freeze-up season, including 1,175 FDD in March.

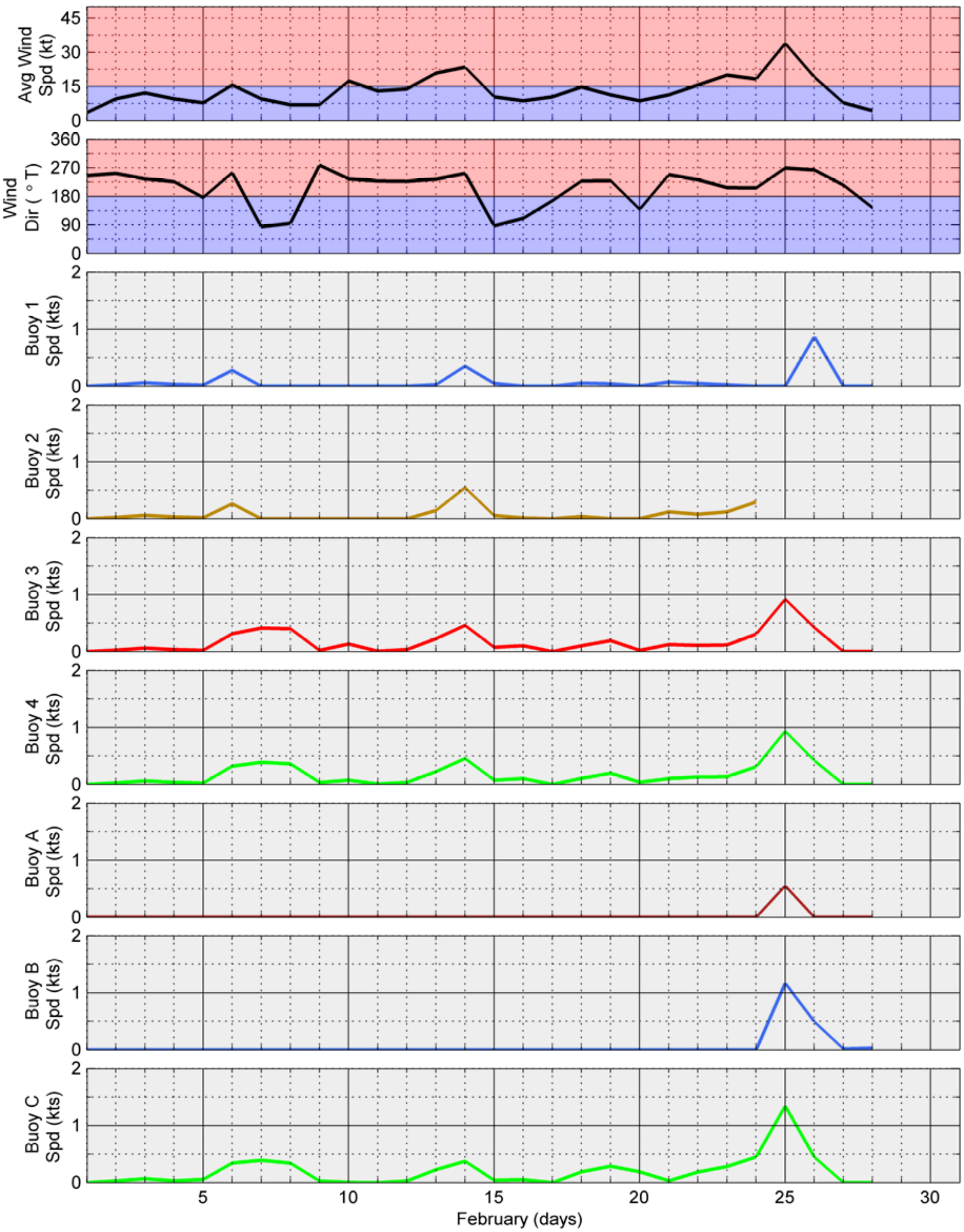


Figure 37. Time Series of Iridium Buoy Average Daily Speed in February 2011

Table 5. Maximum Daily Buoy Speeds (kt) during February 2011 Storm Events[1]

Buoy	Storm Date			
	Feb 6	Feb 10	Feb 13-14	Feb 22-26
1	0.3	0.0	0.4	0.9
2	0.3	0.0	0.5	0.3[3]
3	0.3	0.1	0.5	0.9
4	0.3	0.1	0.5	0.9
A	0.0	0.0	0.0	0.6
B	0.0	0.0	0.0	1.2
C	0.3	0.0	0.4	1.3
Maximum (kt)	**0.3**	**0.1**	**0.5**	**1.3**
Wind Factor (%)[2]	**1.9**	**0.6**	**2.2**	**3.8**

Notes: [1] Each buoy speed represents the maximum value in knots recorded between successive daily positions (at midnight) over the duration of the storm.

[2] The "Wind Factor" shown for each storm represents the ratio between the maximum daily buoy speed and maximum daily wind speed recorded at Deadhorse Airport.

[3] Continuous data transmission from Buoy 2 ceased on February 25th. The other buoys attained maximum speeds thereafter, on the 25th or 26th.

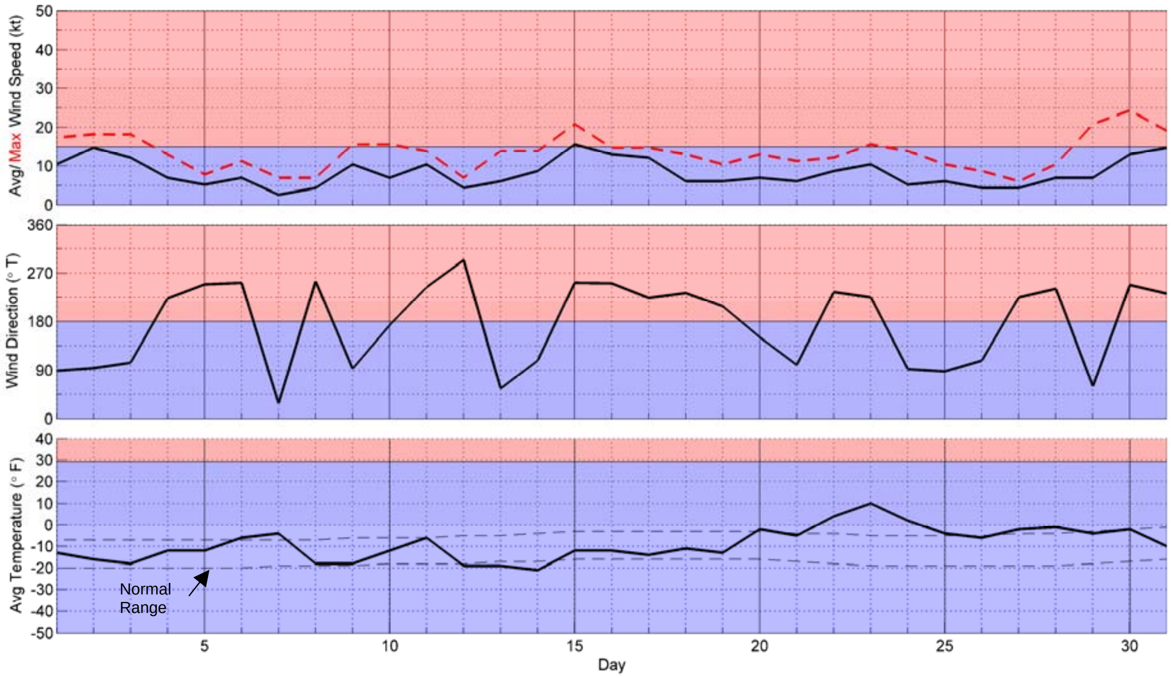
Table 6. Maximum Hourly Buoy Speeds (kt) during February 2011 Storm Events[1]

Buoy	Storm Date			
	Feb 6	Feb 10	Feb 13-14	Feb 22-26
1	0.9	0.0	0.6	n/a[3]
2	0.9	0.0	0.9	1.2
3	0.9	0.3	0.6	1.6
4	0.8	0.2	0.6	1.6
A	0.0	0.0	0.0	1.7
B	0.0	0.0	0.0	2.1
C	0.9	0.1	0.5	2.2
Maximum (kt)	**0.9**	**0.3**	**0.9**	**2.2**
Wind Factor (%)[2]	**3.5**	**1.3**	**3.0**	**4.6**

Notes: [1] Each buoy speed represents the maximum value in knots recorded between successive hourly positions over the duration of the storm.

[2] The "Wind Factor" shown for each storm represents the ratio between the maximum 1-hour buoy speed and maximum sustained wind speed recorded at Deadhorse Airport.

[3] Buoy 1 failed to transmit hourly position data during portions of the February 22nd-26th storm.



Source: Weather Underground, 2011

Figure 38. Meteorological Conditions at Deadhorse Airport in March 2011

Multi-Year Ice: A CIS mosaic prepared from RADARSAT images obtained between March 25th and 28th indicates that the perennial pack ice remained far north of the Alaskan Beaufort Sea coast. The southern boundary was located slightly south of the 71°N parallel in the eastern portion, and near the 74°N parallel in the western portion.

Ice Movement: Ice movement patterns during the month of March are indicated by the Iridium buoy tracks shown in Figure 39. The figure includes six of the seven the original buoys (Buoy 2 ceased data transmission in late February) and five new buoys deployed on March 16 off Spy Island (Buoys A-2, B-2, and C-2) and Flaxman Island (Buoys 1-2 and 3-2).

Among the original buoys, those located farther offshore (Buoys B, C, 3, and 4) reversed direction relative to February and headed west northwest in the early part of March. Significant motion ceased on or before March 11th, apparently reflecting the re-establishment of confinement after the disruption caused by the February 22nd-26th storm. The average speeds computed for the month were extremely low, ranging from 1.5 to 1.7 nm/day (2.7 to 3.1 km/day). The original inshore buoys (A and 1) remained stationary, implying that they were located inside the prevailing landfast ice edge.

The five new buoys moved minimally between March 17th and 31st, confirming that the ice canopy was essentially static during the second half of the month.

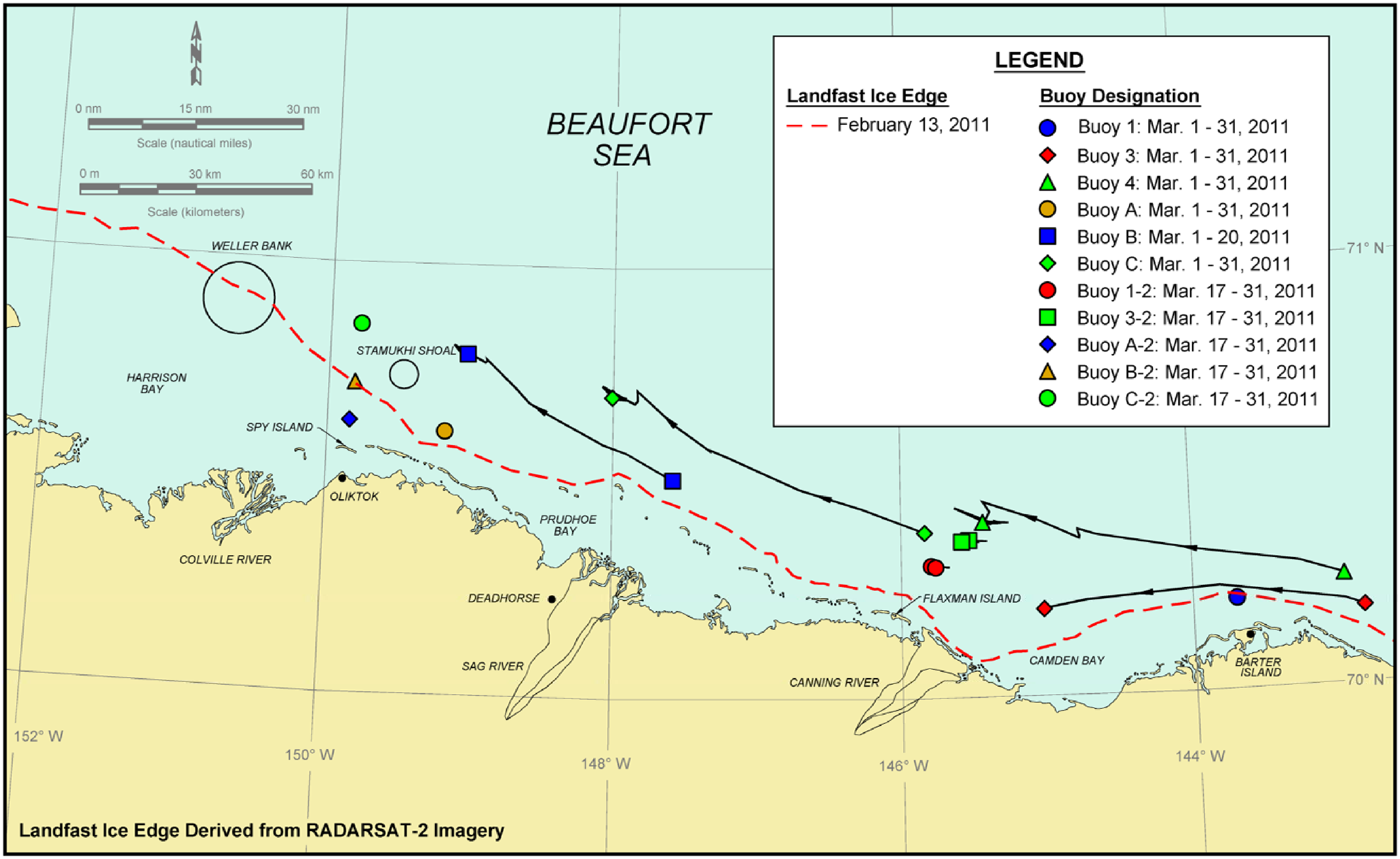


Figure 39. Beaufort Sea Iridium Buoy Tracks in March 2011

5. CHUKCHI SEA

5.1 Late Summer 2010

At the beginning of August, open water prevailed in the northeast portion of the Chukchi Sea but a tongue of ice occupied the central portion as far south as the 70°N parallel. The ice edge retreated to the north and west throughout August and much of September under the combined influence of warm air temperatures and the Alaska Coastal Current, which transports warm water north from the Bering Strait (Figure 1). Ice-free conditions prevailed south of the 75°N parallel and east of the 178°W meridian on September 13th (Figure 40), and throughout the entire Chukchi with the exception of the extreme northwest corner (in the vicinity of 74.5°N and 175.5°E) on September 27th.

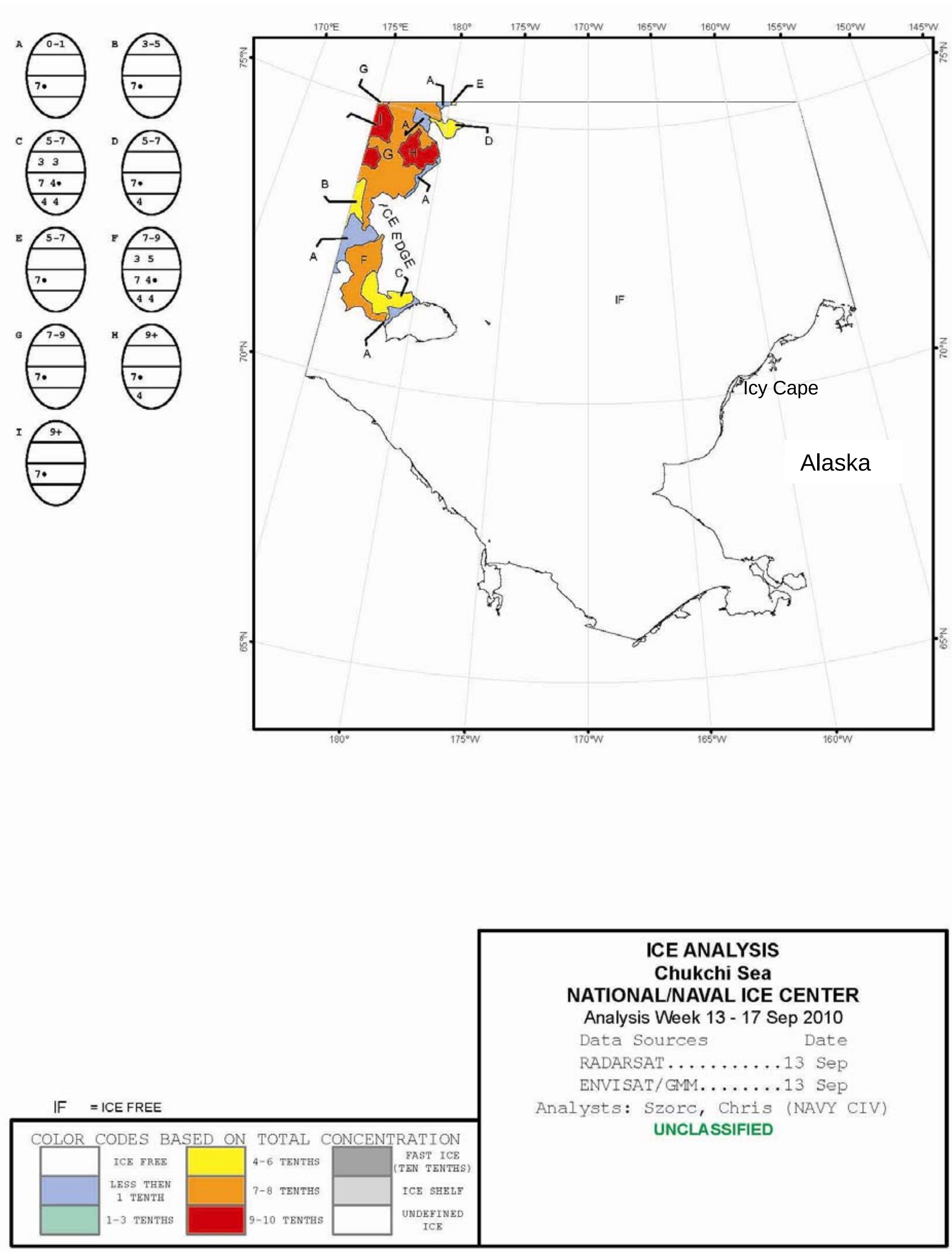
5.2. Freeze-Up

5.2.1. October 2010

Meteorological Conditions: The daily values of average and maximum sustained wind speed, average wind direction, and average air temperature at Barrow Airport are shown in Figure 41. As in Section 4, the red and blue color bands in this and all subsequent meteorological plots are intended to denote the ranges of parameters defined in Table 3. Unless indicated otherwise, the wind speeds discussed in the text refer to the daily average values of the sustained wind speed (rather than the daily maximum sustained values). The characteristics of all storms with a daily average sustained wind speed exceeding 15 kt (8 m/s) at Barrow Airport are presented in Table 7 for the six-month period from October 2010 through March 2011.

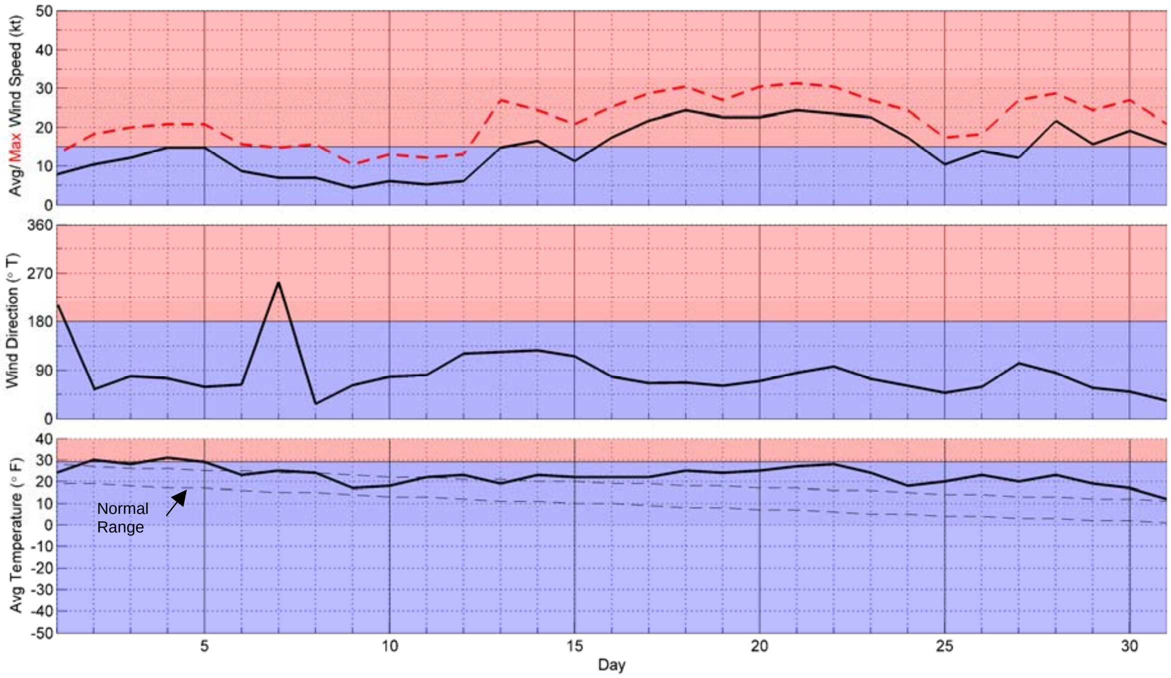
Like the Beaufort, air temperatures in the Chukchi remained above normal for most of October. Easterly winds predominated, with light southwesterlies interrupting the easterly flow on only two days. Easterly storms occurred on three occasions: a one-day event with a maximum wind speed of 16 kt (8 m/s) on the 14th, a protracted, nine-day event with a maximum wind speed of 24 kt (12 m/s) from the 16th through 24th, and a four-day event with a maximum wind speed of 22 kt (11 m/s) from the 28th through 31st.

Ice Cover: Freeze-up in the Chukchi Sea began during the first week in October, when the ice edge passed the 75°N parallel at the start of a slow, southward progression that continued for two months. By October 7th, new ice had begun to form in the protected waters of Kasegaluk Lagoon and Peard Bay. Ice growth continued in the nearshore area



After: National Ice Center, 2011

Figure 40. Chukchi Sea Ice Conditions on September 13, 2010



Source: Weather Underground, 2011

Figure 41. Meteorological Conditions at Barrow Airport in October 2010

through mid-month as air temperatures remained below freezing, but most of the new ice between Icy Cape and Barrow was dislodged from the coast by the easterly storm of October 16th through 24th. A RADARSAT-2 image obtained on October 28th shows a narrow strip of ice refreezing along the coast to the north of Icy Cape, a much larger expanse of new ice to the south of Icy Cape, and a southern boundary for the advancing pack ice that lies near the 72°N parallel off Barrow and 74°N parallel at 168°W (Figure 42).

Ice Thickness: The thickness of undisturbed first-year ice in the Chukchi Sea at the end of October was approximately 20 cm. This value was calculated using the relationship of Bilello (1960) with an accumulated total of 199 FDD at Barrow Airport (Table 1).

Multi-Year Ice: Large, well-consolidated multi-year ice floes were not detected in any of the RADARSAT-2 images obtained in October (Figure 42).

5.2.2. November 2010

Meteorological Conditions: The wind and temperature data acquired at Barrow Airport in November are shown in Figure 43. The average daily air temperatures remained between +1 and +17°F (-17 and -8°C) for the first two weeks before rising as high as +28°F (-2°C) in the third week. They then dropped back to between +8 and -13°F (-13 and -25°C) during the final six days of the month.

Table 7. Chukchi Sea Storm Characteristics, October 2010 – March 2011[1]

Month	Day	Duration (days)	Maximum Wind Speed (kt)[2]	
			Easterly	Westerly
October	14	1	16	
	16-24	9	24	
	28-31	4	22	
November	2-5	4	23	
	16-17	2		25
December	4	1	17	
	13	1	16	
	18-19	2	18	
	21	1		16
January	2-3	2	27	
	17	1		16
	28-29	2	16	
February	3	1		17
	5	1		16
	7	1	16	
	13-14	2		18
	18-19	2		19
	23-25	3		27
March	None	-		
Total Number of Events			**10**	**8**

Notes:

1. Table 7 includes all storm events with a daily average sustained wind speed exceeding 15 kt at Barrow Airport.
2. "Maximum Wind Speed" refers to the highest daily average sustained wind speed that occurred during each storm event.

Easterly winds predominated in November, occurring on eighteen of the thirty days. Storm events were limited to one easterly on the 2nd through 5th with a maximum wind speed 23 kt (12 m/s), and one westerly on the 16th and 17th with a maximum wind speed of 25 kt (13 m/s; Table 7).

