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7.6-m Ice Pile-Up on Narwhal Island (February 4, 2012)

2011-12 FREEZE-UP STUDY
OF THE
ALASKAN BEAUFORT AND CHUKCHI SEAS

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2011-12 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 2011-12 freeze-up season in the Alaskan Beaufort and Chukchi Seas. The study was performed on behalf of Shell International Exploration and Production, Inc. ("Shell") and the U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement ("BSEE"), by Coastal Frontiers Corporation and Vaudrey & Associates, Inc.

The 2011-12 Freeze-Up Study was designed to address five specific objectives:

1. Describe the ice conditions that evolve during the freeze-up and early winter seasons, including the development of the landfast ice zone and early shear zone;
2. Locate and map features of potential importance for offshore exploration and production activities, including ice movement lines, leads (linear openings in the sea ice), polynyas (areal openings in the sea ice), first-year ridges and rubble fields, and multi-year floes;
3. Locate and map ice pile-ups on natural shorelines and man-made structures, and estimate the dimensions and ice block thicknesses associated with such features;
4. Correlate significant changes in the ice canopy with the corresponding meteorological conditions;
5. Using the data acquired during the past three years, characterize present-day freeze-up processes and compare them with those documented in the 1980s.

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 September 2011, and continued through March 2012. Shell provided thirty six high-resolution RADARSAT-2 images acquired between October 4, 2011 and March 15, 2012, as well as the tracks of seven Iridium telemetry buoys deployed on the sea ice in Camden and Harrison Bays in January 2012. Shell's willingness to contribute these proprietary data at no cost to the project is gratefully acknowledged.

Two aerial reconnaissance missions were conducted in late November 2011 followed by five in early February 2012 to supplement the remotely-sensed data obtained from other

sources. The November flights were used to document the conditions that prevailed early in the freeze-up season, while the February flights were used to document the conditions at the end of the freeze-up season.

The principal study findings are summarized below:

Study Methods

1. ***Remote Sensing:*** RADARSAT-2 images, when combined with AVHRR images, MODIS images, and publicly-available ice charts, 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. Nevertheless, remote sensing must be supplemented with on-site observations to detect and quantify local ice features and processes.

2. ***Aerial Reconnaissance Missions:*** Reconnaissance flights provide invaluable opportunities to refine the findings derived from remote sensing, and to identify small-scale features and processes that otherwise would escape detection. The flights conducted in late November 2011 not only provided insight into the early stages of freeze-up, but also fostered a realistic understanding of the conditions that might be encountered when responding to a drilling incident that occurred at the end of the open-water season. The flights conducted in February 2012 were instrumental in characterizing the features that had formed during freeze-up, such as the landfast ice zone and ice pile-ups. In addition, these missions led to the discovery of extraordinary ice features that had become grounded off the Chukchi Sea coast.

Findings for Entire Study Area

1. ***Air Temperatures***: In contrast to 2009-10 and 2010-11, which were among the warmest winters since 1970-71, last winter was the coldest since 1999-2000 and colder than 23 others in the 42-year period of record. Nevertheless, the drop in air temperatures probably reflected normal interannual variability rather than a reversal of the long-term trend toward warming.
2. ***First-Year Ice Growth***: The computed thickness of undeformed first-year ice at the end of the 2011-12 winter season was 176 cm in the Alaskan Beaufort Sea and 167 cm in the Chukchi, based on accumulations of 8,275 and 7,556 FDD at Deadhorse and Barrow Airports, respectively. In keeping with the relatively cold temperatures that prevailed in 2011-12, these thicknesses were about 10% greater than those computed for the previous two winters.

Findings for Beaufort Sea

1. ***Late Summer:*** The last vestiges of nearshore ice disappeared from the Alaskan Beaufort Sea in mid-August 2011. Subsequently, the pack ice reached its seasonal minimum extent on September 9th. The average extent in September was the second lowest since record-keeping began in 1979, and only 7% larger than the all-time low in 2007. At the end of September, the ice edge was located approximately 110 nm (204 km) off Barter Island and 240 nm (445 km) off Point Barrow.

2. ***Freeze-Up***: Freeze-up began during the second week in October, when ice began to form adjacent to the coast. Complete ice coverage in the nearshore region occurred on October 26th, after 102 FDD had accumulated at Deadhorse Airport. This timing is four days later than in 2009 and 15 days later than in 2010, producing an average date of October 20th for the past three freeze-up seasons. Complete freeze-up in the Alaskan Beaufort Sea occurred on November 1st, at which time 201 FDD had accumulated.

3. ***Wind Regime:*** Based on the average daily wind directions recorded at Deadhorse Airport, westerlies outnumbered easterlies by a ratio of three to two (60% vs. 40%) during the six-month period from October 2011 through March 2012. Storm events with average daily wind speeds exceeding 15 kt occurred on 14 occasions. Eight of the storms were easterlies that produced 16 days of storm conditions ("storm-days"), while the remaining six storms were westerlies that produced 18 storm-days. Both the total number of storms (14) and total number of storm days (34) were lower than those in either of the prior two freeze-up seasons.

4. ***Landfast Ice:*** As in 2009-10 and 2010-11, the landfast ice zone tended to expand during periods of easterly winds and contract during periods of westerly winds. After remaining narrow in November, a month dominated by westerlies, the landfast ice zone grew dramatically in December in response to three easterly storms. At the beginning of January, it extended past the 18-m isobath and exceeded 20 nm (37 km) in width over the entire region between Point Barrow and Barter Island. It remained firmly grounded on Weller Bank and Stamukhi Shoal through mid-winter, but narrowed off Smith Bay and from Prudhoe Bay to Camden Bay in January. Easterly winds and an easterly storm triggered another period of expansion in February, but the landfast ice failed to achieve stability to the east of Prudhoe Bay and retreated to the 11-m isobath in March.

5. ***Multi-Year Ice Floes:*** Except in the immediate vicinity of Point Barrow**,** multi-year ice remained well offshore in the Alaskan Beaufort Sea throughout the 2011-12 freeze-up season. Since 2000-01, large multi-year floes have invaded the nearshore region on

only two occasions, 2001-02 and 2009-10. This finding suggests that the probability of an invasion in any given freeze-up season currently is less than 20%.

6. ***Ice Pile-Ups:*** Ten ice pile-ups occurred in central portion of the Alaskan Beaufort Sea during the 2011-12 freeze-up season. Nine were located on natural barrier islands (including four on Narwhal Island) and one on Northstar Production Island. The heights ranged from 2 to 7.6 m, the encroachment distances from 0 to 20 m, the alongshore lengths from 200 to 1,200 m, and the ice block thicknesses from 20 to 30 cm.

Findings for Chukchi Sea

1. ***Freeze-Up:*** Freeze-up in the Chukchi Sea began during the first week in October with initial ice formation in Kasegaluk Lagoon. Complete coverage in the nearshore region followed on November 20th, after 601 FDD had accumulated at Barrow Airport. This date is four days later than in 2009 and 16 days later than in 2010, yielding an average of November 13th for the past three freeze-up seasons. Complete coverage of the Chukchi Sea north of Cape Lisburne occurred on November 30th, concurrent with the accumulation of 1,022 FDD.

2. ***Wind Regime:*** Easterly winds occurred with a frequency of 71% at Barrow Airport during the 2011-12 freeze-up season, versus 29% for westerlies. As in the case of the Beaufort, both the number of storms (11) and number of storm-days (27) were less than those recorded in either of the prior two freeze-up seasons. Eight of the storms were easterlies that accounted for 21 storm-days, while the remaining three were westerlies that accounted for six storm-days.

3. ***Landfast Ice:*** The characteristically narrow landfast ice zone in the northeast Chukchi Sea remained unstable and discontinuous until January, when a predominance of westerly winds coupled with two westerly storms produced a continuous, quasi-stable strip between Point Lay and Barrow. When a coastal reconnaissance flight was conducted on February 6th, the edge of the fast ice was located 0.9 nm (1.7 km) off Barrow, 0.1 nm (200 m) off Point Belcher, and 6.0 nm (11.3 km) off Point Lay. This strip persisted for the remainder of February despite the frequent occurrence of easterly winds.

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 present during a significant portion of the 2011-12 freeze-up season, including more than half of the months of December and February. The width typically ranged from 10 to 30 nm (19 to 56 km) but expanded to as much as 60 nm (111km) in December and 50 nm

(93 km) in January. The length typically varied between 120 and 180 nm (222 and 334 km) but equaled or exceeded 200 nm (371 km) on several occasions. In both mid-December and late March, the lead extended northeast of Point Barrow to such an extent that it entrained multi-year ice floes arriving from the Beaufort Sea.