Ice Cover: Aided by consistent sub-freezing temperatures and strong easterly winds that began on October 28th, the Chukchi Sea ice cover advanced rapidly to the southwest

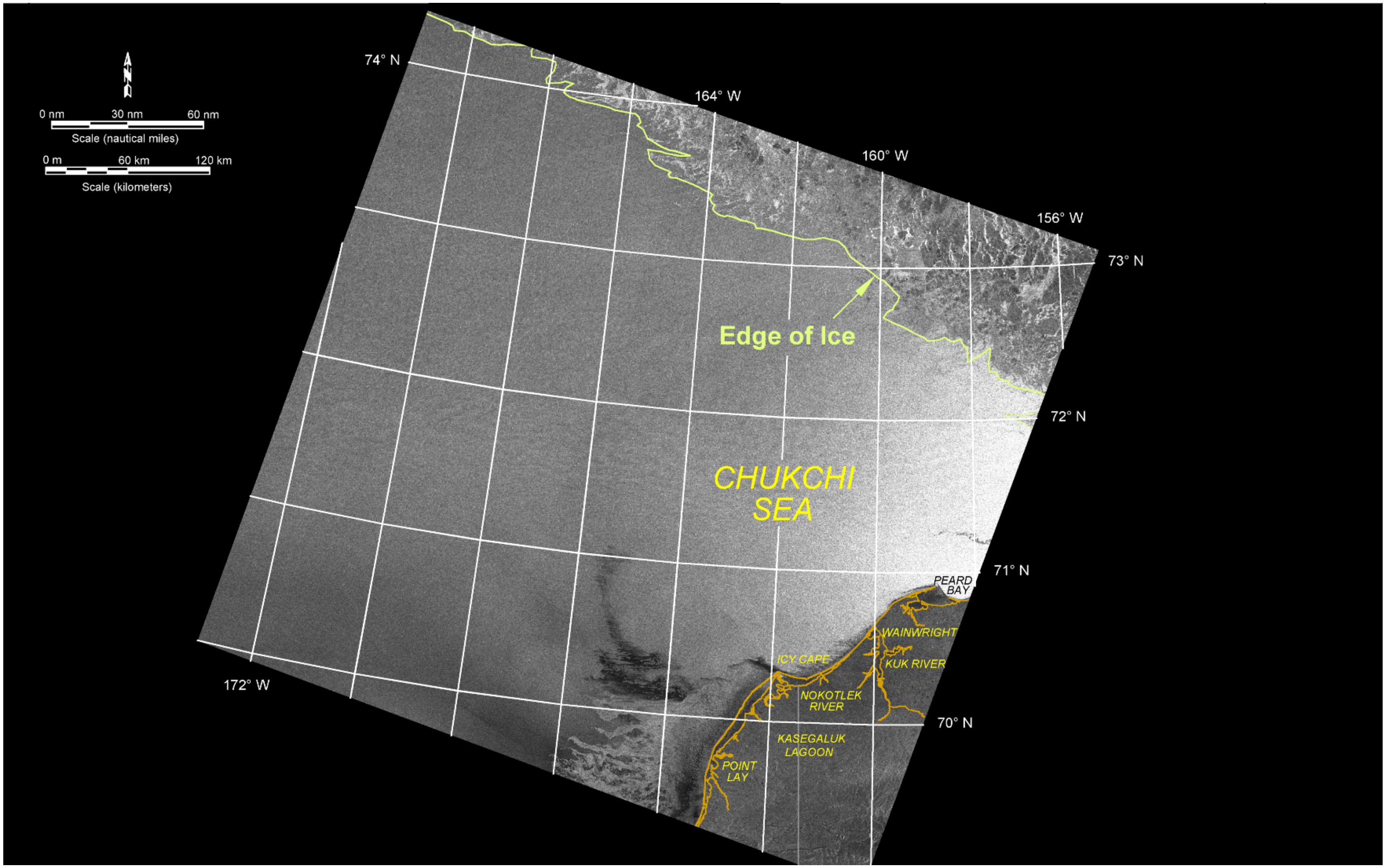
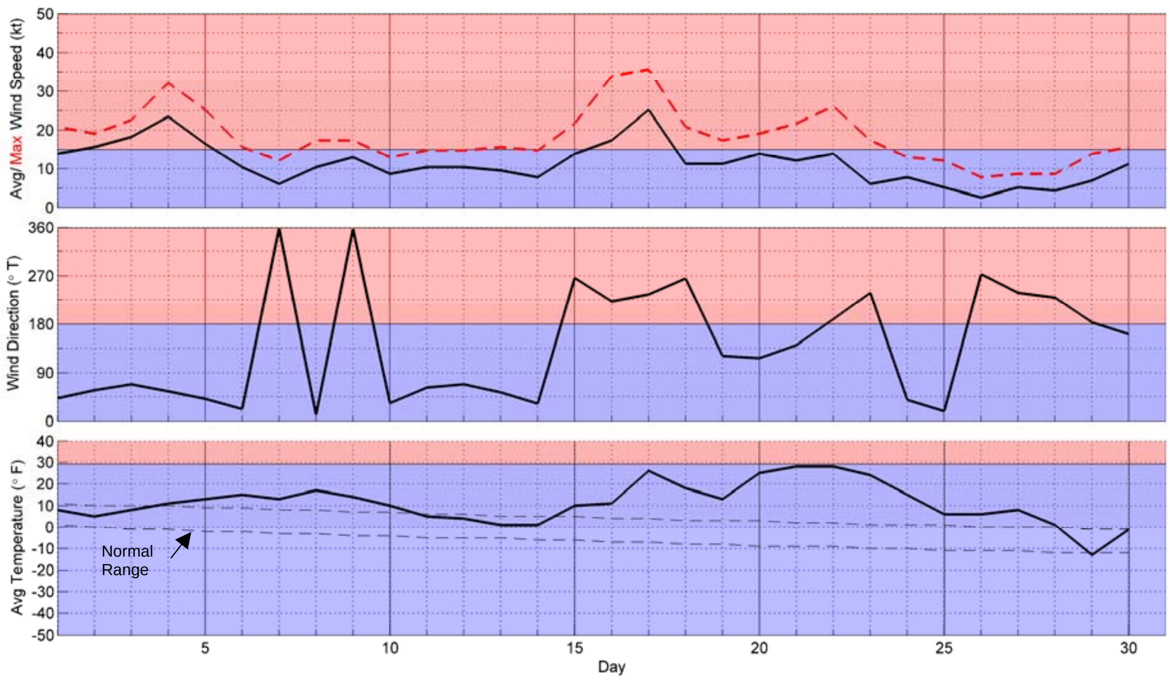


Figure 42. RADARSAT-2 Image of Chukchi Sea Acquired on October 28, 2010



Source: Weather Underground, 2011

Figure 43. Meteorological Conditions at Barrow Airport in November 2010

between that date (Figure 42) and November 4th (Figure 44). The advance continued at a much-reduced rate between the 4th and 11th (Figure 45), a period marked by alternating easterly and westerly winds. During the following two weeks (November 11th-25th), the ice edge consolidated and retreated to the east. The primary motive force was the westerly storm that occurred on the 16th and 17th. Between November 25th and December 1st, when cold temperatures and light winds prevailed, the northern ice edge moved south to the vicinity of 72.5°N while the western edge experienced little change.

All four Shell prospects (Hanna Shoal, West, Crackerjack, and Burger) were ice-free on October 28th but fully covered with ice on November 4th and 11th. The Hanna Shoal and Burger Prospects remained covered for the remainder of the month, but the West Prospect reverted to open water on November 18th and 25th as well as December 1st. At Crackerjack, five tenths ice cover prevailed on November 18th, less than 1 tenth on November 25th, and open water on December 1st.

Freeze-up in the nearshore region (assumed for the present purpose to encompass the region south of Point Barrow and east of the 163°W meridian, which passes through Point Lay) occurred on or about November 4th (Figure 45). Approximately 265 FDD had accumulated at Barrow Airport on this date.

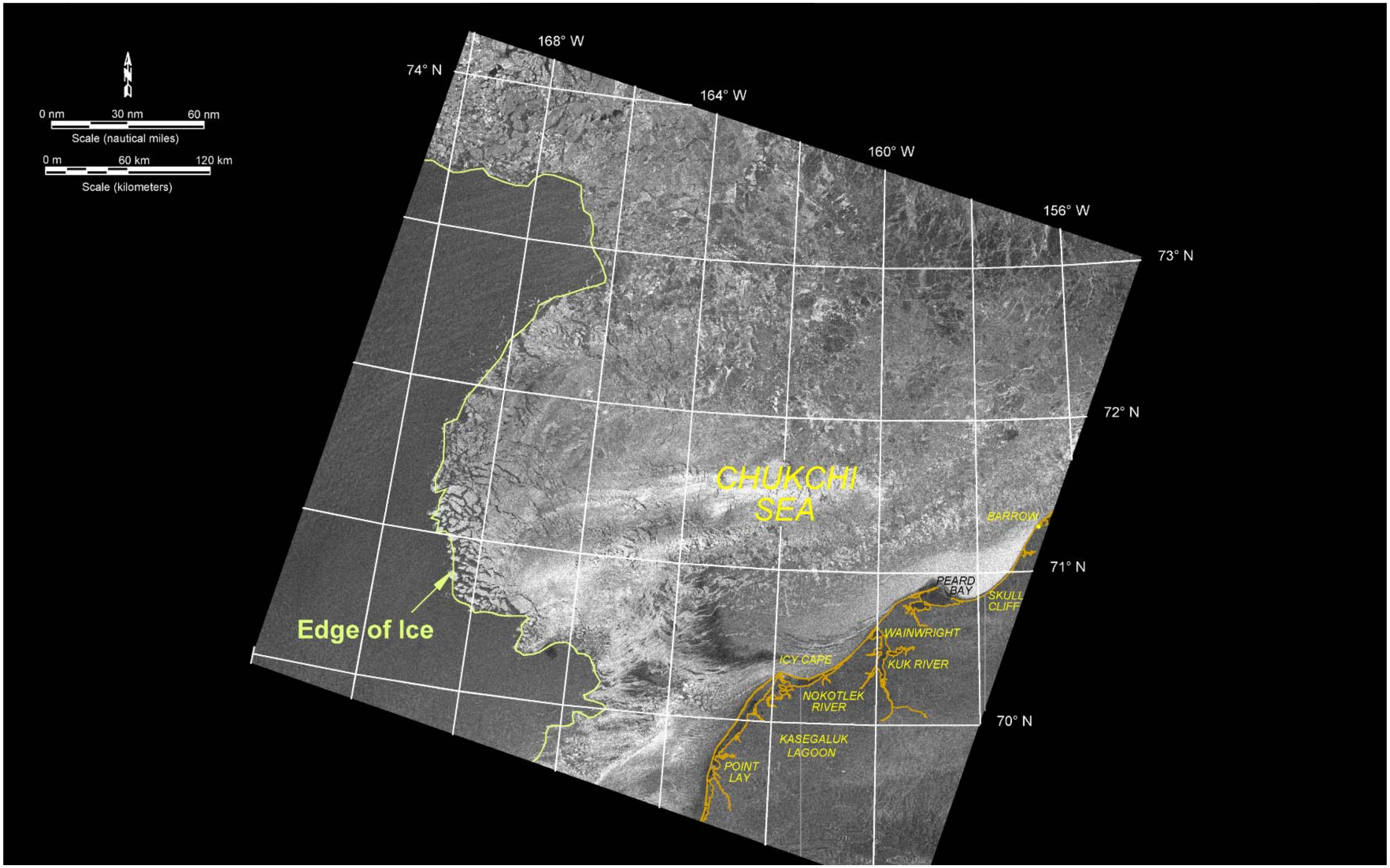


Figure 44. RADARSAT-2 Image of Chukchi Sea Acquired on November 4, 2010

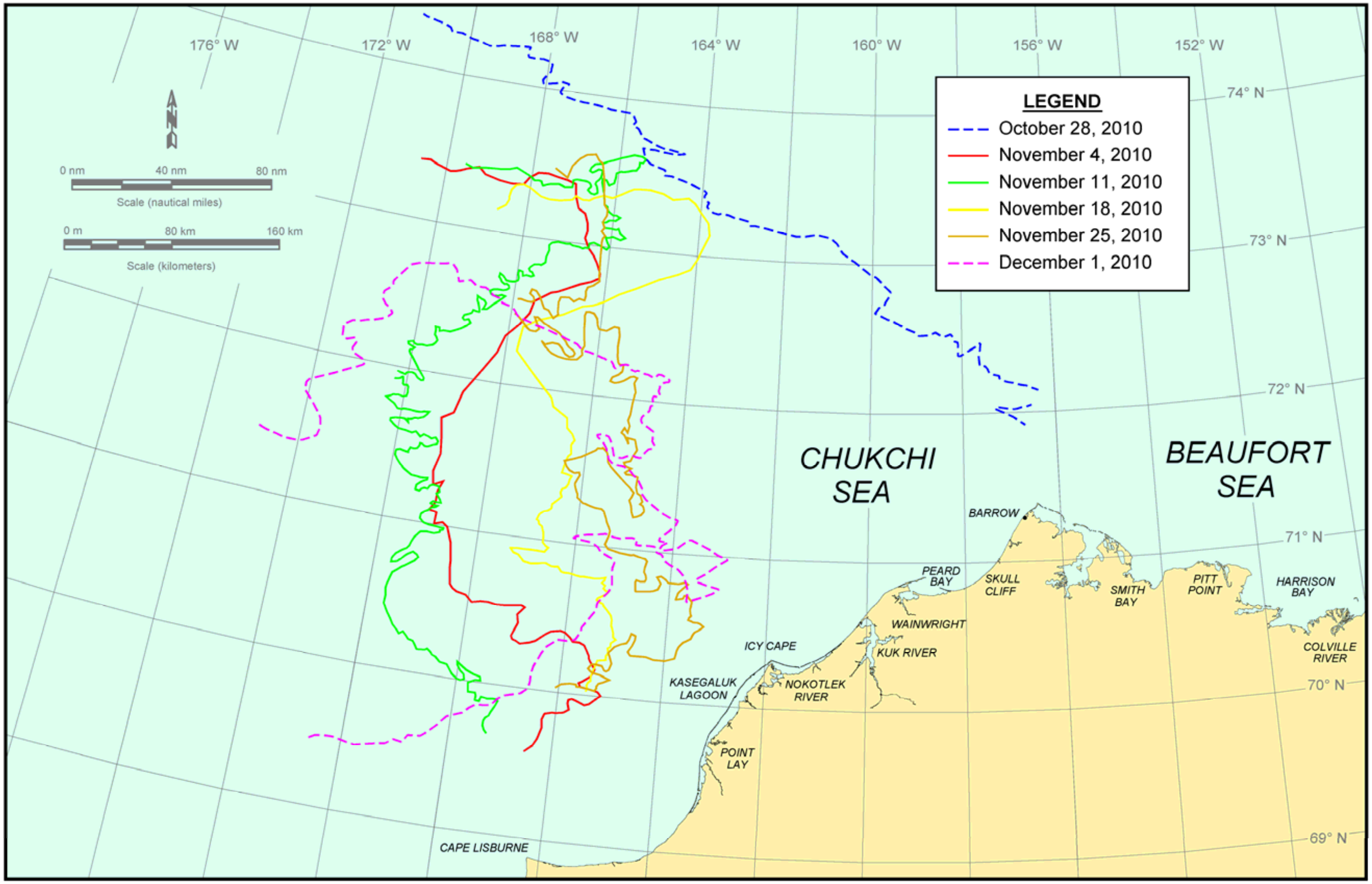


Figure 45. Chukchi Sea Ice Edge during Freeze-Up

Ice Thickness: The calculated thickness of undisturbed first-year ice increased from 20 cm at the beginning of the month to 43 cm at the end. The calculation is based on an accumulated total of 739 FDD at Barrow Airport (Table 1), including 540 FDD in November.

Landfast Ice: The first RADARSAT-2 image to display landfast ice was acquired on November 25th. As shown in Figure 46, the fast ice extended from Point Barrow to the mouth of the Kuk River in a narrow strip that rarely exceeded 2 km in width.

Ice Pile-Up: During the aerial reconnaissance flight conducted on February 5, 2011, (Section 3.5), twenty seven ice pile-ups were observed on the Chukchi Sea coast between Skull Cliff and Point Lay. The blocks comprising these features were estimated to be 30 to 40 cm thick (Section 5.3). The piles probably formed in mid-November, when loosely-consolidated ice was driven ashore by winds that shifted from east to west on the 15th and accelerated to 25 kt (13 m/s) on the 17th (Figure 43).

Multi-Year Ice: In November, as in October, large multi-year ice floes were absent from the Chukchi Sea.

5.2.3. December 2010

Meteorological Conditions: The wind and temperature data recorded at Barrow Airport in December 2010 are provided in Figure 47. Air temperatures trended close to normal during the first part of the month, spiked to +11°F (-12°C) on the 20th, returned to normal on the 22nd, and remained normal or slightly below normal thereafter.

Easterly winds prevailed more than 70% of the time, with easterly storm events occurring on the 4th, 13th, and 18th-19th (Table 7). The maximum daily wind speeds during these storms were 17, 16, and 18 kt (9, 8, and 9 m/s), respectively. The sole westerly storm in December occurred on the 21st, with a maximum daily wind speed of 16 kt (8 m/s).

Ice Cover: Based on an NIC ice chart prepared from satellite imagery obtained from December 5th through 7th and a RADARSAT-2 image acquired on the 8th, complete freeze-up in the Chukchi Sea north of Cape Lisburne occurred on or about December 7th. The temperature data from Barrow Airport indicate that 959 FDD had accumulated prior to this date. Despite the storms that followed on the 13th, 18th-19th, and 21st, the ice canopy remained intact for the remainder of the month.

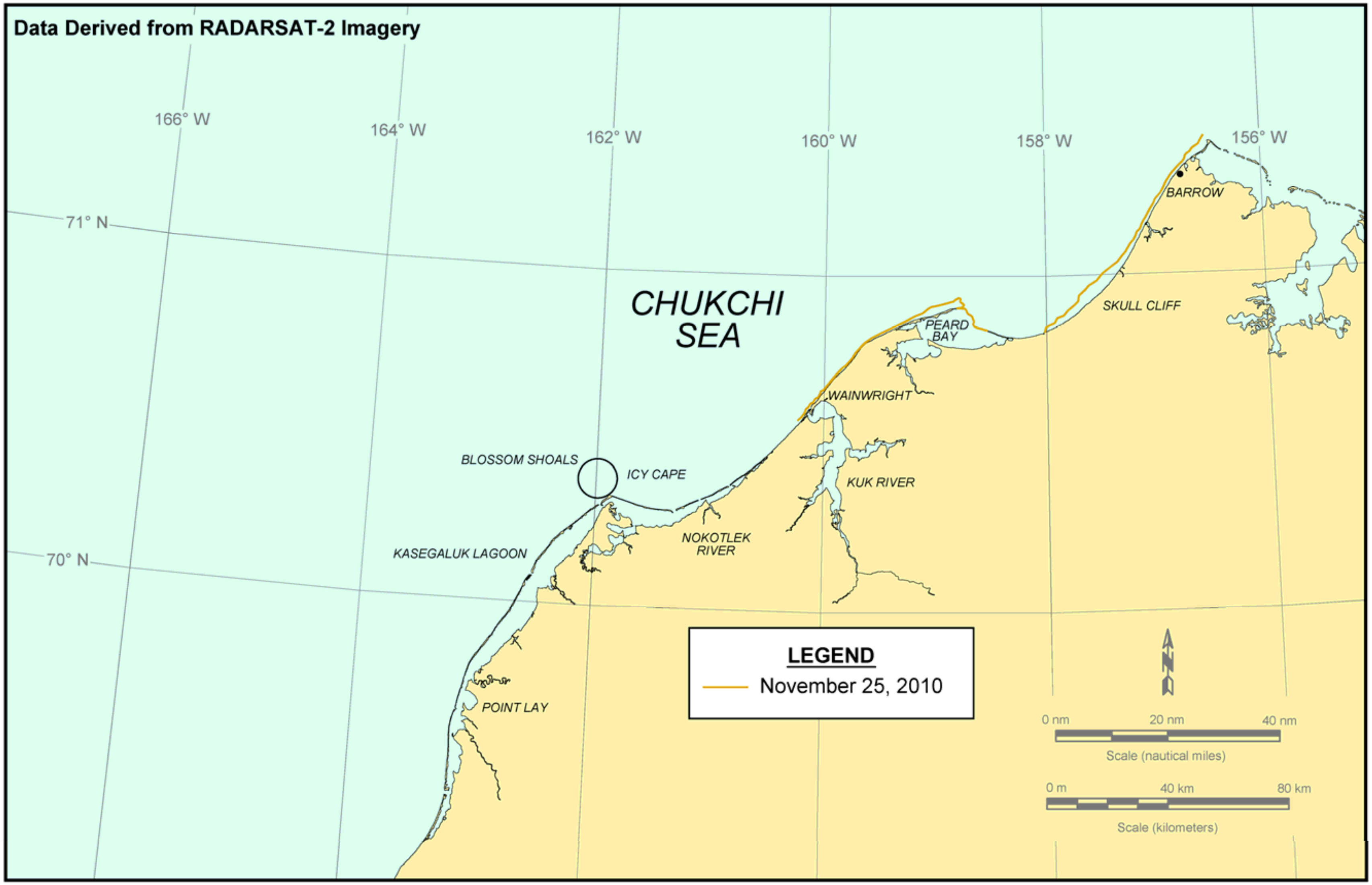
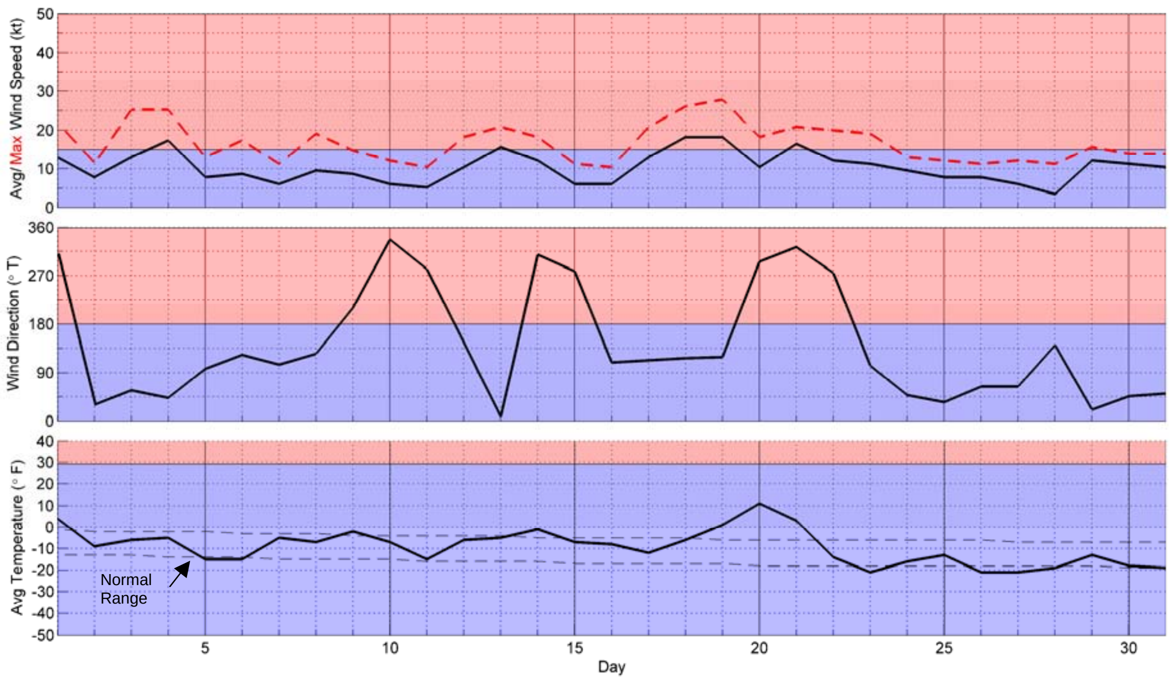


Figure 46. Chukchi Sea Landfast Ice Edge in November 2010



Source: Weather Underground, 2011

Figure 47. Meteorological Conditions at Barrow Airport in December 2010

Ice Thickness: The calculated thickness of undisturbed first-year ice increased by 33 cm in December, from 43 to 76 cm. This change resulted from the addition of 1,186 FDD, producing an accumulated total of 1,925 FDD since

Landfast Ice: The successive locations of the landfast ice edge in December were interpreted from RADARSAT-2 images obtained on the 1st, 8th, 15th, 22nd, and 29th. As shown in Figure 48, the zone of landfast ice remained extremely narrow except in the semi-protected areas to the east of Icy Cape and Point Franklin. A bulge off Icy Cape that first appeared in the December 8th image (Figure 48) is indicative of rubble formation on Blossom Shoals, where depths as shallow as 5.5 m are indicated on NOS Chart No. 16005 (1976).

On December 29th, the width of the landfast ice zone was 1.1 nm (2.0 km) off Barrow, 0.3 nm (0.5 km) off Point Belcher and Wainwright, 1.5 nm (2.7 km) off the mouth of the Nokotlek River, and 0.5 nm (1.0 km) off Point Lay. These meager dimensions are consistent with the near-absence of westerly storms capable of pushing the ice against the coast with sufficient force to generate grounded rubble in the nearshore area.

Leads: Numerous leads and polynyas are evident in the RADARSAT-2 image obtained immediately after complete freeze-up in the Chukchi Sea, on December 8th (Figure 49). The heaviest concentration was located within 100 nm (185 km) of the coast

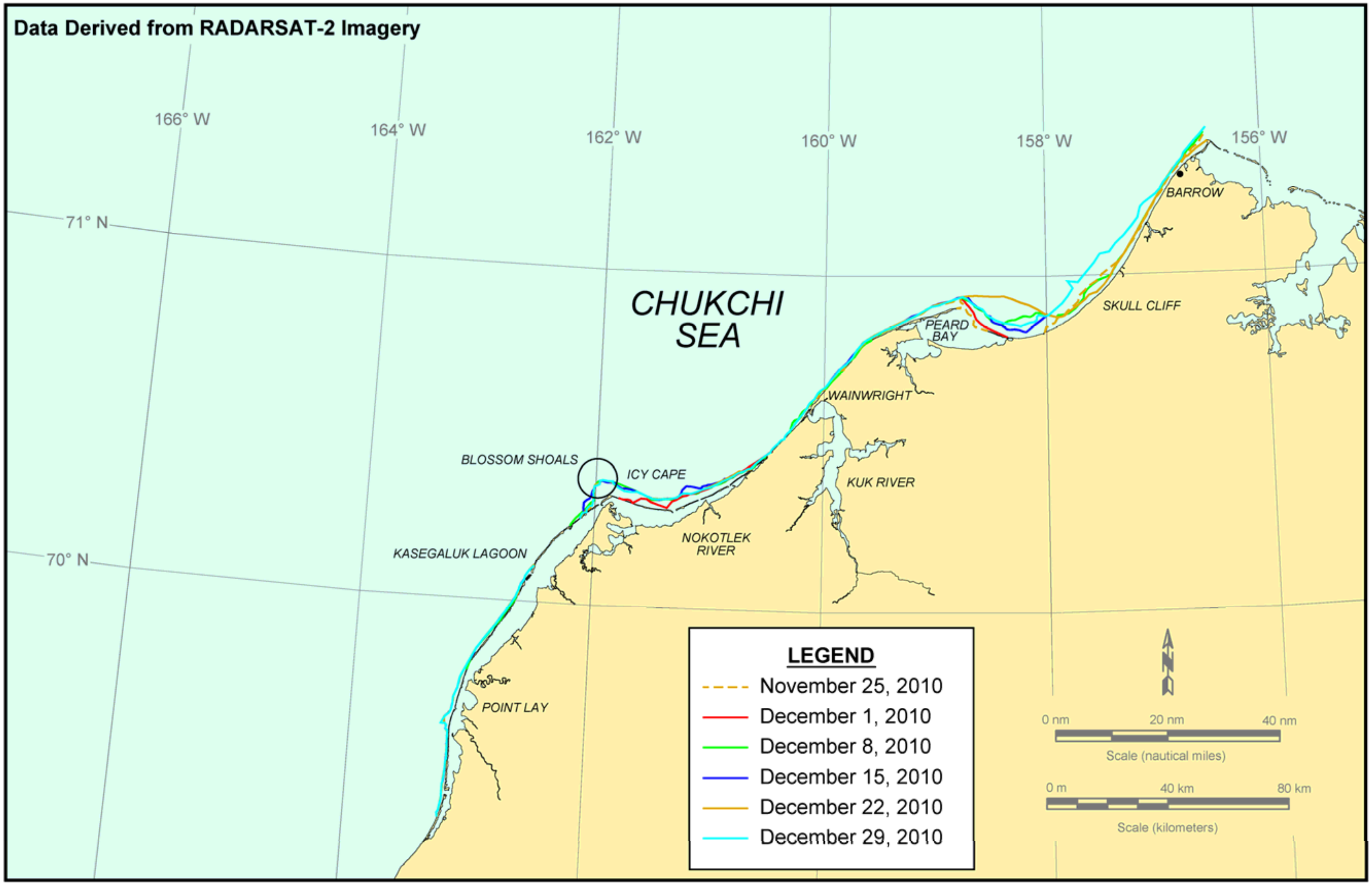


Figure 48. Chukchi Sea Landfast Ice Edge in December 2010

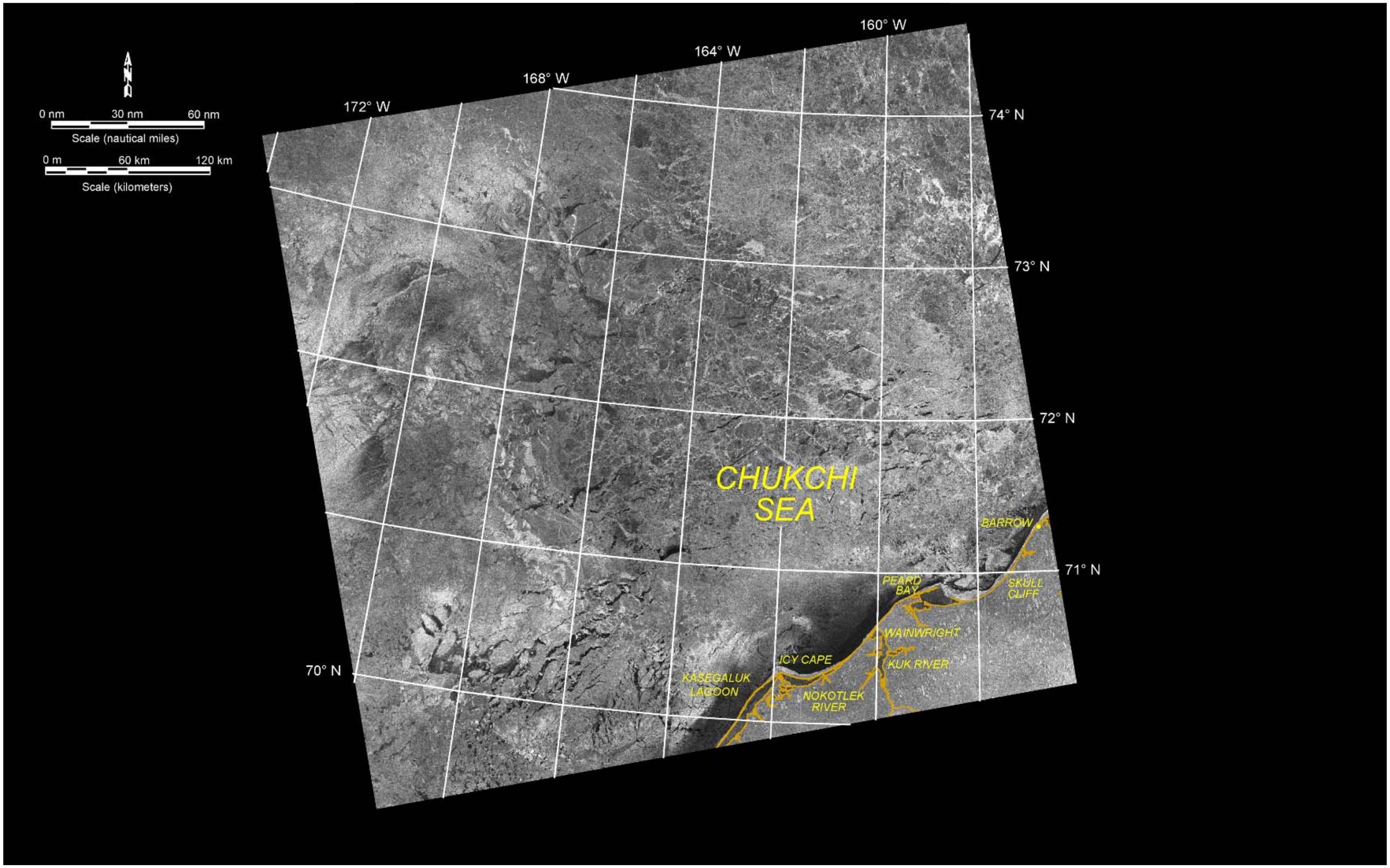


Figure 49. RADARSAT-2 Image of Chukchi Sea Acquired on December 8, 2010

between Icy Cape and Point Lay. One week later, on December 15th, these features had been replaced by widely-spaced, elongated leads trending southwest-northeast and located from 40 nm (75 km) off Point Lay to well beyond the West Prospects. The leads attained lengths as great as 65 nm (120 km) with widths typically less than 0.5 nm (0.9 km).

On December 22nd, the only leads present were several small, widely-spaced features oriented perpendicular to the coast off Icy Cape. The absence of major leads at this time probably reflects the compaction of the ice pack that resulted from the westerly storm on December 21st. Significant leads also were absent on December 29th, when the final RADARSAT-2 image of the month was acquired, but small polynyas were evident off the coast between Wainwright and Barrow.

The coastal flaw lead that typically develops off the Chukchi Sea coast during strong easterly winds was not detected in any of the RADARSAT-2 images for December. A small version was evident in an AVHRR image obtained on December 27th, however. This relatively narrow feature extended approximately 50 nm (93 km) from the vicinity of Point Franklin to Barrow with an estimated width of 5 nm (9 km). It probably formed in response to moderate but sustained easterly winds that began on December 23rd.

Multi-Year Ice: The large multi-year ice floes that entered the Alaskan Beaufort Sea from Canada in November (Section 4.2.2) began arriving in the northern Chukchi Sea in mid-December. When the last RADARSAT-2 image of the month was obtained on December 29th, the first scattered floes had moved past the 165°W meridian. The southern boundary of the multi-year ice was located approximately 60 nm (111 km) north of Point Barrow.

Ice Movement: Ice movement rates at the south edge of the perennial pack ice in the northern Chukchi were investigated using two of the large multi-year floes that had been identified in the Beaufort (Floes A and D), and one newly-identified floe (Floe K, with a diameter of 5 km). The successive positions of these floes were derived from RADARSAT-2 images acquired on December 15th (Floes A and K), 22nd (all three floes), and 29th (all three floes).

The tracks of the three floes were extremely similar, with northwesterly movement prior to December 22nd followed by west southwesterly movement thereafter (Figure 50). The change in direction correlates with a shift from westerly to northeasterly winds that occurred on the 22nd and 23rd (Figure 47).

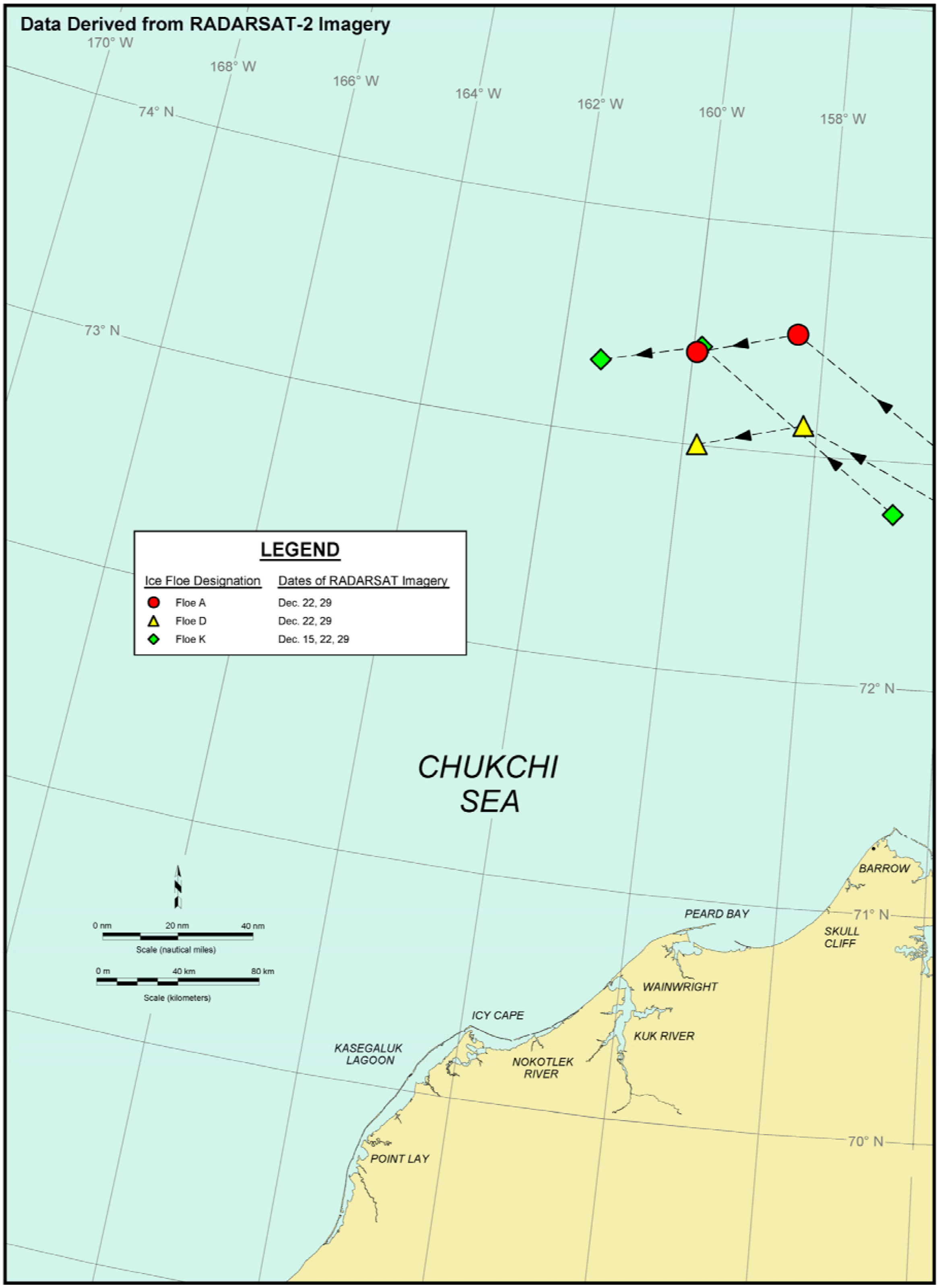
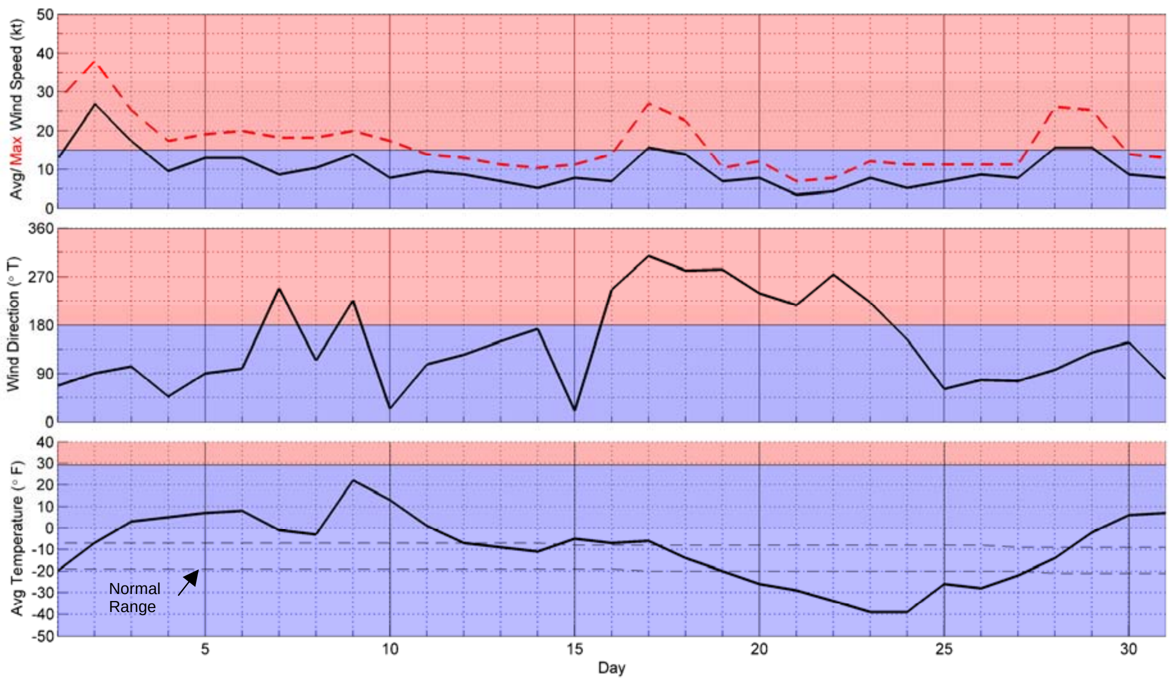


Figure 50. Chukchi Sea Multi-Year Ice Floe Displacements in December 2010

The speeds computed between successive floe positions varied between 3.9 and 9.7 nm/day (7.2 and 18.0 km/day). Monthly speeds of 5.5 and 6.3 nm/day (10.2 and 11.7 km/day) were computed for Floes A and K based on the net displacements that occurred between December 15th and 29th. A monthly speed was not computed for Floe D, as its period of record in the Chukchi was limited to seven days.

5.2.4. January 2011

Meteorological Conditions: Figure 51 presents the wind and temperature data recorded at Barrow Airport in January 2011. Air temperatures fluctuated widely during the course of the month, attaining a high of +22°F (-6°C) on the 9th before falling to a low of -39°F (-39°C) on the 23rd and 24th.



Source: Weather Underground, 2011

Figure 51. Meteorological Conditions at Barrow Airport in January 2011

Easterly winds prevailed at the beginning and end of the month, but were interrupted by westerly winds that began on the 16th and ended on the 23rd. With respect to storms, a two-day easterly on the 2nd and 3rd with a maximum wind speed of 27 kt (14 m/s) was followed by a one-day westerly on the 17th and a two-day easterly on the 28th and 29th. The maximum wind speed during each of the latter two events was 16 kt (8 m/s).

Ice Thickness: One thousand, one hundred and ninety six FDD were recorded at Barrow Airport in January, bringing the total to 3,121 FDD since the inception of freeze-up.

The predicted ice thickness increased by 24 cm, from 76 cm at the beginning of the month to 100 cm at the end.

Landfast Ice: Figure 52 illustrates the locations of the landfast ice edge derived from RADARSAT-2 images obtained on December 29th, January 22nd, and January 29th (Figure 53). As in December, the zone of landfast ice remained extremely narrow except in the areas east of Icy Cape and Point Franklin. At Icy Cape, the rubble field on Blossom Shoals expanded temporarily during the period of sustained westerly winds that preceded the January 22nd RADARSAT image. It then receded to its prior configuration in response to the easterly storm that followed on the 28th and 29th. A substantial loss of landfast ice also occurred off Skull Cliff during this period, presumably caused by the same easterly storm event.

Leads: As shown in the NIC ice chart presented as Figure 54, the coastal flaw lead reopened in response to the easterly storm of January 2nd-3rd. The lead extended more than 200 nm (371 km) along the coast from Barrow to the vicinity of Cape Lisburne, with a width that varied between 10 and 30 nm (19 and 56 km). AVHRR imagery obtained on January 9th indicated that the feature had closed, presumably in response to southwesterly winds on the 7th and 9th (Figure 51).

With the exception of several small, shore-perpendicular features measuring up to 10 nm long and 1 nm wide (19 km x 1.9 km), significant leads were absent from the RADARSAT-2 image acquired on January 22nd.

The coastal flaw lead reappeared on January 25th, soon after the wind direction had shifted from west to east (Figure 51). As illustrated in Figure 55, which was excerpted from an AVHRR image obtained on the 26th, the lead stretched from northeast of Point Barrow to the vicinity of Icy Cape. Its width increased with distance to the southwest, measuring 25 nm (46 km) off Barrow and 60 nm (111 km) off Icy Cape. On January 29th, when the final RADARSAT-2 image of the month was obtained, the lead appeared to have refrozen (Figure 53).

Multi-Year Ice: The southern boundary of the perennial pack ice remained well north of the 72°N parallel throughout the month of January. It was located 60 nm (111 km) north of Point Barrow on December 29th, and 80 nm (148 km) north on January 29th (Figure 53).

Ice Movement: Ice movement rates were computed from the locations of Floes A and D as noted in RADARSAT-2 images obtained on December 29th, January 22nd, and

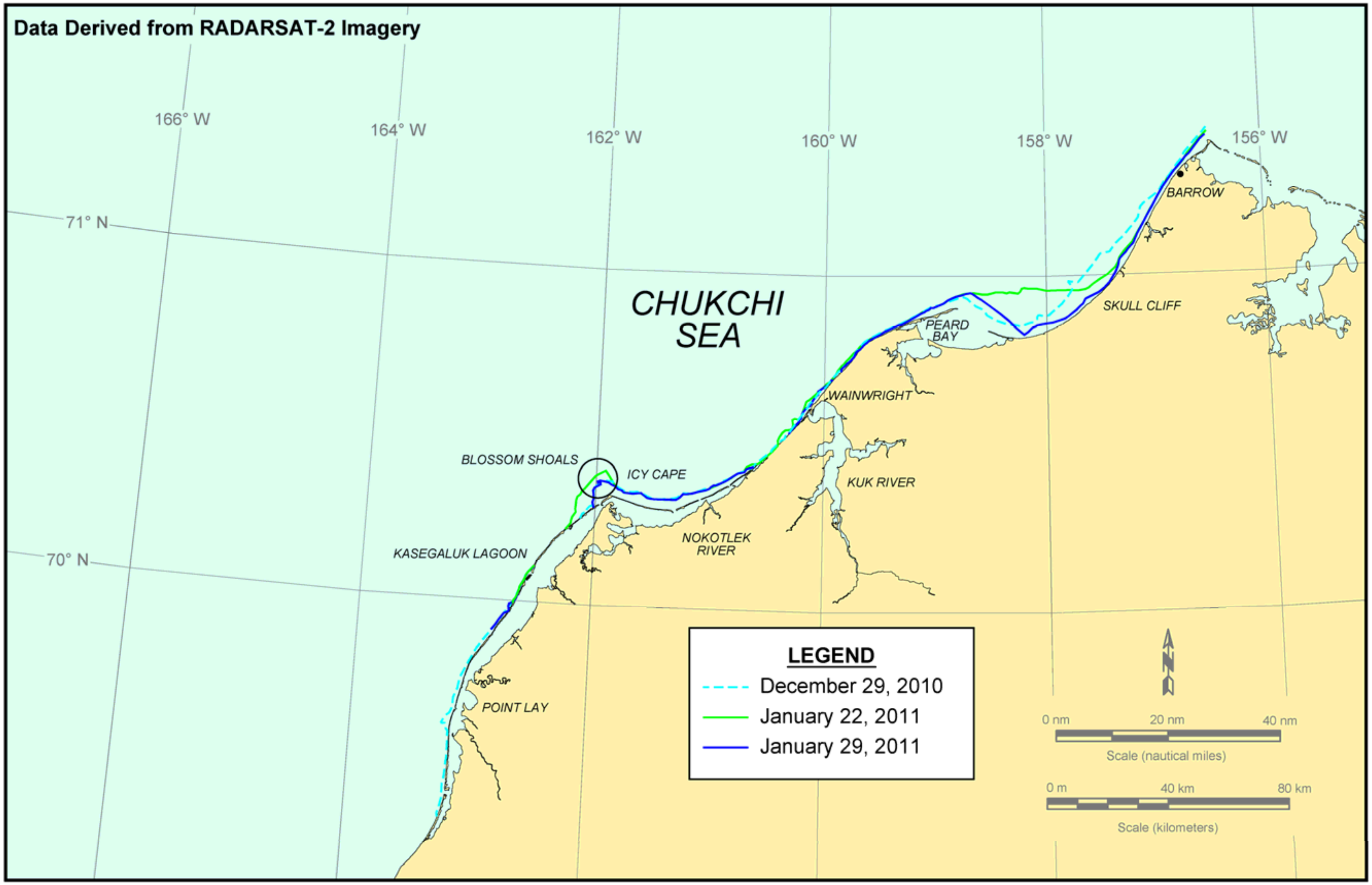


Figure 52. Chukchi Sea Landfast Ice Edge in January 2011

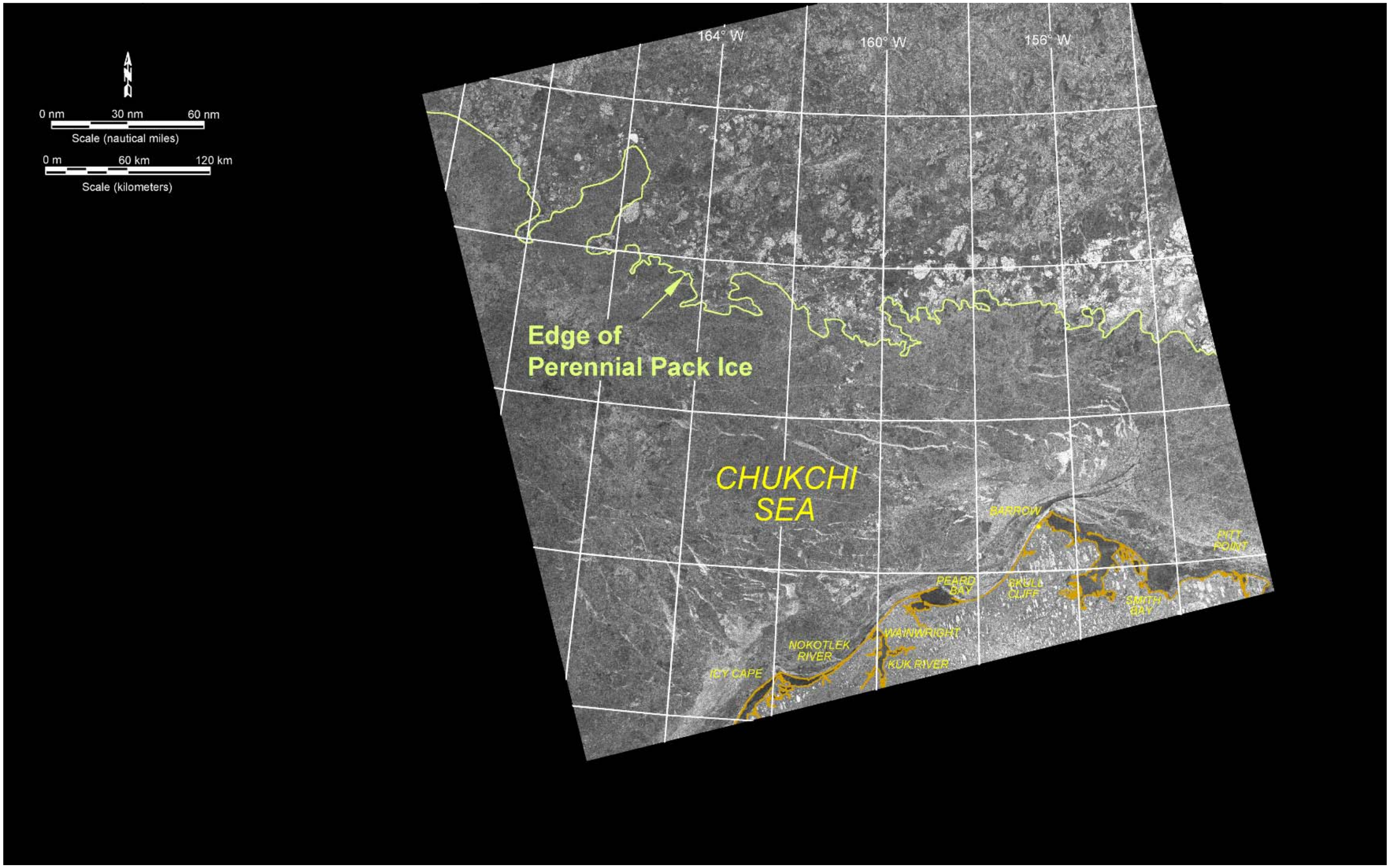
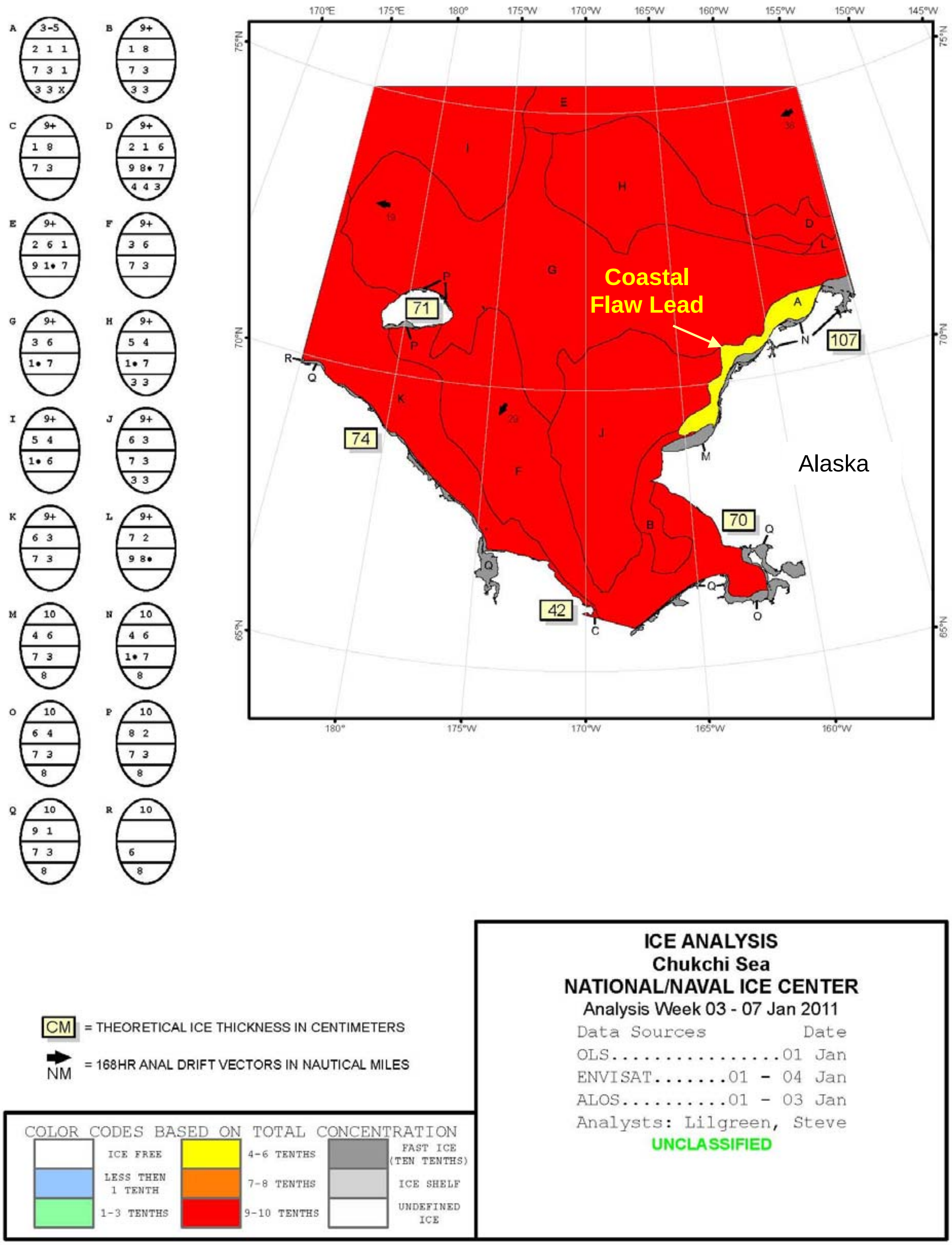
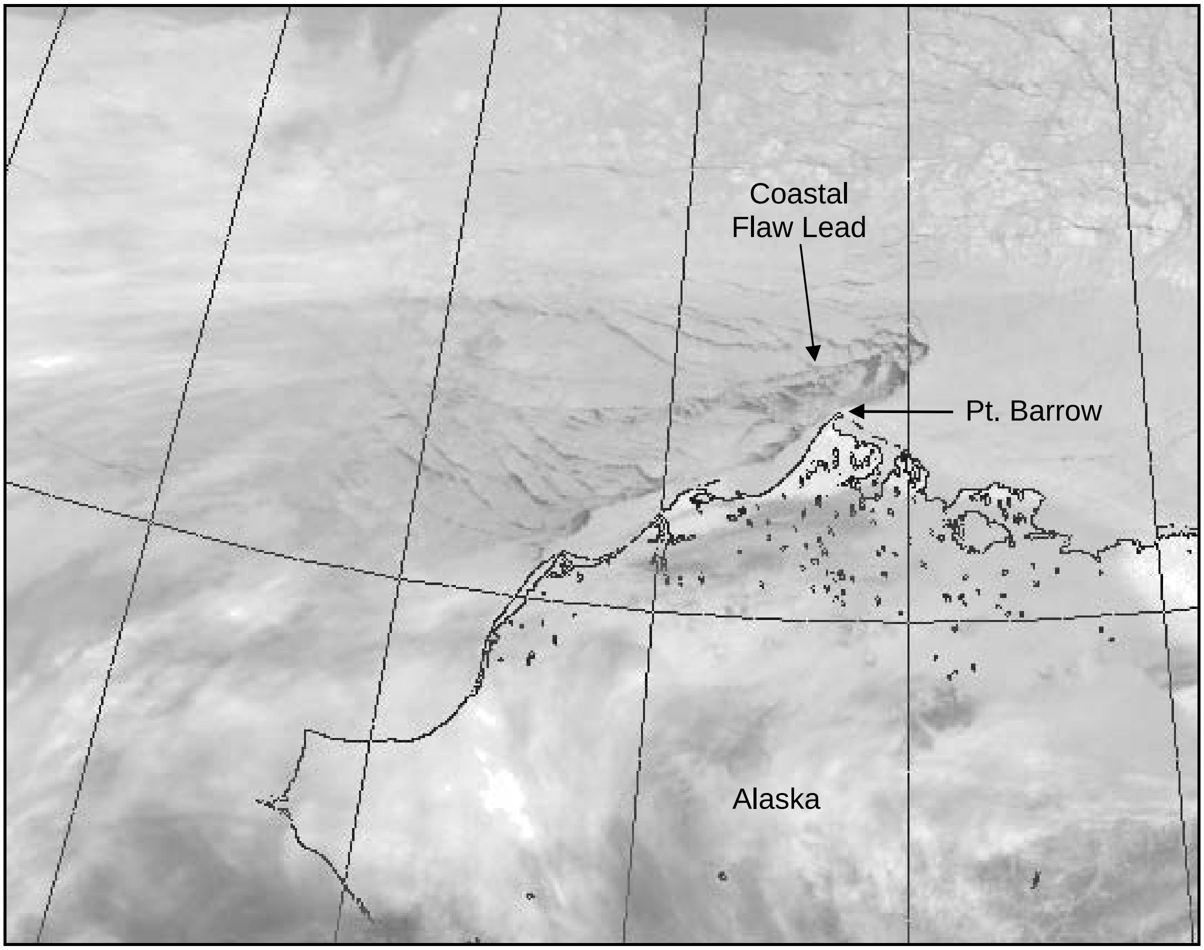