5. ***Nearshore vs. Offshore Ice Cover:*** As in 2010 and 2011, a distinct change in the nature of the offshore ice canopy was noted approximately 40 to 50 nm (74 to 93 km) off the coast during the aerial reconnaissance flights conducted in February 2012. Inshore of this location, the ice evidenced significant deformation with ridge and rubble heights to 8 m. Farther offshore, the ice tended to be relatively flat. Ridges and rubble fields were more widely spaced, with heights typically less than or equal to 3 m. This difference reflects the influence of the coastal flaw lead, which causes the nearshore ice to lose confinement. The rapid movements that result can produce extensive ridging and rafting as floating pans of ice collide with, or rotate about, one another.

6. ***Multi-Year Ice Floes:*** Large multi-year ice floes began streaming into the region south and west of Barrow in mid-December when they encountered an extension of the coastal flaw lead off Point Barrow that caused them to turn to the southwest. This pattern of southwesterly movement, which persisted through mid-winter, included another episode of the flaw lead entraining multi-year floes in late March. Floes with diameters from 100 m to more than 20 km attained concentrations as high as 90%, and moved as far south as the 68°N parallel. Large multi-year ice floes have invaded the region south and west of Barrow in six of the past twelve freeze-up seasons: 2000-01, 2001-02, 2003-04, 2005-06, 2009-10 and 2011-12. This finding suggests that the probability of an invasion in any given freeze-up season currently is about 50%.

7. ***Ice Pile-Ups:*** Thirty-one ice pile-ups were observed on the coast of the northeast Chukchi Sea during the 2011-12 freeze-up season. The highest concentrations were located on the spit that ends at Point Franklin and on the barrier islands that bracket Icy Cape. The heights ranged from 3 to 18 m, the encroachment distances from 0 to 40 m, the alongshore lengths from 100 to 5,400 m, and the ice block thicknesses from 30 to 60 cm. All of the maximum dimensions were associated with a massive pile-up that overtopped the 15-m high bluff at Skull Cliff and spilled 3 m onto the tundra.

8. ***Grounded Ice Features:*** Two grounded ice features believed to be ice island fragments from Ellesmere Island were discovered off the Chukchi Sea coast in February 2012. The larger of the two, located approximately 3 nm (6 km) off Point Belcher in a charted water depth of 32 m, was estimated to be 80 m long, 40 m wide and 20 m above sea level.

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 42 per year. Nevertheless, as demonstrated in 2011-12, a substantial deviation from this trend can occur in any given year.

2. ***Winds:*** Since the mid-1970s, the frequency of storm events during freeze-up has increased by more than 50%. The frequency of storm events in mid-winter (January through April) also may have increased, but additional data will be required to quantify the extent of the change.

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 since the 1980s. Freeze-up in the nearshore region currently tends to occur during the third week in October in the Beaufort, and during the second week in November in the northeastern 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 8% (14 cm) since the early to mid-1980s. However, a significant increase in 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 and rubble fields, probably exert greater impacts 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 during the past three freeze-up seasons as in previous decades, but the landfast ice developed more slowly while the lead widths and polynya sizes tended to increase. An additional difference in the Beaufort Sea was the absence of a stable, grounded shear zone to the east of Prudhoe Bay. In the Chukchi, the data acquired during late freeze-up and mid-winter suggest that the coastal flaw lead tends to attain greater widths and persist longer than in the 1980s.

6. ***Multi-Year Ice in the Alaskan Beaufort Sea:*** The probability of large multi-year ice floes invading the nearshore portion of the Alaskan Beaufort Sea in any given year is substantially less than in the 1980s. Nevertheless, as demonstrated in 2009-10, the possibility of multi-year ice encounters cannot be ruled out for developments in the nearshore region. Furthermore, fragments of old ice analogous to those observed in 2010-11 can be present even if large multi-year floes remain well offshore.

7. ***Multi-Year Ice in the Chukchi Sea:*** The probability of multi-year ice entering the Chukchi Sea to the south and west of Barrow also appears to have decreased since the 1980s, but the validity of this conclusion is challenged by the invasions that occurred in two of the past three freeze-up seasons. If northward extensions of the coastal flaw lead beyond Point Barrow become commonplace, as occurred in 2011-12, a rebound in the frequency of multi-year ice incursions into the Chukchi is likely to ensue.