Figure 53. RADARSAT-2 Image of Chukchi Sea Acquired on January 29, 2011



After: National Ice Center, 2011

Figure 54. NIC Ice Chart for January 3, 2011, Showing Coastal Flaw Lead



Source: National Weather Service, 2011

Figure 55. AVHRR Image on January 26, 2011 Showing Coastal Flaw Lead

January 29th. The trajectories of both floes were nearly identical, with a net displacement to the west northwest occurring between the first two dates followed by a negligible displacement thereafter (Figure 56). Based on the ice floe trajectories recorded in the western Beaufort (Figure 30), which include multiple positions for dates prior to the 22nd, it is likely that Floes A and D moved farther to the west northwest during the period of easterly winds that ended on the 15th, reversed direction during the westerlies that followed for the next eight days, and then headed back to the west northwest when the easterlies resumed on the 24th. As a result, it is likely that the tracks shown in Figure 56 obscure the larger and oppositely-directed movements that actually occurred.

The monthly speeds, like the trajectories, were nearly identical: 3.3 nm/day for Floe A and 3.4 nm/day for Floe D (6.1 and 6.3 km/day). These values were computed from the floe positions on December 29th and January 29th.

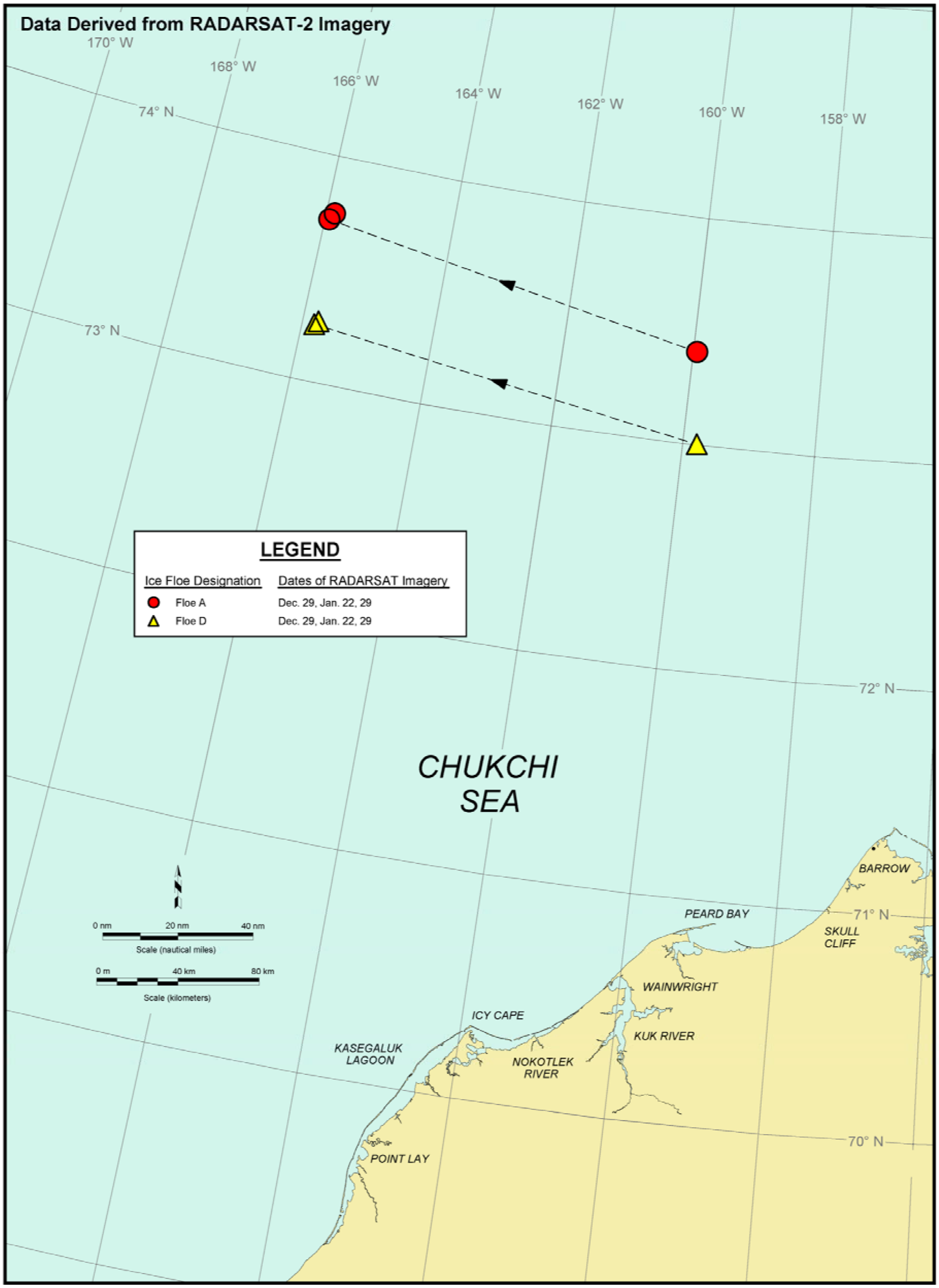


Figure 56. Chukchi Sea Multi-Year Ice Floe Displacements in January 2011

5.3. Field Observations

Fixed-wing aerial reconnaissance missions were undertaken in the north Chukchi Sea on February 5th and 6th. Chukchi Sea Flight No. 1 (Flight "C1" on Drawing CFC-835-01-003) was used to observe nearshore ice conditions between Barrow and Point Lay, while Chukchi Sea Flight No. 2 (Flight "C2" on the same drawing) focused on offshore ice conditions to the northwest and west of Barrow. The flight path included Hanna Shoal and Shell's Hanna Shoal, West, Crackerjack, and Burger Prospects. (Note: as shown in Figure 4, the Hanna Shoal Prospects are centered approximately 25 nm or 46 km to the southwest of Hanna Shoal itself.)

Three changes in wind direction and two modest storm events occurred in early February prior to and during the two flights. The average daily wind direction shifted from easterly to westerly on February 2nd, from westerly back to easterly on the 4th, and from easterly to westerly again on the 5th. Both storm events were one-day westerlies; the first occurred on February 3rd with a wind speed of 17 kt (9 m/s), while the second occurred on February 5th with a wind speed of 16 kt (8 m/s; Table 7).

5.3.1. Landfast Ice and Shear Zone

The landfast ice zone observed during the 2011 reconnaissance flights resembled that noted a year earlier during the 2009-10 freeze-up study (Coastal Frontiers and Vaudrey, 2010). In the protected waters of Peard Bay and Kasegaluk Lagoon, where freeze-up occurred in early and mid-October, the ice was flat and featureless. Off the remainder of the coast, where the waters are largely unprotected, the landfast ice was confined to a narrow, ephemeral strip that remained unstable through the time of the reconnaissance flight on February 5th. This strip was even narrower than that which existed in February 2010, measuring only 0.7 nm (1.2 km) off Barrow, 0.5 nm (0.9 km) off Point Belcher, and 0.1 nm (200 m) off Point Lay. Even the semi-protected region that lies to the east of Icy Cape was virtually bereft of landfast ice at the time of the flight.

The minimal size of the landfast ice zone in 2010-11 reflects the imbalance between easterly and westerly storms that prevailed during freeze-up. Nine easterly events occurred from October 1st through January 15th, compared with only two westerlies. The easterlies push the ice away from the coast, causing freeze-up to begin anew, whereas the westerlies drive the ice back onshore, creating pile-ups and offshore rubble fields. The paucity of westerly storms in 2010-11 limited the production of grounded rubble, thereby leaving the landfast ice susceptible to break-out and removal by easterly winds. The absence of stable, grounded landfast ice is illustrated in Plates 26 and 27, which show poorly-grounded rubble

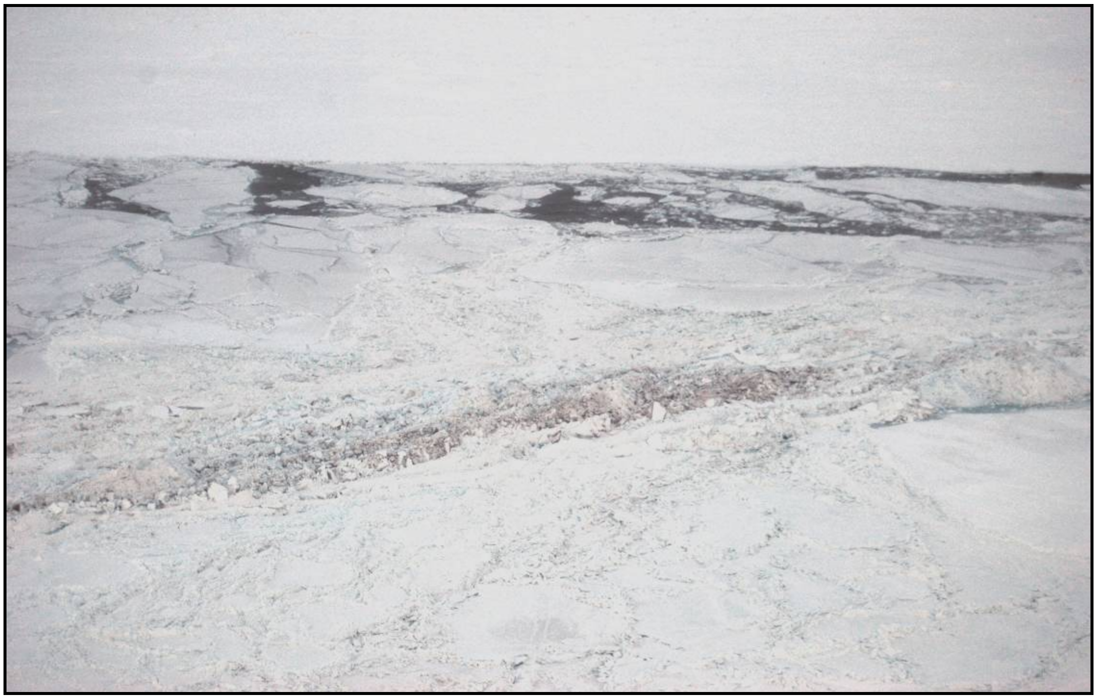


Plate 26. Poorly-Grounded Rubble off Coast 12 nm Southwest of Wainwright on February 5, 2011 (looking offshore)

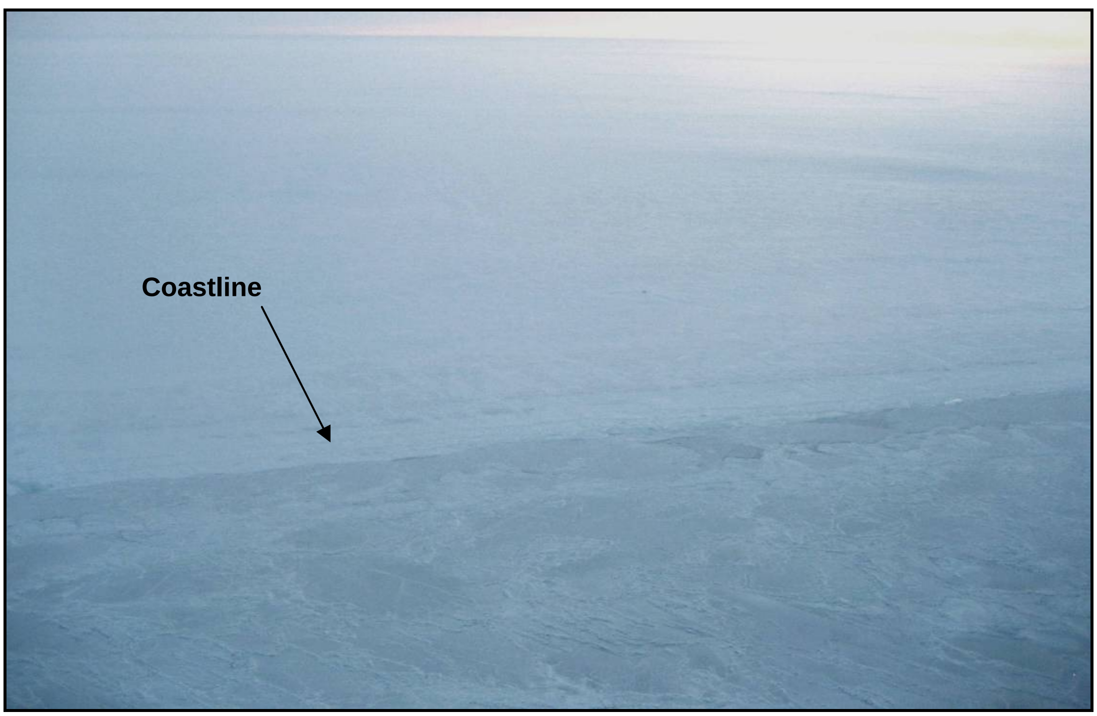


Plate 27. Newly-Formed Ice Adjacent to Coast 14 nm Southwest of Wainwright on February 5, 2011 (looking onshore)

adjacent to the coast 12 nm (22 km) southwest of Wainwright, and a stretch of coast completely devoid of landfast ice 2 nm (3.7 km) farther to the southwest.

In keeping with the unstable nature of the landfast ice zone, shear lines were poorly-developed or absent in much of the nearshore region. The most prominent shear lines were located off Barrow (Plate 28) and Point Belcher.

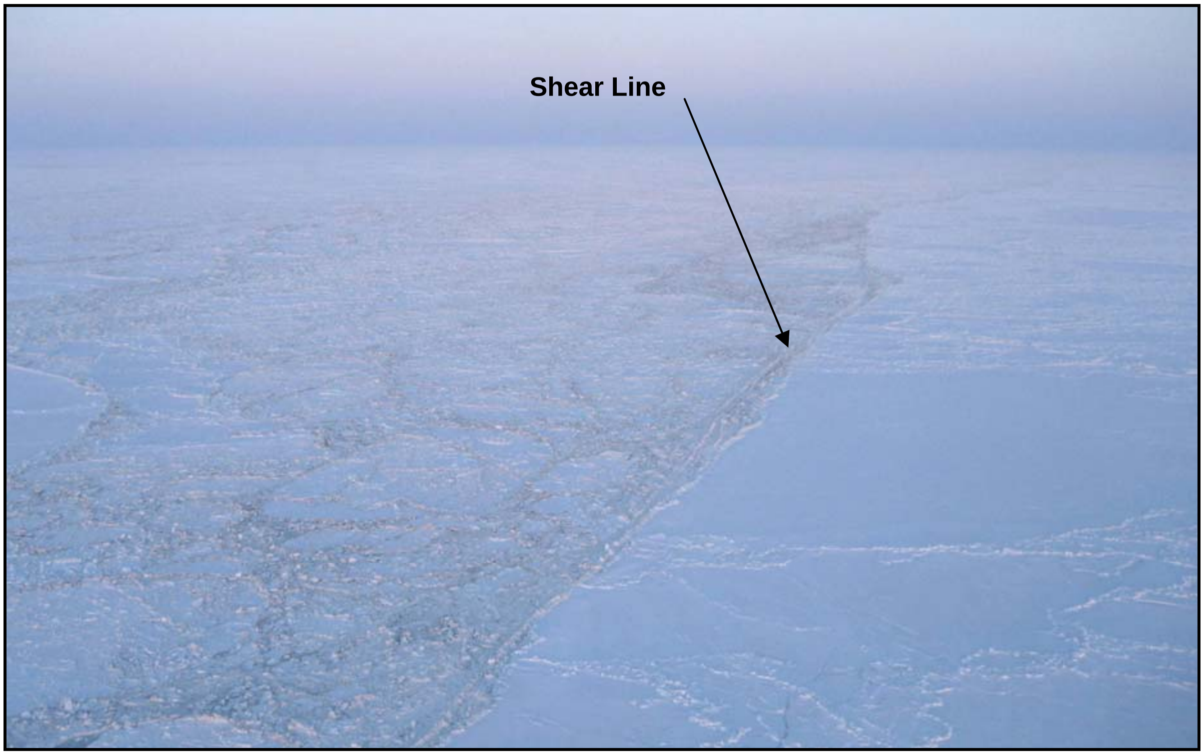


Plate 28. Shear Line off Barrow on February 6, 2011 (looking northeast)

5.3.2. Fragments of Old Ice

Large multi-year floes analogous to those that invaded the Chukchi Sea in 2009-10 (Coastal Frontiers and Vaudrey, 2010) were not detected during the reconnaissance flights conducted in February 2011. However, what appeared to be fragments of old ice embedded in first-year ice floes were observed in Shell's Burger Prospect. As illustrated in Plates 29 and 30, which provide representative examples, the fragments displayed the type of rolling topography typically found on multi-year ice (Plate 31). The maximum horizontal dimensions ranged from one hundred to several hundred meters.

The source of the old ice fragments is unknown. One possibility is that they broke off from the perennial pack ice in sizes that were too small and concentrations that were too low to be detected in RADARSAT-2 imagery. Alternatively, they may have drifted west from

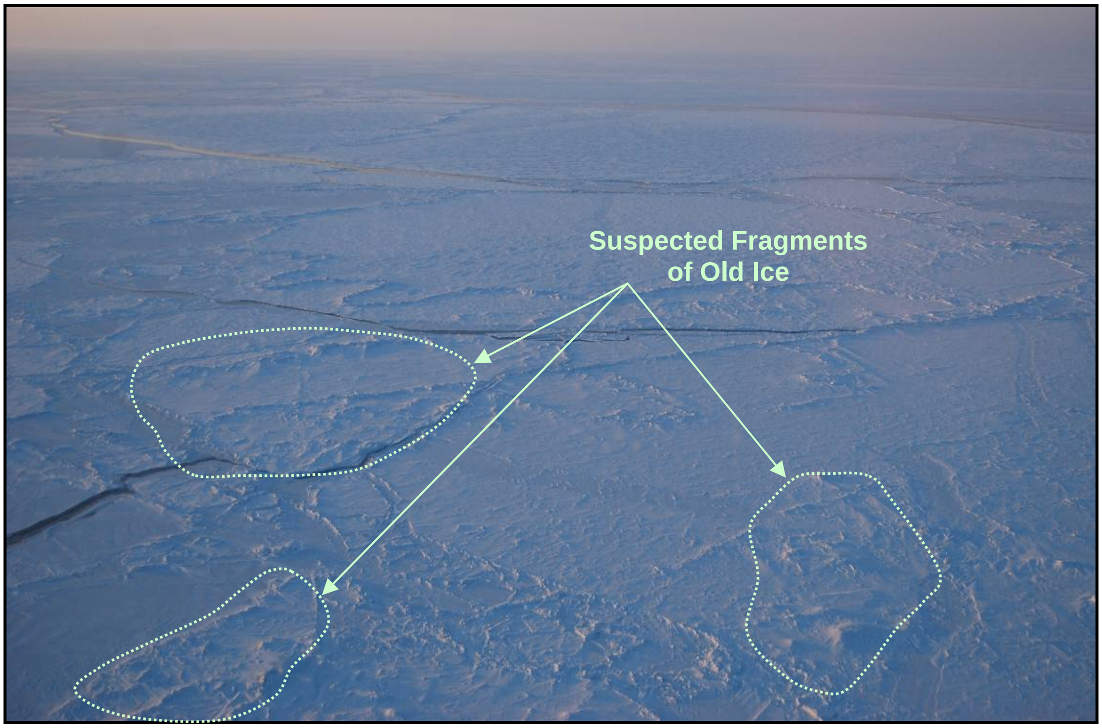


Plate 29. Suspected Fragments of Old Ice in Burger Prospects on February 6, 2011.

Plate 30. Suspected Fragment of Old Ice in Burger Prospects on February 6, 2011.

Plate 31. Multi-Year Ice Floe 17 nm North of Point Franklin in February 2010

the nearshore band of grounded ice that persisted in the Alaskan Beaufort Sea throughout the 2010 open-water season (Figure 14; Section 4.1). In either case, they were observed at concentrations less than 5% in the Burger Prospects, and at no other locations in the Chukchi Sea.

5.3.3. Leads

The distinctive flaw lead that develops off the Chukchi Sea coast in response to easterly winds was absent at the time of the reconnaissance flights – a finding consistent with the occurrence of westerly storms on February 3rd and 5th. Nevertheless, as indicated in Drawing CFC-835-01-003, numerous smaller leads were observed in the nearshore area outside the zone of landfast ice (Plate 32). The leads tended to parallel the coast, and evidenced various stages of refreezing.

The most striking lead encountered during the flights began on the east side of Blossom Shoals (off Icy Cape) and trended east northeast for more than 15 nm (29 km). The landfast ice in this region that was evident in the January 29th RADARSAT-2 image (Figure 53) apparently had been dislodged by westerly winds and the accompanying storm surge shortly before the flight, leaving open water with small whitecaps and lines of newly-formed ice (Plate 33).

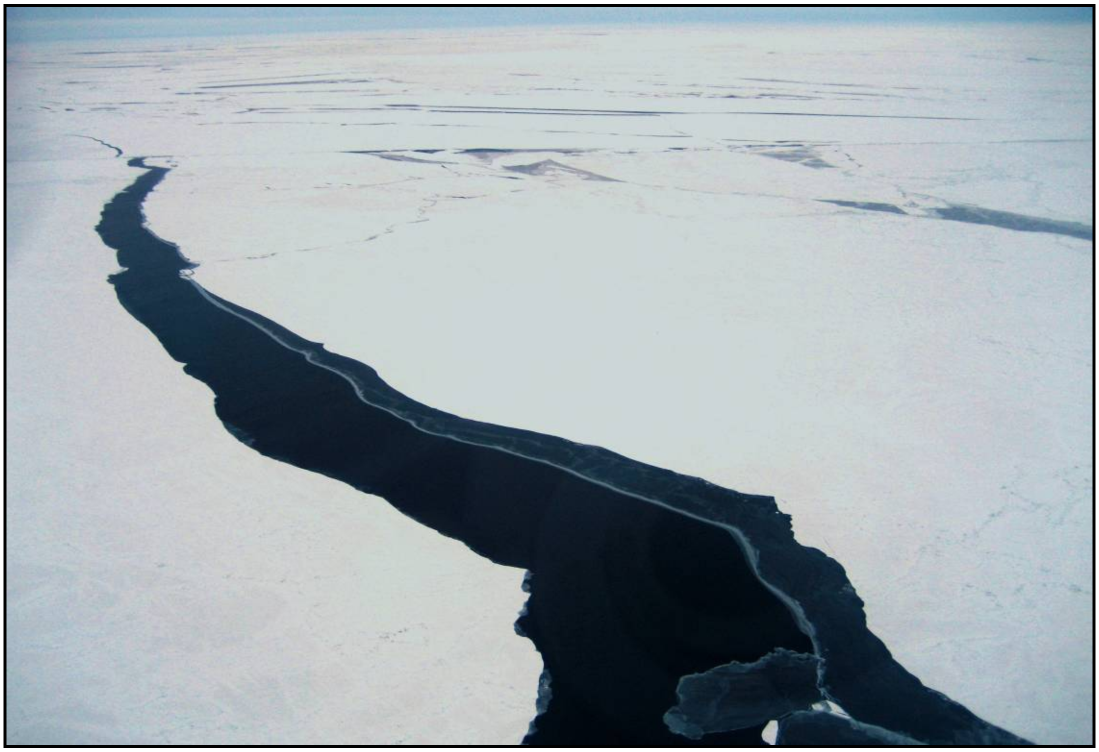


Plate 32. Open Lead 13 nm West of Barrow on February 5, 2011

Plate 33. Open Lead East of Blossom Shoals on February 5, 2011

Offshore, leads and broken ice indicative of a loosely-consolidated ice canopy were encountered as far west as the region between the Burger and Crackerjack Prospects, in the vicinity of the 165°W meridian. Plate 34 presents a representative example, a large refreezing lead approximately half way between the Burger Prospects and Barrow.

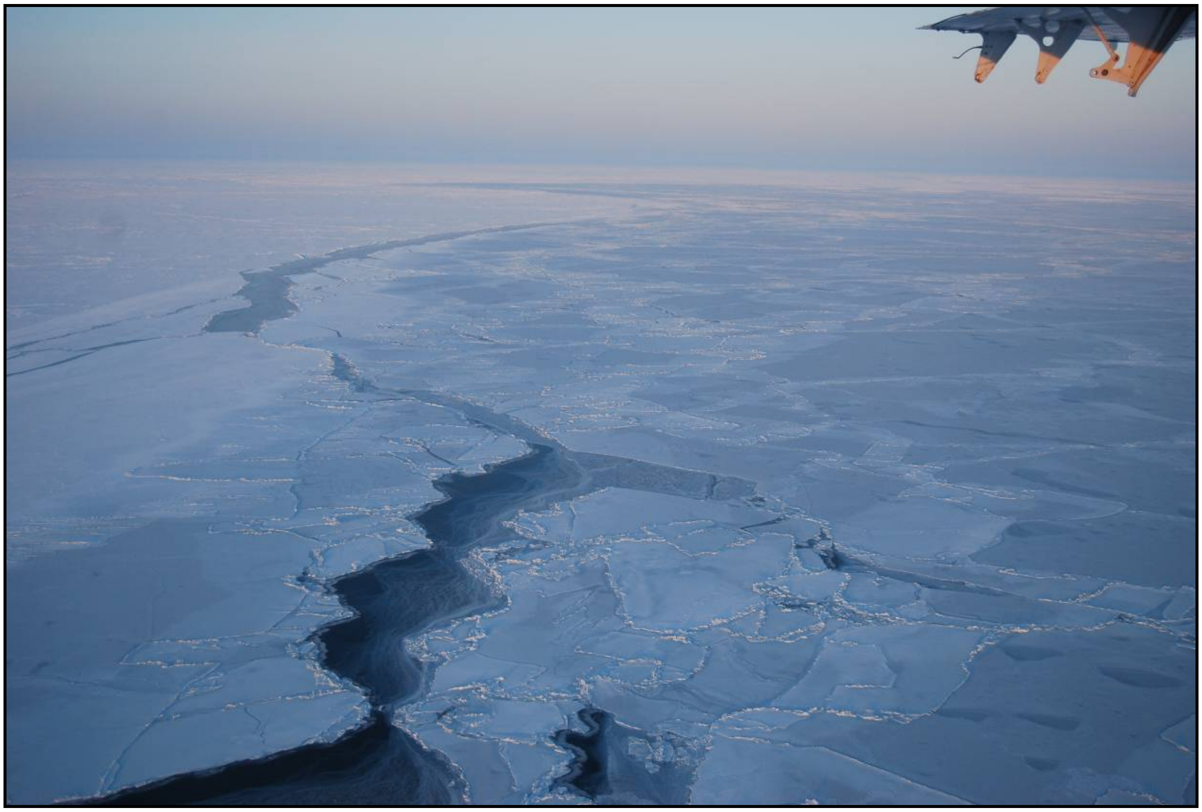


Plate 34. Large Refreezing Lead between Burger Prospects and Barrow on February 6, 2011

5.3.4. Ice Pile-Ups

Twenty seven ice pile-ups were observed on the Chukchi Sea coast during the February 5th reconnaissance flight, representing eight more than a year earlier (Coastal Frontiers and Vaudrey, 2010). As discussed in Section 5.2.2, the piles were composed of blocks estimated to be 30 to 40 cm thick. They probably formed in mid-November, when loosely-consolidated ice was driven ashore by winds that shifted from east to west on the 15th and accelerated to 25 kt (13 m/s) on the 17th (Figure 43).

The locations of the pile-ups are indicated in Drawing CFC-835-01-003 while their characteristics are presented in Table 8. Two were located at the base of Skull Cliff, eight from Point Belcher to Wainwright, two near the mouth of the Kuk River, six on the barrier

Table 8. Ice Pile-Ups on Chukchi Sea Coast[1]

No.	Region	Length[2] (m)	Max. Height (m)	Encroachment[3] (m)
1	Skull Cliff	100	2	0
2	Skull Cliff	100	2	0
3	Pt. Belcher-Wainwright	200	4	20
4	Pt. Belcher-Wainwright	100	5	20
5	Pt. Belcher-Wainwright	2,000	4	10
6	Pt. Belcher-Wainwright	600	4	10
7	Pt. Belcher-Wainwright	2,300	3	5
8	Pt. Belcher-Wainwright	1,400	3	10
9	Pt. Belcher-Wainwright	900	4	30
10	Pt. Belcher-Wainwright	500	8	40
11	Kuk River Mouth	1,000	2	0
12	Kuk River Mouth	1,000	2	0
13	Barrier Is. E of Icy Cape	400	4	0
14	Barrier Is. E of Icy Cape	400	2	0
15	Barrier Is. E of Icy Cape	300	2	0
16	Barrier Is. E of Icy Cape	300	5	0
17	Barrier Is. E of Icy Cape	400	3	0
18	Barrier Is. E of Icy Cape	300	4	0
19	Barrier Is. S of Icy Cape	300	3	0
20	Barrier Is. S of Icy Cape	300	3	0
21	Barrier Is. S of Icy Cape	300	3	0
22	Barrier Is. S of Icy Cape	500	3	7
23	Barrier Is. S of Icy Cape	300	3	0
24	Barrier Is. S of Icy Cape	1,300	4	5
25	Barrier Is. S of Icy Cape	200	3	0
26	Barrier Is. S of Icy Cape	200	3	5
27	Barrier Is. S of Icy Cape	700	3	5

Notes:

[1] Estimated ice block thickness for all pile-ups was 30-40 cm.
[2] "Length" indicates alongshore extent of pile-up.
[3] "Encroachment" indicates distance ice advanced onto subaerial beach.

islands fronting Kasegaluk Lagoon to the east of Icy Cape, and nine on the barrier islands fronting Kasegaluk Lagoon from Icy Cape to Point Lay. The largest pile-ups were those between Point Belcher and Wainwright, where one pile attained both the maximum estimated height of 8 m and maximum estimated encroachment distance of 40 m onto the beach. The longest ice pile, stretching 2,300 m alongshore with a height of 3 m, also occurred in this region.

Of the twenty seven pile-ups, twelve encroached 5 m or more onto the beach. Not surprisingly, eight of these piles were located in the active region between Point Belcher and Wainwright. The example shown in Plate 35 was estimated to extend 100 m along the beach south of Point Belcher, with a height of 5 m and encroachment distance of 20 m.

Plate 35. 5-m High, 100-m Long Ice Pile-Up South of Point Belcher on February 5, 2011

5.3.5. Nearshore vs. Offshore Ice Conditions

The Chukchi Sea ice cover tends to remain mobile due to the predominance of easterly winds, which push the ice away from the coast and re-open the flaw lead to widths as great as 50 to 60 nm (93 to 111 km). Because the lead reduces confinement, it leaves the nearshore ice susceptible to rapid movements, especially when the wind shifts to the west. These movements can produce extensive first-year ridging and rafting, which occur at the boundaries of the floating ice pans as they collide with or rotate about one another. During the 2009-10 freeze-up study, a significant contrast was noted between heavily-deformed ice in the nearshore pack within 30 to 50 nm (56 to 93 km) of the coast and relatively undeformed ice in the offshore pack (Coastal Frontiers and Vaudrey, 2010).

A similar but less pronounced difference between nearshore and offshore ice conditions was noted during the 2011 aerial reconnaissance missions. As shown in Plate 36, the nearshore zone contained ridges and rubble fields interspersed with small-to-moderate-sized first-year floes. Although significant ice deformation was evident, it was far less prevalent than that observed a year earlier. This finding reflects the aforementioned paucity of westerly storms during the freeze-up season.

At distances greater than about 60 nm (111 km) from the coast, where the influence of the coastal flaw lead tends to diminish, the ice cover evidenced less deformation and consisted largely of vast first-year pans with diameters as large as 5 nm (9 km). These characteristics indicate that the differential motion between ice floes was far less than that in the nearshore zone.

5.3.6. Ice Conditions in Shell Prospects

All four of Shell's Chukchi Sea prospects – Hanna Shoal, West, Crackerjack and Burger – were included in the reconnaissance flight conducted on February 6th. Floe sizes in the Hanna Shoal Prospects ranged from 0.25 to 1.5 nm (0.5 to 2.9 km) in the northern portion and 0.5 to 3 nm (0.9 to 5.6 km) in the southern portion. As illustrated in Plate 38, the floes tended to be flat with scattered ridges and rubble fields up to 4 m high. Two large refreezing leads were noted paralleling the flight path from northeast to southwest.

The ice cover in the West Prospects appeared to move as a quasi-rigid body with minimal deformation. Vast, flat first-year pans with diameters of 0.5 to 5 nm (0.9 to 9 km) were interspersed with small leads in various stages of refreezing (Plate 39). Ridges and rubble accumulations ranging from 2 to 4 m high were observed at the edges of some of the large floes.

In the Crackerjack Prospects, large first-year pans with modest ridging and rafting at the edges predominated in some areas (Plate 37), while smaller floes with ridges and rubble up to 5 m high predominated in others (Plate 40). The floe diameters ranged from 0.25 to 3 nm (0.5 to 5.6 km). In aggregate, the ice cover appeared to be more dynamic than in the West Prospects, with smaller floe sizes, more ridging and rubbling, and a greater density of refreezing leads.

The trend toward an increasingly mobile, dynamic ice cover as one proceeded from west to east was maintained in the Burger Prospects relative to the Crackerjack Prospects.

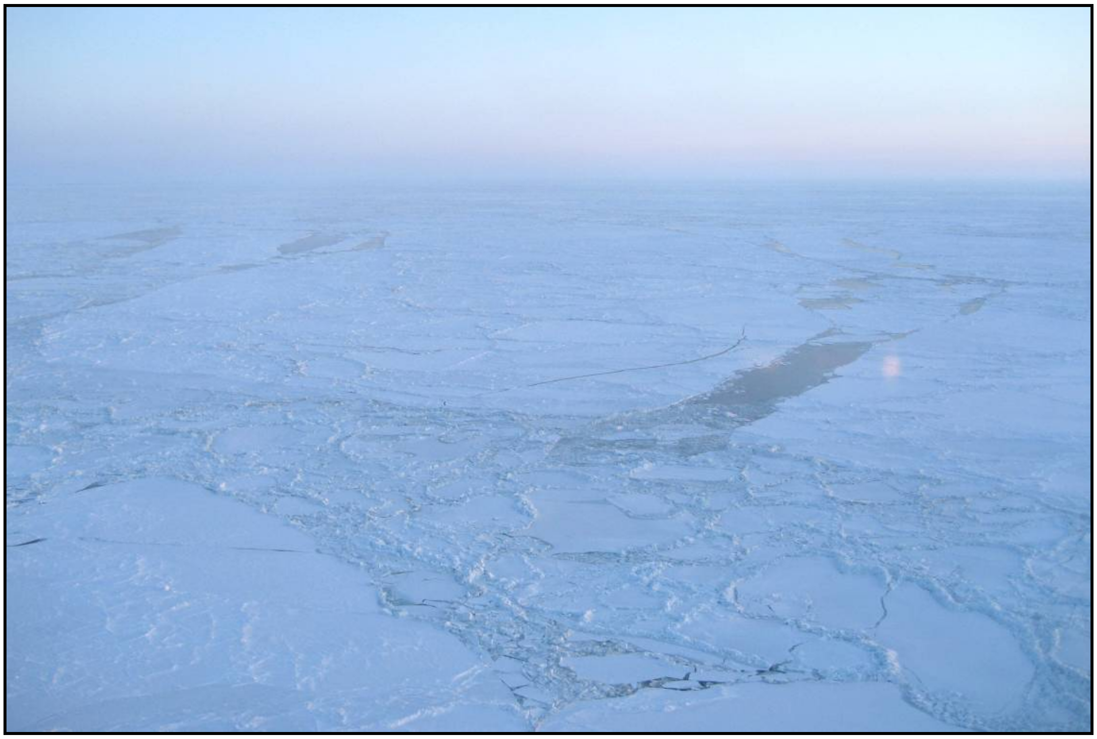


Plate 36. Nearshore Ice Conditions 14 nm West of Barrow on February 5, 2011

Plate 37. Offshore Ice in Crackerjack Prospects on February 6, 2011

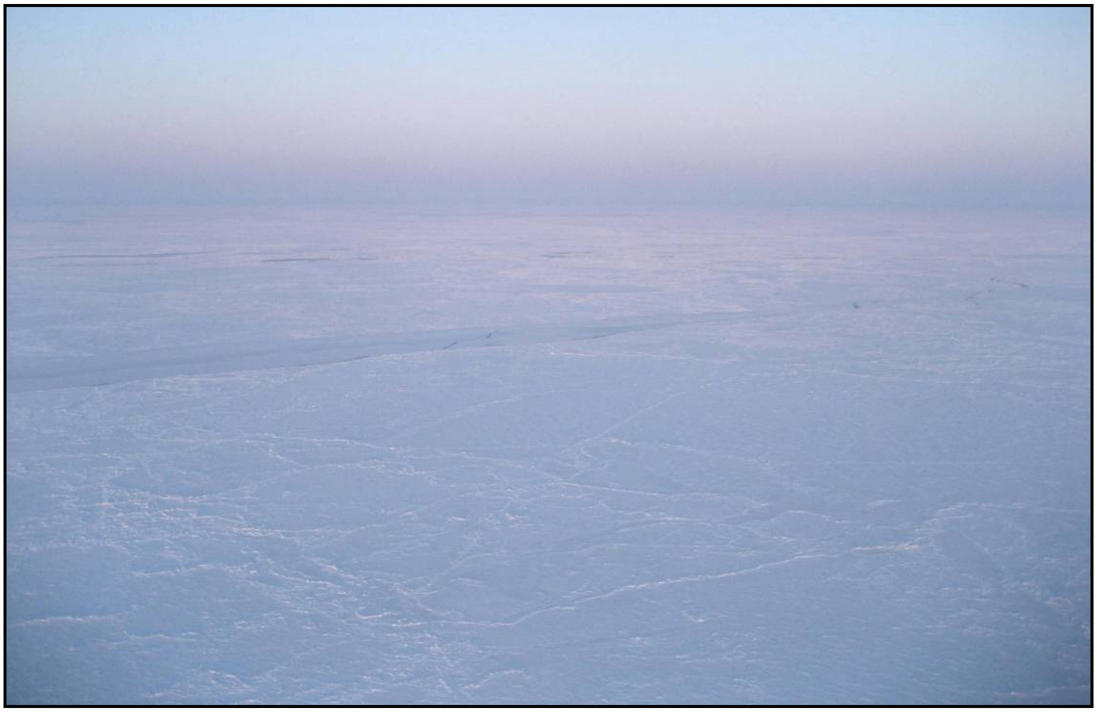


Plate 38. First-Year Pans with Scattered Ridges and Rubble Fields in Hanna Shoal Prospects on February 6, 2011

Plate 39. Vast, Flat First-Year Pans in West Prospects on February 6, 2011

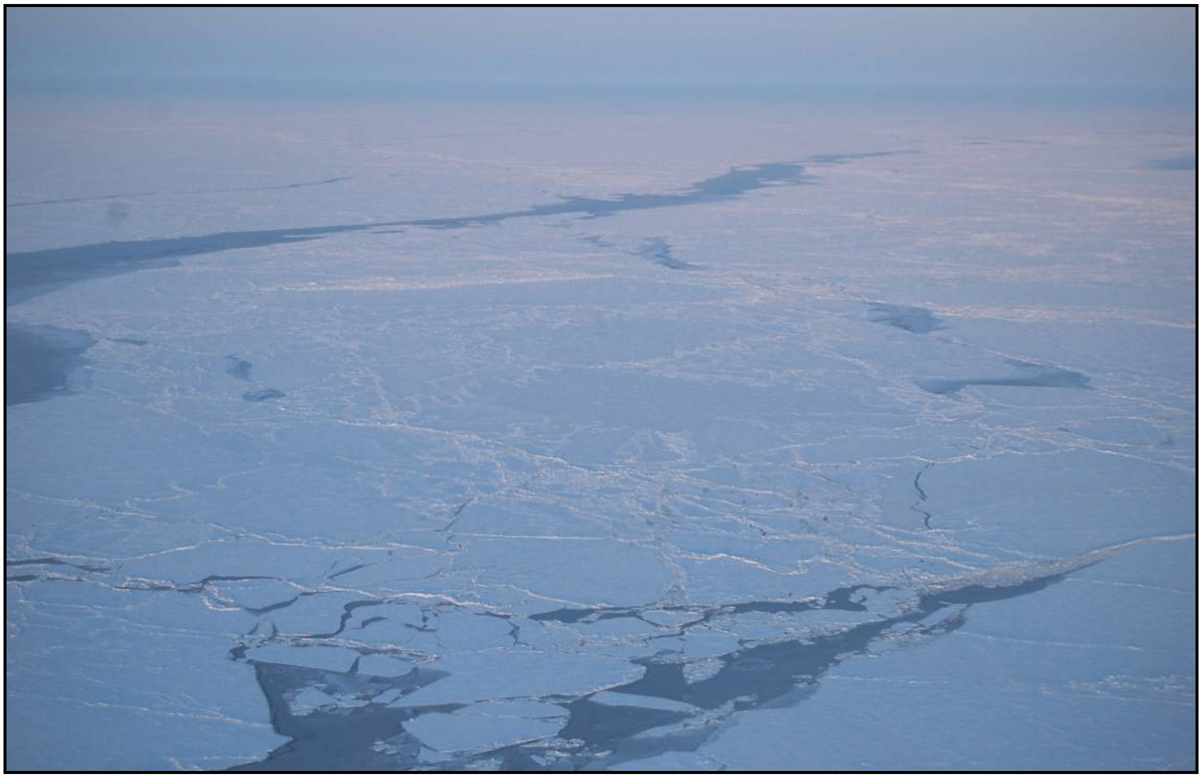


Plate 40. First-Year Floes with Ridges and Rubble up to 5 m High in Crackerjack Prospects on February 6, 2011

The diameters of the first-year floes typically varied between 0.25 and 1.5 nm (0.5 and 2.9 km) but occasionally reached 3 nm (5.6 km). Ridges and rubble accumulations with heights of 3 to 5 m were present at the edges of many the floes (Plate 41). As discussed in Section 5.3.2, a limited number of the floes appeared to contain fragments of old ice (Plates 29 and 30). Leads (both open and refreezing) were more common than in Crackerjack, with finger-rafting evident in areas of newly-formed ice.

The frequency of leads, ridges, rubble piles and broken ice tended to increase to the east of Burger (Plate 42; Drawing CFC-835-01-003), indicating that the ice cover was less consolidated and more mobile than in any of the Shell Prospects.

5.3.7. Katie's Floeberg

Katie's Floeberg forms each winter when ice rubble accumulates on Hanna Shoal, which lies 110 nm (204 km) northwest of Barrow at 72°N by 162°W (Drawing CFC-835-01-003). The shallowest water depth on the shoal is 12 m, while the surrounding water depths exceed 30 m.

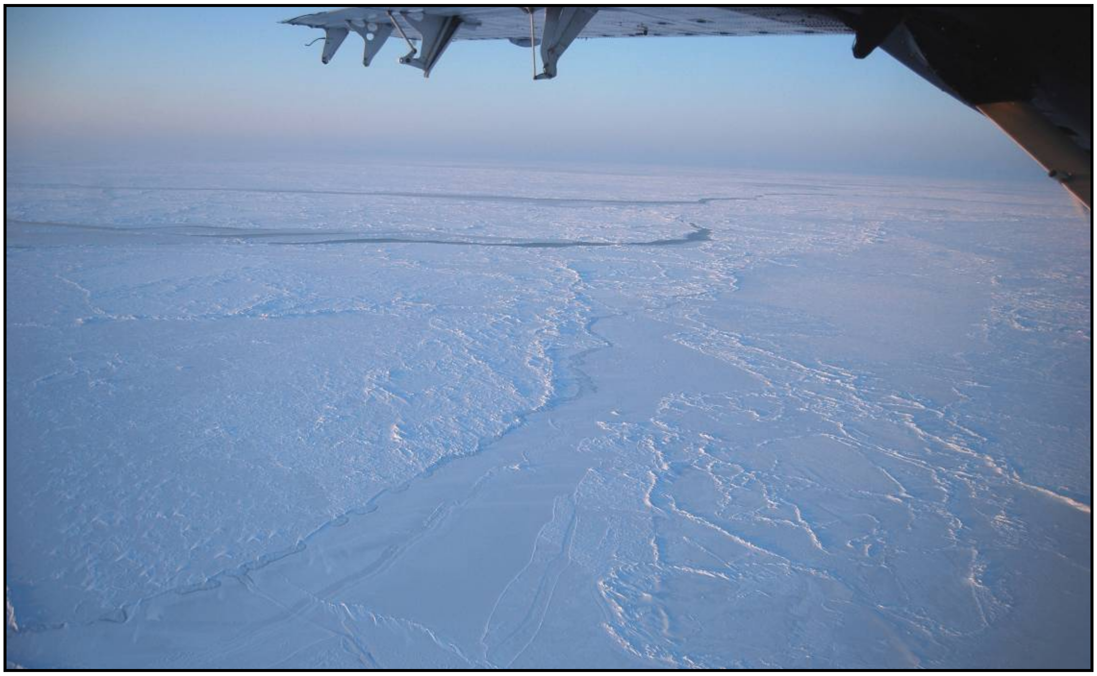


Plate 41. Refreezing Leads and First-Year Floes with Ridges up to 5 m High in Burger Prospects on February 6, 2011

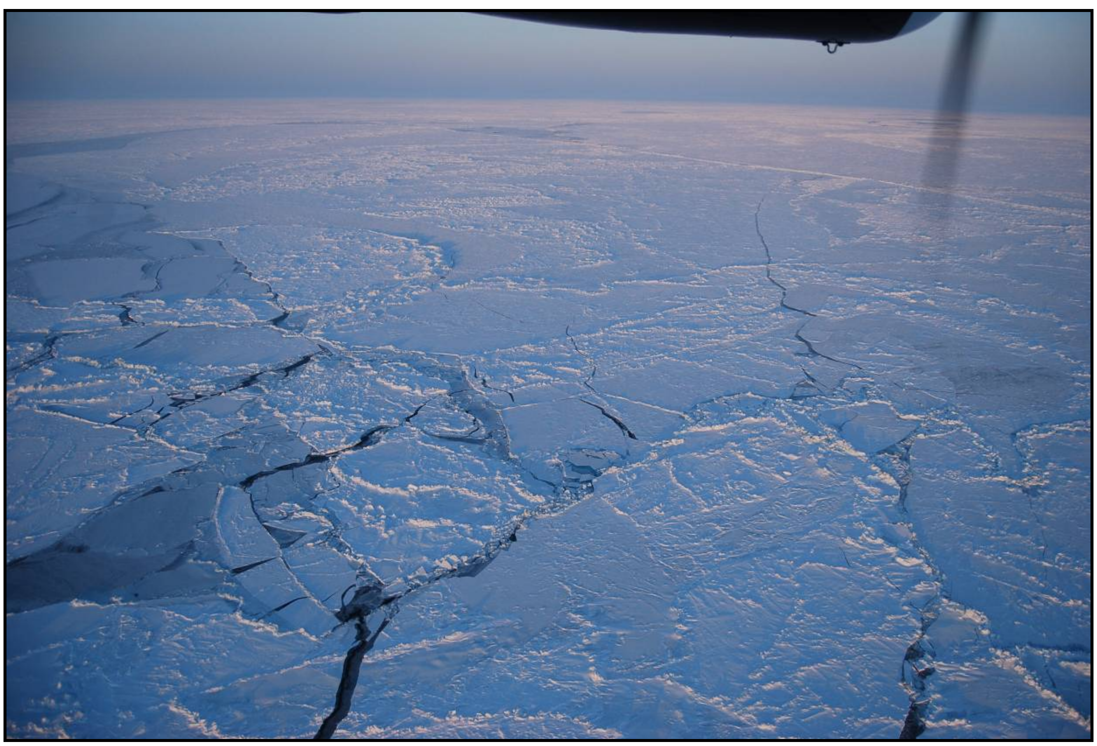


Plate 42. Ridges, Rubble, and Broken Ice 18 nm East of Burger Prospects on February 6, 2011

Katie's Floeberg was identified as early as 1966 using Nimbus satellite imagery (Kovacs, *et al*., 1976). Its formation and growth have been described in a number of prior studies, including those by Stringer and Barrett (1975), Kovacs, *et al*. (1976), Toimil and Grantz (1976), Barrett and Stringer (1978), and Vaudrey and Thomas (1981). In April 1980, the feature was found to consist of a vast oval of grounded first-year and multi-year rubble (Plate 43) measuring 5 nm (9 km) long and 2.5 nm (4.6 km) wide (Vaudrey and Thomas, 1981). Its maximum elevation was 18 m above the ice surface. The long axis was oriented northeast-southwest, and the shallowest water depth was located at the southwest tip.