8. ***Pack Ice Movement:*** The average drift rate measured for pack ice in the Beaufort Sea was 6 nm/day (11 km/day) in 2009-10, 4.8 nm/day (8.9 km/day) in 2010-11, and 4.1 nm/day (7.6 km/day) in 2011-12. The first of these is comparable to the rate obtained in the 1980s, but the second and third are lower. Additional years of observation will be necessary to determine whether the reduced values in 2010-11 and 2011-12 reflect normal fluctuations or a long-term trend. In either case, the lower speeds recorded during the past two years run counter to the findings of Walsh and Eicken (2007), who suggested that thinner sea ice in the winter may lead to increased ice movement.

Operational Considerations

1. ***Multi-Year Ice Invasions:*** If the coastal flaw lead that frequently opens in the northeast Chukchi Sea extends sufficiently far north of Point Barrow to intersect the southern boundary of multi-year ice, it can convey a large quantity of multi-year floes into the region south and west of Barrow in a relatively short time. Early warning of such invasions can be obtained by monitoring satellite imagery for evidence of an extended flaw lead. It should be noted, however, that other circumstances also may lead to multi-year ice floes entering the region south and west of Point Barrow.

2. ***Ice Reconnaissance:*** Ice features analogous to the presumed ice island fragments that were discovered off the Chukchi Sea coast in 2011-21, while too small to be identified in satellite imagery, nevertheless can impart substantial loads on offshore structures and incise massive gouges in the sea bottom. As such features are likely to travel with old rather than first-year ice, the analysis of satellite imagery should be supplemented with aerial reconnaissance flights when old ice approaches an operating area containing facilities susceptible to damage.

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2011-12 FREEZE-UP STUDY OF THE ALASKAN BEAUFORT AND CHUKCHI SEAS

1. INTRODUCTION

This report describes an investigation of the ice conditions that prevailed in the Alaskan Beaufort and Chukchi Seas during the 2011-12 freeze-up season. The study was performed as a joint-industry project on behalf of Shell International Exploration and Production, Inc. ("Shell"), and the U.S. Department of the Interior, Bureau of Safety and Environmental Enforcement ("BSEE"), 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 74°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 include 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 pile-up events when the ice encounters fixed objects such as natural shorelines, shoals, and man-made islands. The storms also can cause substantial deformation of the first-year ice, leading to the formation of ridges and rubble fields.