Plate 43. Katie's Floeberg in April 1980

Unlike 2010, when grounded rubble did not accumulate on Hanna Shoal until mid-February (Coastal Frontiers and Vaudrey, 2010), Katie's Floeberg was clearly evident in early February 2011. As shown in Plate 44, the rubble measured approximately 1.5 nm (2.8 km) to the northeast-southwest and 1 nm (1.9 km) to the northwest-southeast. In keeping with the westerly winds that prevailed during the February 6th reconnaissance flight, ice was seen accumulating on the southwest side while an open-water wake was present on the east side. The highest rubble piles, estimated at 8 to 10 m, were located on the northeast side (Plate 45).

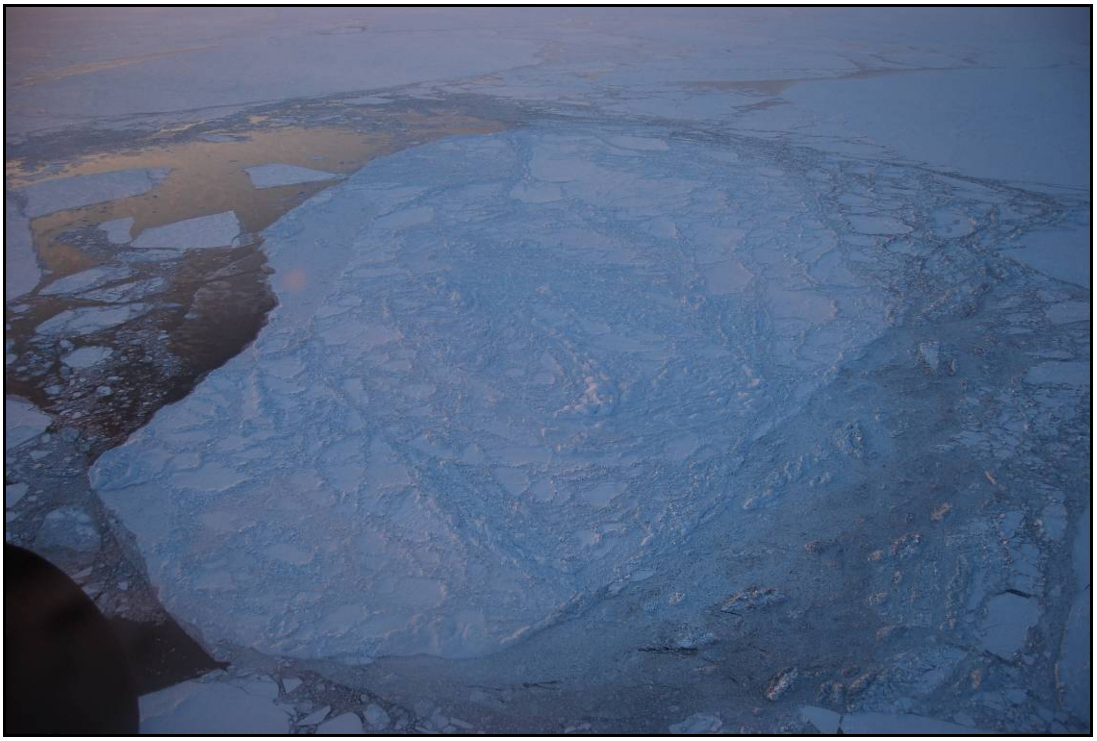


Plate 44. Katie's Floeberg on February 6, 2011 (looking south southwest)

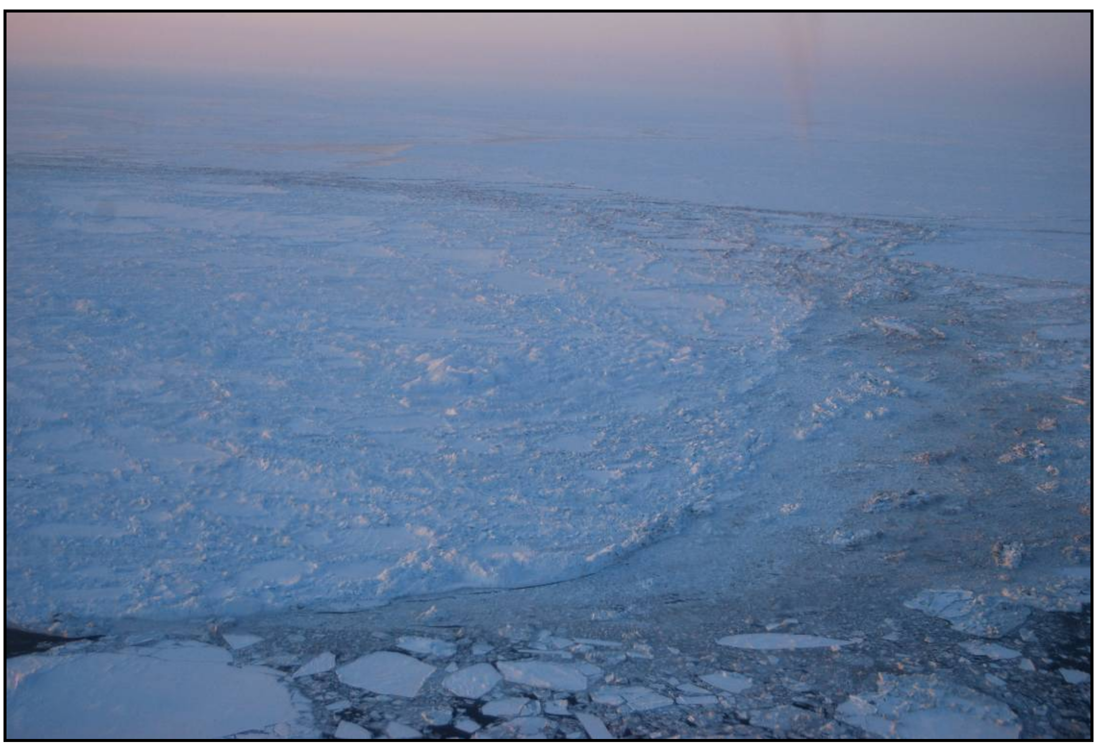
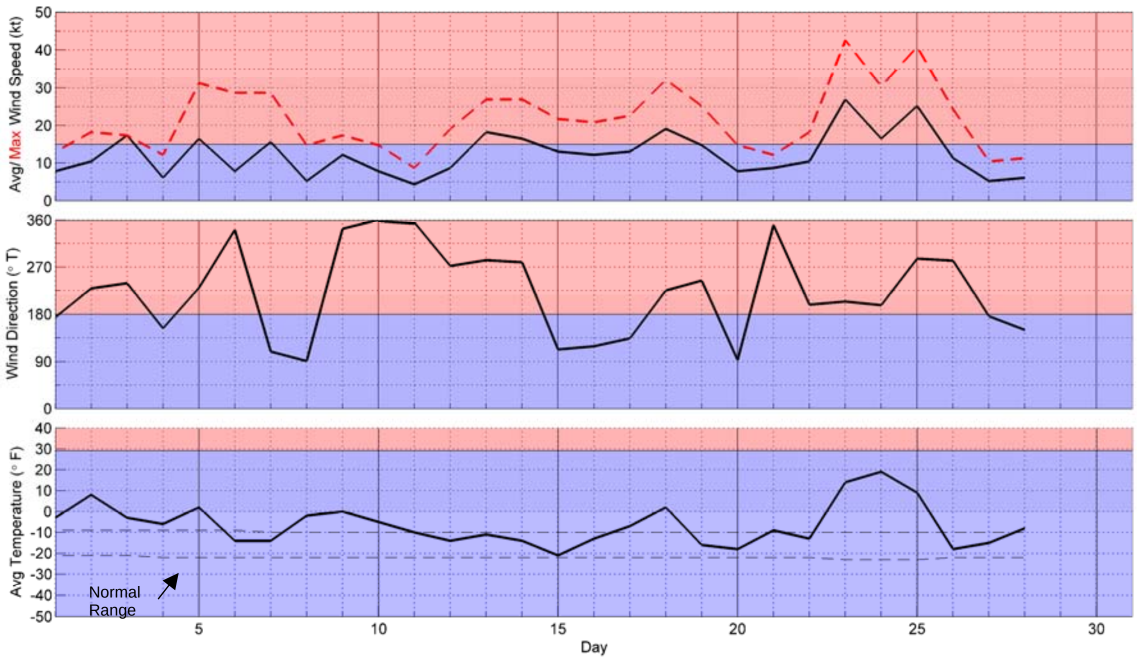


Plate 45. 8-10 m High Rubble on NE Side of Katie's Floeberg (February 6, 2011)

5.4 Midwinter

5.4.1. February 2011

Meteorological Conditions: The wind and temperature data recorded at Barrow Airport in February are presented in Figure 57. Normal to above-normal air temperatures prevailed throughout the month, with a spike to +19°F (-7°C) on February 24th during a prolonged westerly storm.



Source: Weather Underground, 2011

Figure 57. Meteorological Conditions at Barrow Airport in February 2011

Westerly winds predominated in February, occurring on 18 of the 28 days. The month included six storm events, five of which were westerlies. As indicated in Section 5.3, the first two westerly storms took place on the 3rd and 5th with wind speeds of 17 and 16 kt (9 and 8 m/s). These were followed by a 16-kt (8 m/s) easterly on the 7th, an 18-kt (9 m/s) westerly on the 13th and 14th, a 19-kt (10 m/s) westerly on the 18th and 19th, and a 27-kt (14 m/s) westerly on the 23rd, 24th, and 25th.

Ice Thickness: Nine hundred and ninety-two FDD were added in February, bringing the total to 4,113 FDD since the inception of freeze-up. The predicted ice thickness was 117 cm at the end of the month, representing 17 cm more than at the beginning.

Landfast Ice: Figure 58 presents the locations of the landfast ice edge derived from RADARSAT-2 images obtained on January 29th and February 12th (the last Chukchi Sea

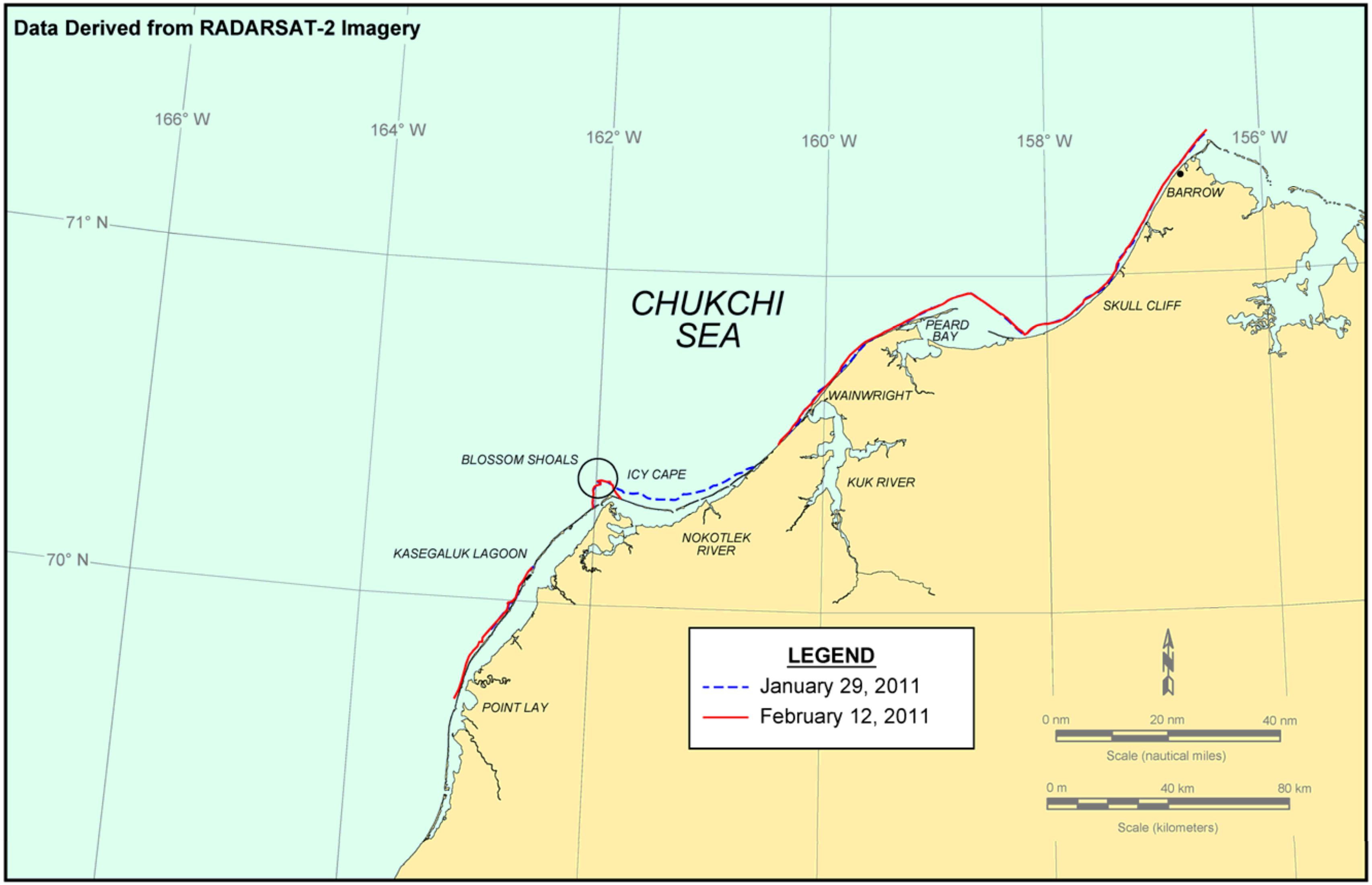


Figure 58. Chukchi Sea Landfast Ice Edge in February 2011

image available for analysis). The only significant change during this period was the loss of the temporary landfast ice to the east of Icy Cape and Blossom Shoals, a development noted during the February 5th reconnaissance flight and discussed in Section 5.3.3

Leads: The coastal flaw lead remained absent from all NIC ice charts prepared in February, as well as from AVHRR images obtained on 14 different days (Appendix B). Significant leads and polynyas also were lacking in the RADARSAT-2 image obtained on February 13th (Figure 59) – a finding that may be explained by the greatly-diminished frequency of sustained easterly winds and easterly storms in February.

Multi-Year Ice: The perennial pack ice moved north between January 29th and February 12th. As shown in Figure 59, the southern boundary was located approximately 100 nm (185 km) north of Point Barrow in the vicinity of the 73°N parallel.

A CIS mosaic prepared from RADARSAT images obtained between February 25th and 28th shows that the pack edge moved even farther north, to approximately 125 nm (232 km) off Point Barrow, during the second half of the month.

Ice Movement: Floe H moved from the Beaufort into the Chukchi at the end of January. Between January 29th and February 12th, it traveled a net distance of 40 nm (74 km) to the northwest at an average speed of 2.9 nm/day (5.4 km/day; Figure 60).

5.4.2. March 2011

Meteorological Conditions: Figure 61 presents the wind and temperature data recorded at Barrow Airport in March. As in February, the air temperatures tended to range from normal to above normal.

Easterly winds returned to dominance in March, occurring about 60% of the time. The most striking change from February, however, was a complete absence of storms from either the east or the west. The highest daily average wind speed, 13 kt (7 m/s), occurred on the last day of the month.

Ice Thickness: The predicted thickness of undisturbed first-year ice at the end of March was 135 cm, an increase of 18 cm over the course of the month. The prediction reflects an accumulation of 5,216 FDD since the beginning of the freeze-up season, including 1,103 FDD in March. By comparison, the predicted thickness in the Beaufort was 5% greater at 142 cm (Section 4.4.2).

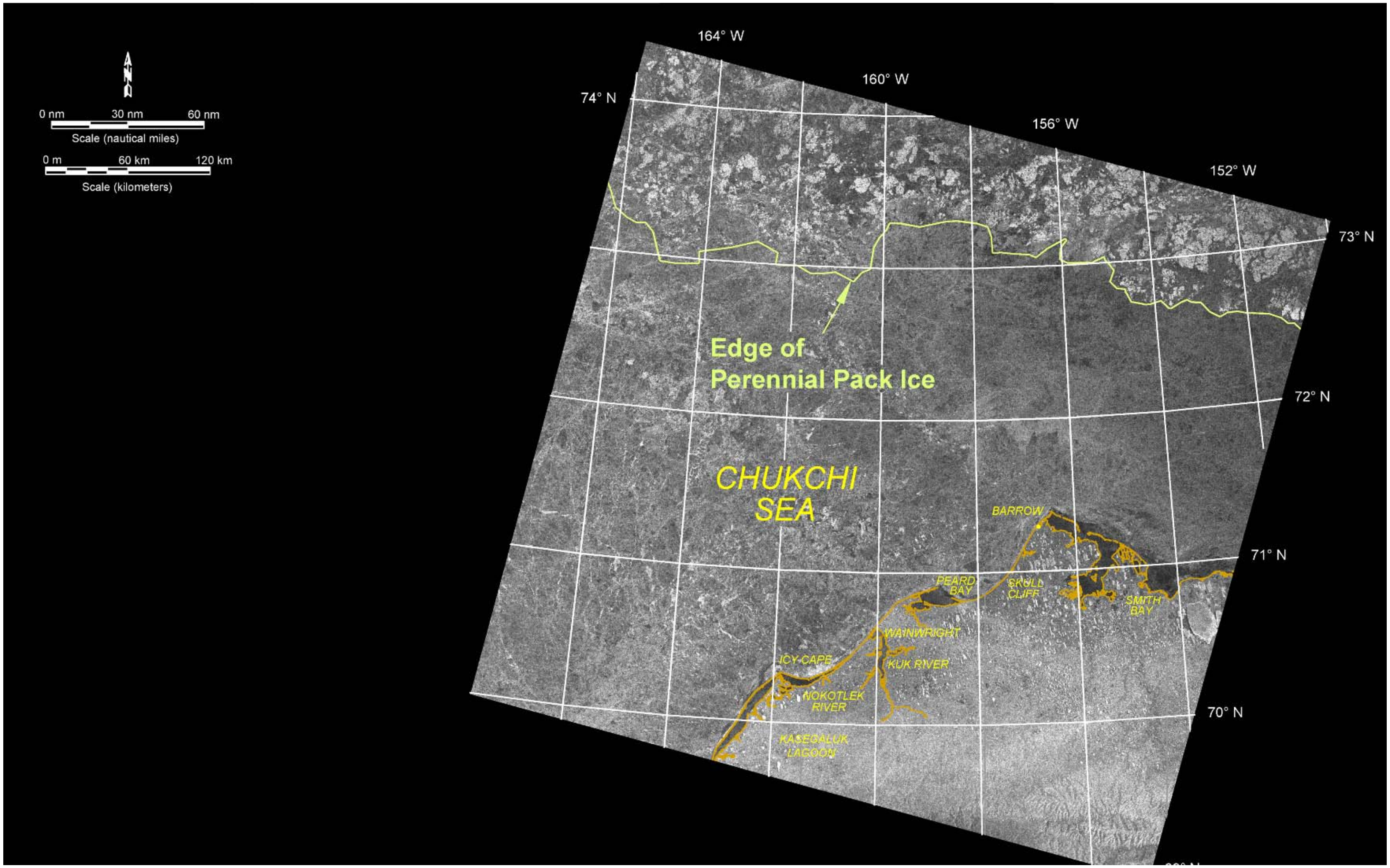


Figure 59. RADARSAT-2 Image of Chukchi Sea Acquired on February 12, 2011

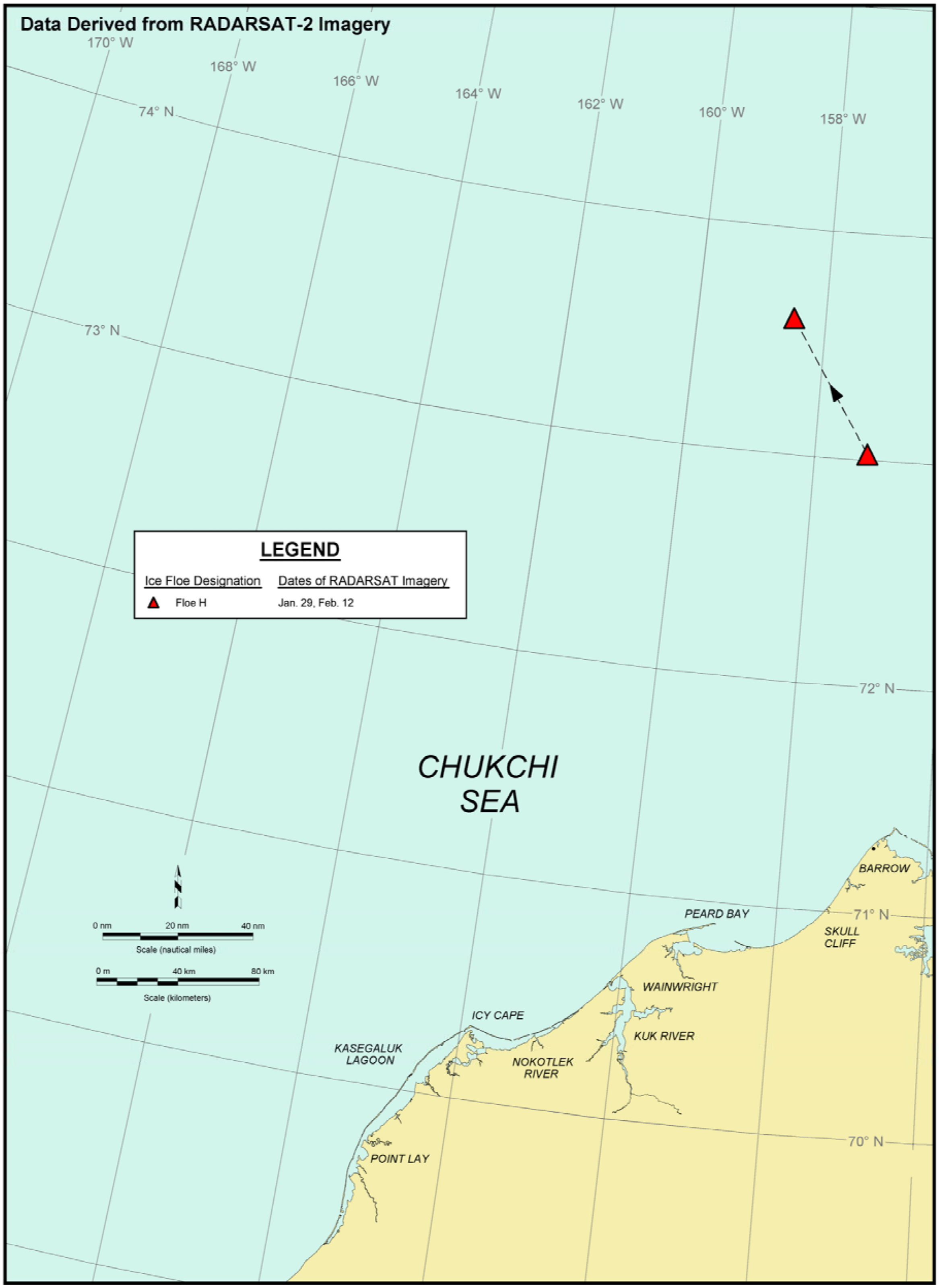
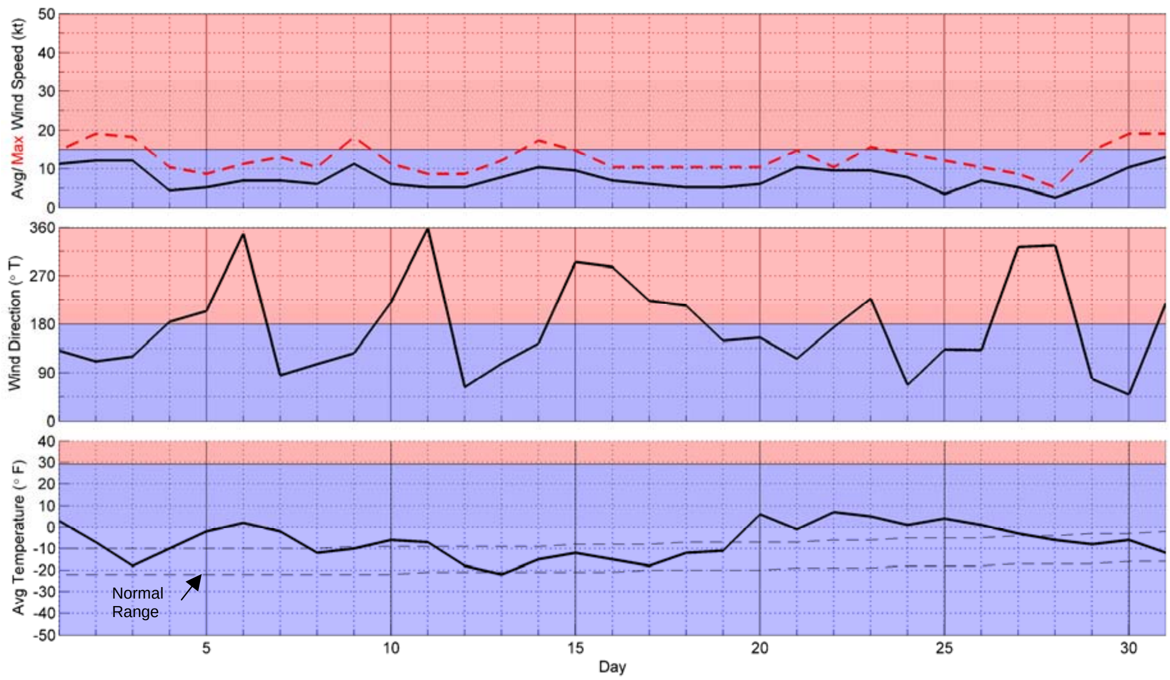


Figure 60. Chukchi Sea Multi-Year Ice Floe Displacement in February 2011



Source: Weather Underground, 2011

Figure 61. Meteorological Conditions at Barrow Airport in March 2011

Because the landfast ice in the northeast Chukchi Sea tended to remain unstable and transient through mid-winter, the predicted ice thickness in the landfast ice zone probably was attained only in protected areas that included Kasegaluk Lagoon, Peard Bay, and the region immediately north of Peard Bay and east of Point Franklin.

Multi-Year Ice: The offshore drift of the pack ice noted in prior months continued in March. Based on CIS mosaics dated March 14th and March 28th, the southern boundary was located near the 74°N parallel, about 150 nm (278 km) off Point Barrow, at mid-month, and 180 nm (333 km) off Point Barrow at month-end.

Leads: AVHRR images obtained on 23 days in March indicate that the coastal flaw lead opened between Barrow and Point Franklin during two periods of light but sustained easterly winds. The first opening peaked on or about March 3rd with an estimated width of 12 nm (22 km), while the second peaked on or about March 14th with an estimated width of 15 nm (28 km).

6. FREEZE-UP IN RECENT YEARS VS. THE 1980s

The primary objective of this section is to compare the ice conditions observed during the 2009-10 and 2010-11 freeze-up studies with those documented during similar studies conducted from 1980-81 through 1985-86.

Two of the most important environmental influences on freeze-up are the air temperatures and wind conditions. Accordingly, air temperature and wind data acquired at Barrow are analyzed to investigate perceived trends toward warmer conditions and higher storm frequencies. Both changes may make the sea ice more dynamic during freeze-up and midwinter.

Following the analysis of air temperatures and winds, five key aspects of the freeze-up season are evaluated and compared: the timing of freeze-up, first-year ice growth, landfast ice development and stability, multi-year ice, and ice movement. Based on comparisons between the past two years and the 1980s, potential long-term trends in ice behavior are identified. It should be recognized that the past two years constitute an abbreviated sample of present-day conditions, and therefore that the assessments presented below are subject to refinement as more data become available.

6.1. Air Temperatures

As discussed in Section 3.1, freezing-degree days (FDD) were computed as the difference between the freezing point of seawater (29°F) and the mean daily air temperature, and then accumulated by month. Negative FDD (>29°F) that occurred after freeze-up had begun were subtracted from the total.

Table 6 presents the FDD accumulated at Barrow on a monthly basis for each winter season from 1970-71 through 2010-11. The values have been computed using the daily mean air temperature. The table is divided into two parts, with the top portion showing the 20-year period from 1970-71 through 1989-90 and the bottom portion showing the subsequent 21-year period from 1990-91 through 2010-11. The column on the right-hand side displays the rank of each winter over the entire 41-year period of record, with the highest ranking (No. 1) assigned to the warmest winter (fewest FDD at the end of May) and the lowest ranking (No. 41) to the coldest (most FDD at the end of May).

Table 9: Accumulated Freezing-Degree Days (<29°F) at Barrow, 1970-71 through 2010-11

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	41-yr Rank
1970-71	129	1013	2009	3224	4727	6270	7734	8738	9098	40
1971-72	7	466	1351	2603	4004	5402	6912	7914	8252	36
1972-73	30	275	1103	2092	3410	4591	6135	7086	7393	21
1973-74	9	307	958	2024	3255	4859	6381	7488	7826	31
1974-75	18	725	1823	3546	5263	6453	7579	8584	8891	39
1975-76	155	893	2102	3677	5162	6667	8043	8976	9342	41
1976-77	12	486	1281	2689	3836	5107	6694	7756	8066	34
1977-78	0	272	1309	2444	3529	4738	5963	6785	7176	14
1978-79	17	696	1404	2734	3710	5082	6496	7393	7684	25
1979-80	0	310	895	2166	3496	4636	5891	6875	7247	15
1980-81	117	566	1586	2969	3896	5148	6384	7221	7389	20
1981-82	105	564	1452	2602	3845	4839	6122	7022	7407	22
1982-83	32	723	1896	3084	4578	5821	7136	7925	8300	37
1983-84	153	835	1666	2546	3919	5717	7128	8316	8700	38
1984-85	0	366	1479	2799	3925	5218	6517	7585	7780	28
1985-86	60	635	1424	2537	3901	4959	6407	7508	7784	29
1986-87	13	404	1262	2359	3661	5033	6295	7306	7579	24
1987-88	51	240	1272	2447	3672	4931	6224	7052	7337	18
1988-89	49	886	2164	3351	4994	5546	6637	7327	7687	26
1989-90	0	363	1611	2805	4417	5878	7131	7776	7903	33
Average	**48**	**551**	**1502**	**2735**	**4060**	**5345**	**6690**	**7632**	**7942**	
Std. Dev.	**54**	**239**	**357**	**460**	**592**	**609**	**601**	**623**	**635**	
Year	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**41-yr Rank**
1990-91	25	400	1477	2863	4177	5499	6947	7718	7748	27
1991-92	27	384	1494	2883	4358	5788	6972	7818	8076	35
1992-93	154	666	1569	2737	4027	5150	6439	7114	7300	17
1993-94	27	210	924	2074	3252	4313	5776	6649	6972	10
1994-95	60	699	1827	3222	4493	5758	7175	7817	7898	32
1995-96	0	326	1076	2343	3463	4776	5849	6719	6830	9
1996-97	87	816	1431	2469	3911	5120	6425	7184	7473	23
1997-98	5	293	830	2089	3441	4661	5644	6178	6339	2
1998-99	0	132	1023	2275	3681	4860	6243	7179	7375	19
1999-00	18	371	1251	2657	3979	5263	6493	7337	7792	30
2000-01	31	392	1251	2300	3510	4388	5764	6584	7137	13
2001-02	39	638	1507	2654	4070	5371	6315	7127	7273	16
2002-03	0	175	849	1811	3028	4269	5483	6104	6329	1
2003-04	0	167	945	2061	3210	4703	6063	6897	7065	12
2004-05	9	243	1045	2205	3341	4501	5636	6436	6648	7
2005-06	8	237	1143	2156	3421	4475	5930	6908	7059	11
2006-07	0	102	790	1769	3160	4258	5615	6232	6599	5
2007-08	0	170	616	1525	2922	4387	5792	6428	6648	7
2008-09	3	195	933	1809	3109	4103	5492	6297	6438	4
2009-10	6	125	981	1988	3391	4479	5687	6312	6608	6
2010-11	7	199	739	1925	3121	4113	5216	6117	6388	3
Average	**24**	**330**	**1129**	**2277**	**3575**	**4773**	**6046**	**6817**	**7047**	
Std. Dev.	**37**	**209**	**321**	**433**	**462**	**528**	**538**	**557**	**540**	

The data in Table 6 show that the last five winters, from 2006-07 through 2010-11, rank among the seven warmest in the past 41 years. The last two years, 2009-10 and 2010-11 rank sixth and third, respectively. Conversely, each winter during the 1970s and 1980s was colder than the average winter from 1990-91 through the present. The average annual accumulated freezing-degree days declined by 4% from the 1970s to the 1980s, 5% from the 1980s to the 1990s, and 9% from 2000-01 through 2010-11. The total decline from 1970-71 to 2010-11 was nearly 17%. The tendency toward warmer winter seasons is clearly evident in Figure 62, which presents a plot of the annual accumulated freezing-degree days at Barrow against time. The linear trend line depicts an average decline of 45 FDD/yr.

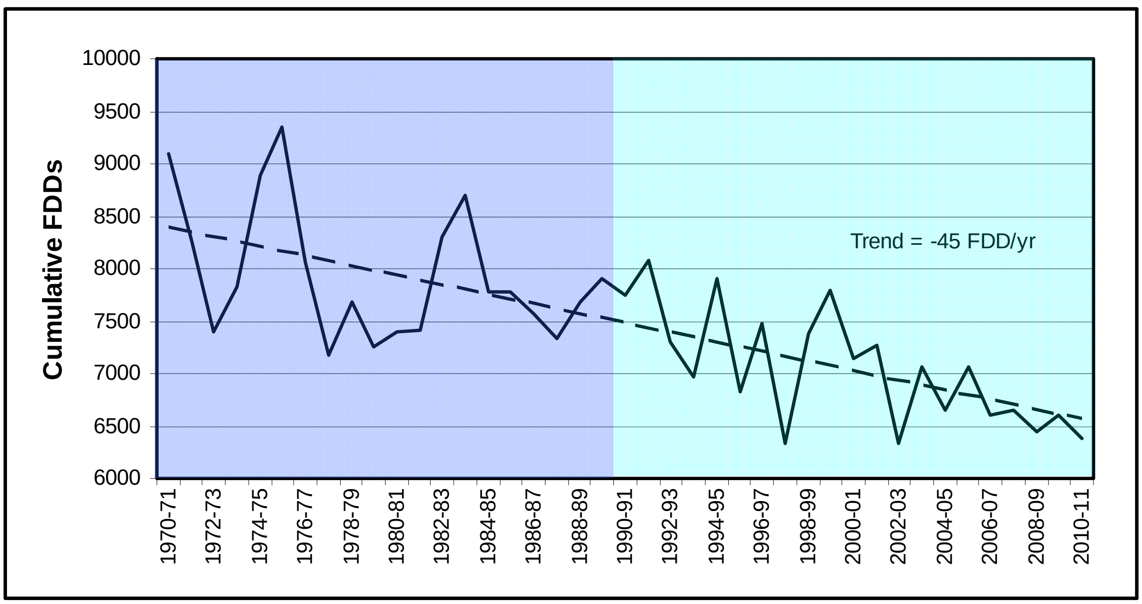


Figure 62. Annual Cumulative Freezing-Degree Days (<29°F) at Barrow, 1970-71 through 2010-11

Melling and Riedel (2005) found a similar trend in the air temperatures at Tuktoyaktuk over the 30-year period from 1975 through 2004. They determined that the number of freezing-degree days decreased at a rate of 3.3% per decade, somewhat less than any of the decadal rates computed for Barrow.

Additional evidence of the dramatic increase in winter air temperatures can be seen in Figure 63, which displays the difference between each monthly value in 2009-10 and 2010-11 and the corresponding long-term average at Barrow derived from the 29-year period from 1971-72 through 1999-2000. The recent value exceeded the long-term value in seven of nine months in 2009-10, and eight of nine months in 2010-11.

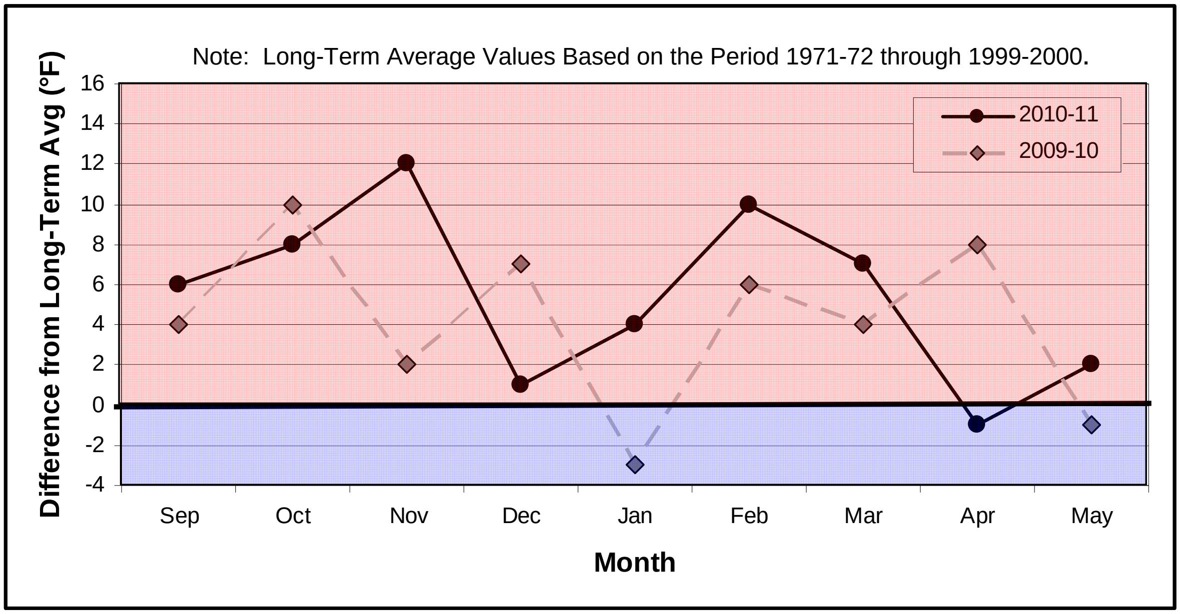


Figure 63. Differences between Monthly Air Temperatures in 2009-10 and 2010-11 and Long-Term Average Values at Barrow

Trend: Since the 1970s, progressively warmer winter seasons have caused the number of freezing-degree days at Barrow to decline at an average rate of 45 FDD/yr.

6.2. Winds

An indication of storm conditions in the 1980s was developed by Dickins and Vaudrey (1994), who compiled mid-winter wind data (January through April) at Barrow for the 18-year period beginning in 1977 and ending in 1994. They defined a storm as having a sustained wind speed exceeding 15 kt (8 m/s) for a period exceeding 12 hr. The six winters from 1981 through 1986 were excerpted from this database in order to compare the storm frequency that occurred at the end of the 1980-81 through 1985-86 freeze-up seasons with that which occurred at the end of the 2009-10 and 2010-11 seasons.

Whereas Dickins and Vaudrey computed an average of 8.5 storm events per mid-winter season for the years 1981-86, a similar analysis of the recent Barrow wind data yielded 13 storms in 2010 and 10 storms in 2011. Although other wind characteristics such as direction, intensity, and duration play significant roles in ice dynamics, the rise in the number of storm events suggests a possible increase in wind-driven ice movement at the end of the freeze-up season.

A similar trend toward increased storm frequency was identified by Walsh and Eicken (2007), who tabulated the number of storm events during the open-water and freeze-up seasons at Barrow from 1950 through 2004. The storm count rose dramatically in the mid-1980s and early 1990s, from 10-15 storms per year from 1977 through 1986 to 20-25 storms per year from 1990 through 2004 (Figure 64). The criteria used to identify storm events are not specified, but the data nevertheless indicate that the jump in storm frequency which occurred during in the 1980s and early 1990s has been sustained since that time.

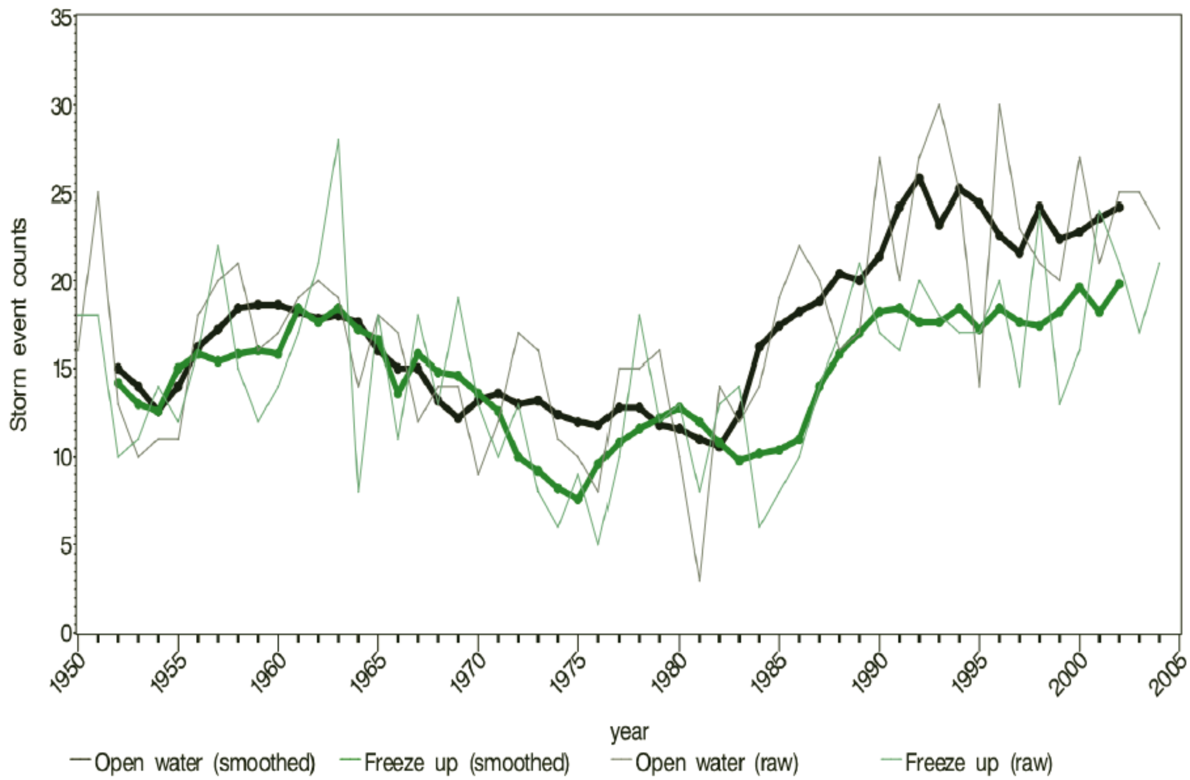


Figure 64. Yearly Storm Count at Barrow for Open-Water and Freeze-Up Seasons, 1950-2004 (Walsh and Eicken, 2007)

<u>**Trend**</u>**:** Since the early 1980s, the frequency of storm events at Barrow during the mid-winter months of January through April has increased by about one third.

6.3. Timing of Freeze-Up

During the last nine freeze-up seasons (2002-03 through 2010-11) the monthly average air temperature at Barrow in October has averaged 9°F (5°C) above the long-term average for the period from 1971-72 through 1999-2000. This substantial increase in October, along with relatively warm Septembers that averaged 4°F (2°C) above normal over the same period, probably has been intensified by the absence of nearby ice and the presence of water warmed by longer exposure to solar radiation. The end result of this feedback loop (warmer air temperatures → reduced ice cover → warmer sea water temperatures → warmer air temperatures) has been a delay in the onset of freeze-up in the nearshore waters of the Alaskan Beaufort and Chukchi Seas.

Freeze-up in the nearshore region of the Beaufort Sea occurred on October 22, 2010, and October 11, 2011. The average, October 17th, is comparable to the average date of October 20th computed for the five-year period from 2002 through 2006, but 13 days later than that determined from 11 years of on-site observations and satellite imagery acquired from 1980 through 1985 (Vaudrey, 1982-86) and 1987 through 1991 (Vaudrey, 1988-92).

In the Chukchi, freeze-up in the nearshore region occurred on November 4, 2010. This timing is comparable to that noted in 2009 (Coastal Frontiers and Vaudrey, 2010) and about one month later than in the mid-1970s (Mahoney, *et al*., 2007). A significant delay in the occurrence of freeze-up also is implied by the research of Rodrigues (2009), who found that the length of the ice-free season off the coast between Point Barrow and Point Lay increased from approximately 30 days in the late 1970s to 125 days at present.

Trend: Since the 1980s, the onset of freeze-up has slipped by about two weeks in the Alaskan Beaufort Sea and one month in the Chukchi Sea. Freeze-up in the nearshore region currently tends to occur during the third week in October in the Beaufort, and during the first week in November in the northern Chukchi.

6.4. First-Year Ice Growth

The growth of undeformed first-year ice during the winter months may be predicted using the relationship derived by Bilello (1960):

$$t = 0.37(\Sigma \mathrm{FDD})^{0.58}$$

where:

t = ice thickness in inches
FDD = freezing-degree days relative to 29°F

Table 10 presents the predicted ice thickness (in cm) on a monthly basis for each winter season from 1970-71 through 2010-11. The values have been computed using the

Table 10. Computed Ice Thickness (cm) at Barrow, 1970-71 through 2010-11

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	41-yr Rank
1970-71	16	52	77	102	127	150	169	182	186	40
1971-72	3	33	61	90	115	137	158	171	176	36
1972-73	7	24	55	79	105	125	148	161	165	19
1973-74	3	26	50	78	102	129	151	166	170	28
1974-75	5	43	73	108	135	152	167	180	183	39
1975-76	18	48	79	110	134	155	173	184	189	41
1976-77	4	34	60	92	113	133	156	169	173	34
1977-78	0	24	60	87	107	127	145	157	162	14
1978-79	5	42	63	93	110	133	153	165	169	25
1979-80	0	26	48	81	107	126	144	158	163	15
1980-81	15	37	67	97	114	134	151	163	165	19
1981-82	14	37	64	90	113	129	148	160	165	19
1982-83	7	43	75	99	125	143	161	172	176	36
1983-84	17	47	69	89	114	142	161	176	181	38
1984-85	0	29	65	94	114	135	153	167	170	28
1985-86	10	40	63	89	114	131	152	166	170	28
1986-87	4	31	59	85	110	132	150	164	167	24
1987-88	9	23	59	87	110	130	149	160	164	17
1988-89	9	48	81	104	131	139	155	164	169	25
1989-90	0	29	68	94	122	144	161	170	171	32
Average	**7**	**36**	**65**	**92**	**116**	**136**	**155**	**168**	**172**	
Std. Dev.	**6**	**9**	**9**	**9**	**10**	**9**	**8**	**8**	**8**	
Year	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**41-yr Rank**
1990-91	6	30	65	95	118	139	159	169	169	25
1991-92	6	30	65	95	121	143	159	170	173	34
1992-93	17	41	67	93	116	134	152	161	164	17
1993-94	6	21	49	79	102	121	143	155	159	10
1994-95	10	42	73	102	123	143	162	170	171	32
1995-96	0	27	54	85	106	128	144	156	157	9
1996-97	13	46	64	87	114	133	152	162	166	23
1997-98	2	25	46	79	106	126	141	149	151	1
1998-99	0	16	52	83	110	129	149	162	165	19
1999-00	5	29	59	91	115	135	153	164	170	28
2000-01	7	30	59	84	107	122	143	154	161	12
2001-02	8	40	66	91	117	137	150	161	163	15
2002-03	0	19	47	73	98	120	139	147	151	1
2003-04	0	18	50	79	102	127	147	158	161	12
2004-05	3	23	53	82	104	124	141	152	155	7
2005-06	3	22	56	81	105	123	145	158	160	11
2006-07	0	14	45	72	101	120	140	149	154	5
2007-08	0	18	39	66	96	122	143	152	155	7
2008-09	2	20	50	73	100	117	139	150	152	4
2009-10	3	15	51	77	105	123	142	150	154	5
2010-11	3	20	43	76	100	117	135	148	151	1
Average	**4**	**26**	**55**	**83**	**108**	**128**	**147**	**157**	**160**	
Std. Dev.	**5**	**9**	**9**	**9**	**8**	**8**	**7**	**7**	**7**	

FDD data for Barrow compiled in Table 9, and are presented in a comparable format with the highest ranking (No. 1) assigned to the lowest predicted ice thickness and the lowest ranking (No. 41) to the highest thickness.

The predicted ice thickness in 2010-11 is 151 cm, which along with identical values computed for 1997-98 and 2002-03 represents the minimum during the 41-year period of record. The predicted thickness in 2009-10, 154 cm, ties 2006-07 for the fifth lowest. The average for these two years, 153 cm, is 18 cm less than that computed for the six-year period between 1980-81 and 1985-86.

The predicted reduction in ice thickness attributable to warmer temperatures may be exacerbated by an increase in the depth of the snow cover. To quantify the relative importance of these and other factors, Brown and Cote (1992) investigated the interannual variability in the maximum ice thickness at four sites in the Canadian High Arctic between 1950 and 1989 using a physical one-dimensional heat transfer model of fast ice growth. The depth of the snow cover was found to be the most important factor, explaining 30% to 60% of the variance in the maximum landfast ice thickness due to its insulating effect. Density fluctuations in the snow cover were estimated to explain an additional 15% to 30% of the variance. In contrast, annual variations in air temperature accounted for less than 4% of the variance in the maximum first-year ice thickness.

The average snowfall at Barrow during the nine-month winter season (September through May) has increased dramatically, from 55 cm in the 1980s to 92 cm in the 1990s and 128 cm from 2000-01 through 2010-11 (Figure 65). The total snowfall at Barrow during the 2010-11 ice season was 162 cm, almost three times the average value in the 1980s.

In addition to reducing ice thickness, higher air temperatures tend to prolong the existence of leads and retard the production of new ice. Furthermore, higher temperatures and heavier snowfall decrease the consolidation within ice ridges and rubble fields and reduce the overall strength of the ice canopy.

Trend: Based on air temperature alone, the thickness of undeformed first-year ice attained during an average winter has decreased by about 10% relative to that attained in the early to mid-1980s. However, increased snowfall may be causing a greater reduction in the ice thickness. Other temperature-related factors, including reduced ice production in leads and decreased consolidation of ridges, probably exert a more significant impact on ice behavior than reduced ice thickness.

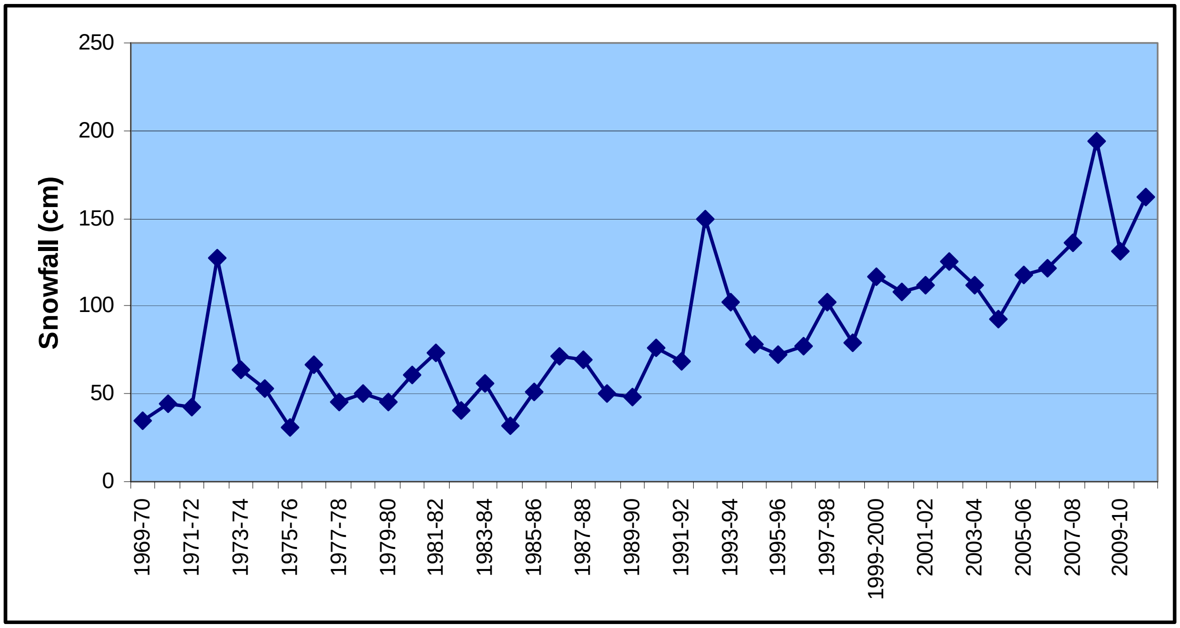


Figure 65. Total Snowfall at Barrow during Nine-Month Winter Season (Sept.-May)

6.5. Landfast Ice Development and Stability

Personal observations and data presented by Eicken, *et al*. (2006), indicate that characteristic patterns and features of the ice cover tend to recur. Such patterns include the distribution of landfast ice and the occurrence of leads and polynyas during the course of the winter. Factors that contribute to the recurring patterns include the seasonal cycles of meteorological and oceanographic conditions, the geometry of the shoreline and bathymetric contours, and the presence of shoals.

Beaufort Sea: Winds constitute the dominant driving force for ice movement in the Alaskan Beaufort Sea. The easterlies that prevail in most years produce ice motion roughly parallel to the shoreline, creating a stable landfast ice zone out to the 18-m isobath. The western Beaufort between Point Barrow and Prudhoe Bay contains numerous shoals that are located as much as 10 to 20 nm (19 to 37 km) offshore. The most prominent is Weller Bank, which is located in northeastern Harrison Bay. Large rubble piles of first-year ice that typically form on this shoal produce a significant seaward extension of the landfast ice. In contrast, water depths in the eastern Beaufort Sea increase more rapidly off the barrier islands from Cross to Flaxman and off the coast in the vicinity of Barter Island. In these areas, the landfast ice zone tends to be only 2 to 5 nm (4 to 9 km) wide. An exception occurs in Camden Bay, where landfast ice can extend 10 to 15 nm (19 to 28 km) offshore.

During the 2009-10 freeze-up season, warm air temperatures and a lack of sustained easterly winds produced an unusually narrow landfast ice zone that persisted through November and most of December (Coastal Frontiers and Vaudrey, 2010). In late December, however, an intense easterly storm created a grounded shear zone and an offshore boundary for the landfast ice west of Prudhoe Bay that were reminiscent of those noted in the 1980s.

Although the pattern of greater landfast ice development to the west of Prudhoe Bay recurred during the 2010-11 freeze-up season, the formation of a securely-grounded shear zone was inhibited by a lack of both easterly storms and sustained easterly winds. As a result, the landfast ice zone remained narrower and less stable than in 2009-10.

To the east of Prudhoe Bay, the contrast between the 1980s and the present encompassed not only the timing but also the extent of landfast ice development. A well-established, firmly-grounded shear zone formed off the barrier islands during five of the six freeze-up periods monitored in the 1980s. In both 2009-10 and 2010-11, however, the ice remained poorly-grounded and mobile through mid-winter except in close proximity to the islands. The difference is illustrated in Plates 46 and 47. The former shows a shear wall that grounded in a water depth of 30 m off Flaxman Island in November 1984, while the latter shows a refrozen lead with a modest accumulation of grounded rubble in a water depth of only 6 m off Mary Sachs Island in February 2011.

Chukchi Sea: As discussed in Section 5, easterly (offshore) winds and relatively steep slopes in the nearshore area limit the extent of the landfast ice in the Chukchi Sea to a narrow strip between the shoreline and grounded rubble located in water depths of 15 to 25 m. The offshore edge typically lies between several hundred meters and five kilometers off the coast, and the ice often experiences severe deformation except for a narrow ice foot adjacent to the shoreline. Local increases in the width of the landfast ice occur in protected locations that typically include the embayments east of Point Franklin and Icy Cape.

The tendency toward a narrow, ephemeral landfast ice zone was maintained in both 2009-10 and 2010-11. The situation was particularly acute in 2010-11, when a dearth of westerly storms minimized the compression and resultant grounding of the ice in the nearshore zone.

Seaward of the landfast ice, the ice cover is driven offshore during periods of easterly winds. The resulting coastal flaw lead separates the landfast ice from the highly mobile pack ice in the Chukchi Sea, and generates new ice throughout the winter as it experiences repeated cycles of opening and refreezing. The width of the lead can vary substantially, depending on the duration and intensity of the easterly winds.

Plate 46. Grounded Shear Wall in 30-m Water Depth off Flaxman Island (created during easterly storm in mid-November 1984)

Plate 47. Refrozen Lead and Rubble in 6-m Water Depth off Mary Sachs Island (February 3, 2011)

Vaudrey (1984; 1985; 1986) reported widths of 1, 5, and 15 nm (2, 9, and 28 km) for the flaw lead at the end of January 1984, 1985, and 1986, respectively. During mid-winter in the 2000s, the width and persistence of the lead appeared to increase. This trend continued in 2010, with sustained easterlies producing a 40- to 50-nm (74- to 93-km) wide feature that remained open for a 25-day period from mid-February to early March, and again for a 10-day period in late March. The lead opened less frequently and for shorter periods in mid-winter 2011, but nevertheless attained a maximum width of 60 nm (111 km) for four days in late January.

Trend: The locations and shapes of the landfast ice zones and the associated leads and polynyas tended to follow the same general patterns in 2009-10 and 2010-11 as in previous decades, but the landfast ice developed more slowly while the lead widths and polynya sizes tended to increase. Additional differences in the Beaufort Sea included the absence of a stable, grounded shear zone to the east of Prudhoe Bay in both years, and a smaller, less stable landfast ice zone to the west of Prudhoe Bay in 2010-11.

The data acquired in mid-winter of 2010 and 2011 suggest that the coastal flaw lead in the Chukchi Sea attains greater widths and may persist longer than in the 1980s. A winter feedback loop may have developed under which warmer air temperatures and more frequent storms produce weaker ice that is more susceptible to wind stress, ice motion commences at lower wind speeds, and the new ice that forms between wind events is thinner and more prone to displacement during the next event.

6.6. Multi-Year Ice

Large multi-year ice floes invaded the Alaskan Beaufort and Chukchi Seas on two occasions over the last decade: (1) 2001-02, when northerly and northeasterly winds drove a low concentration of multi-year floes into the nearshore region of the western Beaufort and northern Chukchi during the initial stages of freeze-up, and (2) 2009-10, when a high concentration of massive floes with embedded ridges entered the nearshore region of the Alaskan Beaufort from Canada, moved west to Point Barrow, and split into northern and southern branches in the Northern Chukchi. In 2010-11, although fragments of old ice were grounded on many of the barrier islands in the Beaufort and embedded in a small number of first-year floes in the Chukchi, large multi-year floes comparable to those noted in 2009-10 were absent from the Alaskan Beaufort and Chukchi.

Two types of "multi-year" or "old" ice can occur in the Beaufort and Chukchi Seas: (1) true multi-year floes from the perennial polar pack in the Arctic Ocean ("pack floes"), and (2) second-year ice formed in the nearshore zone and spared from melting and/or transport offshore during the ensuing summer by a combination of cold air temperatures, mild winds, and a preponderance of northerly or westerly winds. These “second-year floes” are fragments of first-year rubble fields or remnants of the shear zone that develops in water depths of 10 to 30 m off the coast of the Beaufort Sea and Canadian archipelago. Such floes can be distinguished from pack floes by their more jagged appearance, with many embedded ridges, and by greater thicknesses (6 to 9 m for second-year floes versus 3 to 5 m for pack floes).

Beaufort Sea: Large multi-year ice floes were present in the nearshore region of the Alaskan Beaufort Sea during three of the six freeze-up seasons studied in the 1980s: 1980-81, 1983-84, and 1985-86 (Vaudrey, 1981-86). In 1981-82 and 1982-83, the old ice was limited to floe and ridge fragments with diameters of 30 to 60 m grounded in water depths of 10 to 20 m at concentrations of one to three tenths. In addition, numerous smaller fragments were grounded on the mainland coast and the barrier islands (Plates 16 and 17) in a manner analogous to that noted in 2010-11 (Plates 4 and 5). In 1984, the old ice in the nearshore zone consisted of a band of fragments with diameters of 30 to 120 m grounded in 10 to 20 m of water at concentrations of two to eight tenths. The width of the band ranged from 2 to 8 km.

The multi-year ice invasion that occurred in 1980-81 began in late September The floes, mostly second-year features, moved close to shore and eventually became trapped in the landfast ice, evenly distributed over the central Beaufort Sea in a band 10 to 20 nm (19-37 km) wide. The band was located 5 nm (9 km) off of Cape Halkett and 2 nm (4 km) off the barrier islands from Thetis Island to Flaxman Island.

In 1983-84, the invading multi-year ice consisted largely of second-year floes that had survived a very cold summer and remained near the coast due to a lack of strong, sustained winds. Two years later, in 1985-86, vast conglomerate floes consisting of multi- or second-year ice welded together by thin first-year ice appeared to the north of a line that roughly paralleled the coast 15 to 20 nm (28 to 37 km) offshore.

Chukchi Sea: Multi-year ice was present in the northern Chukchi Sea during each of the three freeze-up seasons from 1983-84 through 1985-86 (Vaudrey, 1984-86) and also during the midwinter season of 1987 (Vaudrey, 1987). The invasions were similar to that which occurred in 2009-10, with concentrations up to 70% and southerly limits between 70.5° and 71°N. However, the floe sizes were much larger in 2009-10.

Trend: The probability of large multi-year ice floes invading the Alaskan Beaufort and Chukchi Seas in any given year is less than in the 1980s. This conclusion follows in part from the location of the ice edge, which has retreated farther to the north in recent summers (Section 4.1), and in part from warmer air temperatures and increased storm frequencies, which have reduced the likelihood that remnants of the Beaufort Sea shear zone will survive the summer melt season to become second-year floes. Nevertheless, as demonstrated in 2009-10, the possibility of multi-year ice encounters cannot be ruled out for developments in either the Beaufort or Chukchi. Furthermore, fragments of old ice analogous to those observed in 2010-11 may be present even if large multi-year floes remain well offshore.

6.7 Pack Ice Movement

Pack ice motion in the Beaufort Sea and northern Chukchi Sea can be broken down into two categories: (1) long-term, steady-state movement caused by the relatively constant rotation of the Beaufort Gyre (Figure 1) and (2) short-term, transient movement caused by wind events. As the latter varies greatly depending on the wind conditions and degree of ice confinement, insufficient data exist to support a direct comparison between the short-term motions observed in recent years and in the 1980s. It is worth noting, however, that a multi-year ice floe study conducted in the Alaskan Beaufort Sea during the 1984 open-water season arrived at the following conclusions (1) the wind factor for floes in the nearshore area is not constant, but varies as a function of wind speed, wind direction, bathymetry, and keel depth; (2) although the data exhibited considerable scatter, wind factors of 4 to 6% were typical during periods of strong winds (Tekmarine, Inc., *et al.,* 1985). When the greater confinement that exists during the winter season is taken into consideration, the wind factors of 1.3 to 4.6% that were derived from the hourly positions of Iridium buoys during four storm events in February 2011 (Section 4.4.1) appear to be consistent with these findings.

Long-term pack ice motion, often referred to as “ice flux” or “ice drift”, plays a key role in the design of fixed structures in that it governs the number of encounters with one or more design ice features (typically including multi-year ice floes) that may occur over a specified period or season. Although detailed analyses of ice movement were omitted from the freeze-up studies conducted from 1980-81 through 1985-86, a separate, site-specific buoy measurement program was undertaken in 1985-86 to complement the corresponding freeze-up study (Vaudrey, 1987a). The median ice flux during the 1985-86 freeze-up period was found to be 5 to 7 nm/day (9 to 13 km/day). Similar results were obtained from a number of other Beaufort Sea ice buoy programs conducted in the 1980s (Vaudrey, 1988a; 1989a; 1989b).

An analysis of RADARSAT-2 images of the Beaufort Sea obtained during November and December 2009 yielded an average ice drift rate of 6 nm/day (11 km/day), with a range of 1 to 13 nm/day (2 to 24 km/day). In the Chukchi, where the westward set of the Beaufort Gyre was greatly diminished south of Point Barrow, an average ice flux of 4 nm/day (7 km/day) was obtained for November 2009, December 2009, and January 2010. The rates ranged from 1 to 8.5 nm/day (2 to 16 km/day).

In 2010-11, eleven multi year ice floes in the Beaufort and Chukchi Seas were tracked for various periods from mid-November until mid-February. All of the floes in the Chukchi remained well north of Point Barrow, and hence were not sheltered from the Beaufort Gyre. If the entire period of record is taken into consideration for each floe (in both the Beaufort and Chukchi), the drift rates averaged 4.8 nm/day (8.9 km/day) while ranging from 1.4 to 8.2 nm/day (2.6 to 15.2 km/day). If the analysis is restricted to periods of one to two weeks, the rates varied between 0.2 and 9.7 nm/day (0.4 and 18.0 km/day). The fact that these values are less than those obtained for unsheltered floes in 2009-10 is consistent with the reduced frequency of easterly storms and sustained easterly winds that prevailed in the Beaufort in 2010-11.

Trend: The average drift rate measured for pack ice was 6 nm/day (11 km/day) in 2009-10 and 4.8 nm/day (8.9 km/day) in 2010-11. The former is comparable to that obtained in the 1980s, while the latter is somewhat lower in apparent response to the reduced frequency of easterly storms and sustained easterly winds that prevailed during the 2010-11 freeze-up season. These findings differ from those of Walsh and Eicken (2007), who suggested that thinner sea ice in the winter may lead to increased ice movement.

7. SUMMARY AND CONCLUSIONS

Study Methods

1. ***Satellite Imagery:*** RADARSAT-2 images, if obtained on a weekly basis with a nominal resolution of 100 m, provide an excellent means of tracking the progress of freeze-up and identifying changes in the nature of the ice canopy. They also can be used to investigate large-scale features such as the landfast ice zone, leads and polynyas, and multi-year ice floes. Publicly-available products that include ice charts, low-resolution mosaics prepared from satellite imagery, and AVHRR imagery can be used to confirm and extend the findings derived from the RADARSAT-2 images but are insufficient to support detailed analysis.

2. ***Aerial Reconnaissance Missions:*** Reconnaissance flights provide invaluable opportunities to confirm and refine the findings derived from satellite imagery, and to expand upon those findings with respect to small-scale features and processes. If possible, flights undertaken in early February to document the ice conditions at the end of freeze-up should be preceded by flights in late November or early December both to enhance the interpretation of early-season satellite imagery and to investigate phenomena such as pile-ups that occur when the ice cover is mobile.

Findings for Entire Study Area

1. ***Air Temperatures***: The daily mean air temperatures from September 2010 through May 2011 were the third warmest in the last 41 years, based on freezing-degree days accumulated at Barrow. The total of 6,388 freezing-degree days was 16% less than the average value for the twenty winters from 1970-71 through 1989-90, and 3% less than the value in 2009-10.

2. ***First-Year Ice Growth***: The computed thickness of undeformed first-year ice at the end of the 2010-11 winter season was 159 cm in the Beaufort Sea and 151 cm in the Chukchi Sea, based on the freezing-degree days accumulated at Deadhorse and Barrow, respectively. The thickness in the Beaufort is identical to that in 2009-10, while the thickness in the Chukchi is 3 cm less than the value in 2009-10.

3. ***Multi-Year Ice Floes***: With the exception of small fragments grounded on barrier islands in the Beaufort and embedded in a limited number of first-year floes in the Chukchi, multi-year ice was absent from the nearshore regions of both seas during the 2010-11 freeze-up season. Over the past decade, invasions of large multi-year floes

have occurred on two occasions: 2001-02 and 2009-10. This finding suggests that the probability of a multi-year ice invasion in any given year currently is about 20%.

Findings for Beaufort Sea

1. ***Late Summer:*** The pack ice reached its seasonal minimum extent in mid-September 2010. Its total area was slightly lower than in 2009, and the third lowest since 1979. The distance between the ice edge and the coast ranged from about 120 nm (222 km) off Barter Island to more than 200 nm (370 km) off Point Barrow. By month-end, the distance had decreased to 100 nm (185 km) off Barter Island but remained steady at 200 nm (370 km) off Point Barrow.

2. ***Freeze-Up***: Freeze-up in the nearshore region of the Alaskan Beaufort Sea occurred on October 11, 2010, after about 80 freezing degree days (FDD) had accumulated at Deadhorse Airport. This timing is 11 days earlier than in 2009 but 7 days later than the average computed for the 11 years from 1980 through 1985 and 1987 through 1991. Complete freeze-up occurred on November 2nd, at which time 305 FDD had accumulated.

3. ***Wind Regime:*** Winds tended to be light and variable during freeze-up and early winter. Based on the average daily wind directions recorded at Deadhorse Airport, easterlies and westerlies occurred with equal frequency. Storm events with average daily wind speeds exceeding 15 kt occurred on 19 occasions during the six-month period from October 2010 through March 2011. Eight of the storms were easterlies, while eleven were westerlies. Only two easterly storms occurred after December 1st: a one-day event on December 4th, and a two-day event on January 2nd and 3rd.

4. ***Landfast Ice:*** The landfast ice zone remained narrow and unstable during the 2010-11 freeze-up season due to a lack of both easterly storms and sustained easterly winds. Although three easterly storm events occurred in November 2010, the ice was too thin and weak to become securely grounded at that time. Thereafter, when the ice became sufficiently thick to generate competent rubble, the easterly storms needed to energize the process failed to materialize. In the western Beaufort, the landfast ice edge passed through Weller Bank but had not reached its other typical anchor point on Stamukhi Shoal at the end of January. In the central Beaufort, the landfast ice edge was located in close proximity to the barrier islands east of Prudhoe Bay and within 10 nm (19 km) of the shoreline in Camden Bay at this time.

5. ***Multi-Year Ice Floes:*** In contrast to 2009-2010, large multi-year ice floes did not invade the nearshore region of the Alaskan Beaufort Sea during the 2010-11 freeze-up season. Between November 2010 and mid-February 2011, such floes remained north

of the 71°N parallel in the eastern Beaufort and the 72°N parallel in the western Beaufort.

6. ***Fragments of Old Ice:*** Notwithstanding the absence of large multi-year ice floes from the nearshore area, grounded fragments of old ice with diameters ranging from 1 to 5.5 m were observed on the seaward shorelines of many of the barrier islands. The fragments originated from a band of grounded ice that persisted in the nearshore area between Flaxman Island and Smith Bay throughout the 2010 open-water season. Similar accumulations of old ice fragments were observed on the shorelines of the barrier islands during the 1981 and 1982 freeze-up seasons.

7. ***Thermal Cracks:*** Thermal cracks with extruded ridges were present in the semi-protected region between the Sagavanirktok River Delta and Leffingwell Lagoon. They probably formed during a four-day period at the end of November when the air temperatures fell and then rose abruptly. In the past, cracks of this nature have disrupted ice road operations.

8. ***Ice Pile-Ups:*** Only one ice pile-up was observed in the Alaskan Beaufort Sea in 2010-11. It was located at the Oooguruk Offshore Drillsite in the shallow waters of the Colville River Delta, and consisted of 10- to 15-cm thick plates that were stacked against the south corner and southwest side in multiple waves with heights of 3 m. The pile-up did not encroach beyond the waterline area of the island's gravel-bag armor.

Findings for Chukchi Sea

1. ***Freeze-Up:*** Freeze-up in the Chukchi Sea began during the first week in October but progressed slowly due to above-normal air temperatures and a prolonged easterly storm that dislodged the newly-formed landfast ice from the coast in mid-month. Complete coverage in the nearshore region occurred on November 4th, after 265 FDD had accumulated at Barrow Airport. The entire Chukchi Sea north of Cape Lisburne became ice-bound on December 7th, coincident with the accumulation of 959 FDD. Whereas freeze-up in the Chukchi began a full month earlier in 2010 than in 2009, it ended one week later.

2. ***Wind Regime:*** The wind data recorded at Barrow Airport suggest that two contrasting wind regimes prevailed in the Chukchi Sea during the 2010-11 freeze-up season. From October 1, 2010, through January 15, 2011, easterlies occurred more than 75% of the time and constituted eight of the ten storm events. From January 16th through March 31st, easterlies and westerlies occurred with nearly equal frequency while six of the eight storm events were westerlies.

3. ***Landfast Ice:*** Except in Peard Bay, Kasegaluk Lagoon, and the semi-protected area east of Point Franklin, the landfast ice that developed off the coast between Barrow and Point Lay was confined to a narrow strip that remained unstable through mid-February 2011. The paucity of westerly storms through mid-January limited the production of grounded rubble, thereby leaving the nearshore ice susceptible to break-out and removal during periods of easterly winds. When a coastal reconnaissance flight was conducted on February 5^{th}, the edge of the fast ice was located 0.7 nm (1.2 km) off Barrow, 0.5 nm (0.9 km) off Point Belcher, and 0.1 nm (200 m) off Point Lay. Even the semi-protected region that lies to the east of Icy Cape was virtually bereft of landfast ice at the time of the flight.

4. ***Coastal Flaw Lead:*** The distinctive flaw lead that opens off the Chukchi Sea coast in response to easterly winds and closes in response to westerly winds was detected on five occasions during the 2010-11 freeze-up season: late December, early January, late January, and twice in the first half of March. The dimensions of the lead varied substantially, from an estimated 50 nm (93 km) long by 5 nm (9 km) wide in late December to 140 nm (259 km) long by up to 60 nm (111 km) wide in late January. The feature's persistence also varied, from as little as several days during each appearance in March to about a week in early January. Whenever it was open, the lead left the ice in the nearshore zone susceptible to movement and deformation until it refroze.

5. ***Nearshore vs. Offshore Ice Cover:*** A significant contrast between heavily-deformed ice in the nearshore pack and relatively undeformed ice in the offshore pack was noted during the aerial reconnaissance flights conducted in February 2010. A similar but less-pronounced difference existed in February 2011. The nearshore zone contained ridges and rubble fields interspersed with small-to-moderate-sized first-year floes. Although significant ice deformation was evident, it was less prevalent than that observed a year earlier due to the paucity of westerly storms during the freeze-up season. At distances greater than about 60 nm (111 km) from the coast, where the influence of the coastal flaw lead tends to diminish, the ice cover evidenced less deformation and consisted largely of vast first-year pans with diameters as large as 5 nm (9 km).

6. ***Multi-Year Ice Floes:*** The large multi-year ice floes that entered the offshore portion of the Alaskan Beaufort Sea in November began arriving in the northern Chukchi Sea in mid-December. These floes remained well offshore throughout the 2010-11 freeze-up season, with the southern boundary located approximately 60 nm (111 km) off Barrow at the end of December and 180 nm (333 km) off Barrow at the end of March.

7. ***Fragments of Old Ice:*** Although the large multi-year ice floes remained north of the 72°N parallel during the freeze-up season, fragments of old ice embedded in first-year floes were observed in Shell's Burger Prospect during the reconnaissance flight conducted on February 6th. They comprised less than 5% of the ice cover, while their maximum horizontal dimensions ranged from one hundred to several hundred meters. The fragments may have broken off from the perennial pack ice in sizes that were too small and concentrations that were too low to be detected in RADARSAT-2 imagery. Alternatively, they may have drifted west from the nearshore band of grounded ice that persisted in the Alaskan Beaufort Sea throughout the 2010 open-water season.

8. ***Ice Pile-Ups:*** Twenty seven ice pile-ups were observed on the Chukchi Sea coast in February 2011, representing eight more than a year earlier. The piles were composed of blocks estimated to be 30 to 40 cm thick. They probably formed in mid-November, when loosely-consolidated ice was driven ashore by winds that shifted from east to west and accelerated to 25 kt. The largest pile-ups were located between Point Belcher and Wainwright, where one ice pile attained both the maximum estimated height of 8 m and maximum estimated encroachment distance of 40 m onto the beach. The longest ice pile, stretching 2,300 m alongshore with a height of 3 m, also occurred in this region.

Freeze-Up in Recent Years vs. the 1980s

1. ***Air Temperatures:*** Since the 1970s, progressively warmer winter seasons have caused the number of freezing-degree days at Barrow to decline at an average rate of 45 FDD/yr.

2. ***Winds:*** Since the early 1980s, the frequency of storm events at Barrow during the mid-winter months of January through April has increased by about one third.

3. ***Freeze-Up:*** The onset of freeze-up has slipped by about two weeks in the Alaskan Beaufort Sea and one month in the Chukchi Sea relative to the 1980s. Freeze-up in the nearshore region currently tends to occur during the third week in October in the Beaufort, and during the first week in November in the northern Chukchi.

4. ***First-Year Ice Growth:*** Based on air temperature alone, the thickness of undeformed first-year ice attained during an average winter has decreased by about 10% relative to that attained in the early to mid-1980s. However, increased snowfall may be causing a greater reduction in the ice thickness. Other temperature-related factors, including reduced ice production in leads and decreased consolidation of ridges, probably exert a greater impact on ice behavior than reduced ice thickness.

5. ***Landfast Ice Development and Stability*: ** The locations and shapes of the landfast ice zones and the associated leads and polynyas tended to follow the same general patterns in 2009-10 and 2010-11 as in previous decades, but the landfast ice developed more slowly while the lead widths and polynya sizes tended to increase. Additional differences in the Beaufort Sea included the absence of a stable, grounded shear zone to the east of Prudhoe Bay in both years, and a smaller, less stable landfast ice zone to the west of Prudhoe Bay in 2010-11. In the Chukchi, the data acquired in mid-winter of 2010 and 2011 suggest that the coastal flaw lead attains greater widths and may persist longer than in the 1980s.

6. ***Multi-Year Ice:*** The probability of large multi-year ice floes invading the Alaskan Beaufort and Chukchi Seas in any given year is less than in the 1980s. This conclusion follows in part from the location of the ice edge, which has retreated farther to the north in recent summers, and in part from warmer air temperatures and increased storm frequencies, which have reduced the likelihood that remnants of the Beaufort Sea shear zone will survive the summer melt season to become second-year floes. Nevertheless, as demonstrated in 2009-10, the possibility of encountering multi-year ice floes and gouges in the sea floor inflicted by such floes cannot be ruled out for developments in either the Beaufort or Chukchi. Furthermore, fragments of old ice analogous to those observed in 2010-11 may be present even if large multi-year floes remain well offshore.

7. ***Pack Ice Movement:*** The average drift rate measured for pack ice was 6 nm/day (11 km/day) in 2009-10 and 4.8 nm/day (8.9 km/day) in 2010-11. The former is comparable to that obtained in the 1980s, while the latter is somewhat lower in apparent response to the reduced frequency of easterly storms and sustained easterly winds that prevailed during the 2010-11 freeze-up season. These findings differ from those of Walsh and Eicken (2007), who suggested that thinner sea ice in the winter may lead to increased ice movement.

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