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

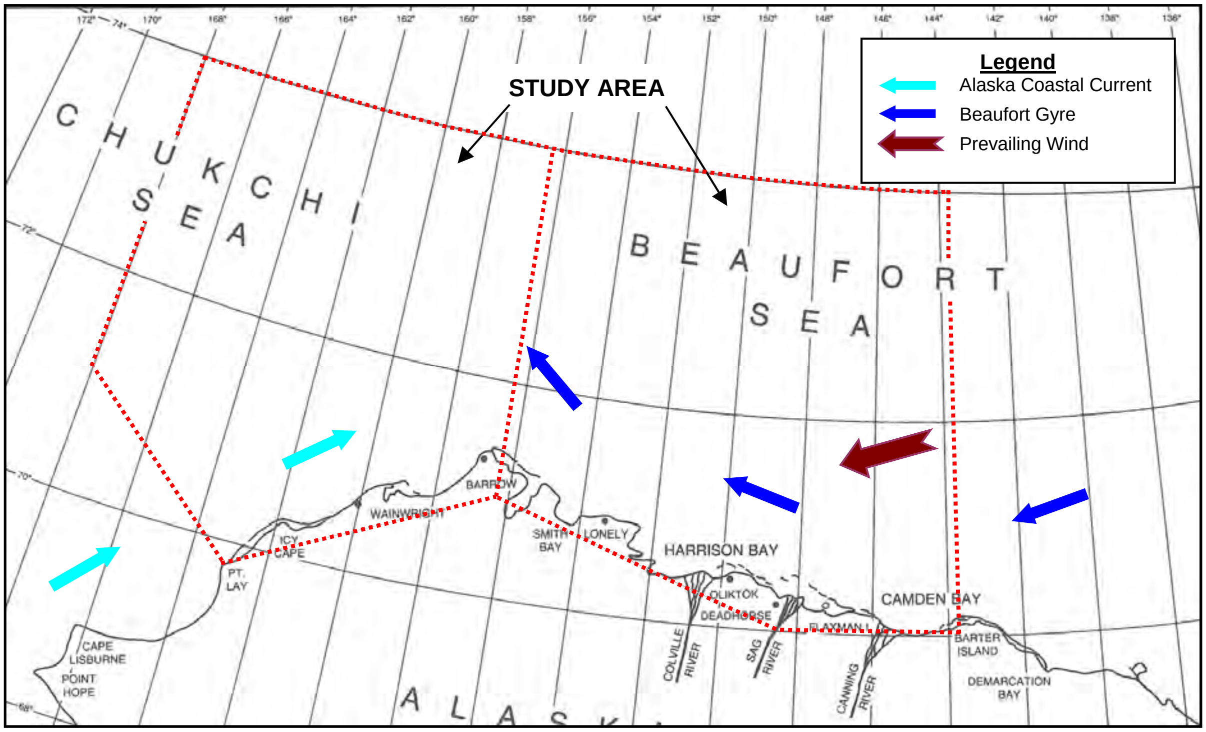


Figure 1. Study Area

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 undertaken 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 that occurred 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 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 character of multi-year ice floes and the locations and characteristics 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 BSEE (known previously as the Minerals Management Service and subsequently as the Bureau of Ocean Energy Management, Regulation, and Enforcement) commissioned studies of the 2009-10 and 2010-11 freeze-up seasons that combined remote sensing with on-site observations. Each 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 (Coastal Frontiers and Vaudrey, 2010; 2011).

To continue documenting the nature and interannual variability of present-day freeze-up processes, a program similar to those in 2009-10 and 2010-11 was conducted in 2011-12. The scope of work was designed to address five specific objectives:

1. Describe the ice conditions that evolve during the freeze-up and early winter seasons, including the development of the landfast ice zone and early shear zone;
2. Locate and map features of potential importance for offshore exploration and production activities, including ice movement lines, leads (linear openings in the sea ice), polynyas (areal openings in the sea ice), first-year ridges and rubble fields, and multi-year floes;
3. Locate and map ice pile-ups on natural shorelines and man-made structures, and estimate the dimensions and ice block thicknesses associated with such features;
4. Correlate significant changes in the ice canopy with the corresponding meteorological conditions;
5. Using the data acquired during the past three years, characterize present-day freeze-up processes and compare them with those documented in the 1980s.

The acquisition of publicly-available meteorological data, ice charts, and satellite imagery began in September 2011 and continued through March 2012. These data were supplemented with RADARSAT-2 images provided to the project at no cost by Shell. In addition, Shell provided the tracks of seven Iridium telemetry buoys deployed on the sea ice in Camden and Harrison Bays in late January 2011. Shell's willingness to contribute these proprietary data is gratefully acknowledged.

Aerial reconnaissance missions were conducted in late November 2011 and early February 2012 to acquire first-hand knowledge and photographic documentation of the ice cover. The November missions, consisting of one fixed-wing flight in each of the Beaufort and Chukchi Seas, were intended to document the conditions the prevailed early in the freeze-up season (when emergency response measures could become necessary to address a drilling incident that occurred late in the open-water season). The February missions, consisting of two fixed-wing flights and one helicopter flight in the Beaufort followed by two fixed-wing flights in the Chukchi, were intended to document the conditions at the end of the freeze-up season (when processes such as nearshore rubble formation and ice encroachment onto the shoreline typically have ceased). Whereas the 2009-10 and 2010-11 freeze-up studies included similar aerial reconnaissance missions in early February (Coastal Frontiers and Vaudrey, 2010; 2011), the current study represented the first since the 1980s to include flights in November.

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 occur 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 near-constant ice motion and the formation of new ice 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 2011-12 Freeze-Up Study. To provide historical context, the findings of the eight prior joint-industry studies (1980-81 through 1985-86, 2009-10, and 2010-11) 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. Section 4 describes the progression of freeze-up in the Beaufort in 2011-12, while Section 5 provides comparable information for the Chukchi. In Section 6, present-day freeze-up processes are compared with those documented in the 1980s. Conclusions are presented in Section 7, followed by references in Section 8. Figures, tables, and plates are interspersed with the text, while five 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 10 cm above Mean Lower Low Water (MLLW) at Prudhoe Bay, 9 cm at Barrow, and 8 cm at Point Hope (National Ocean Service, 2012). For purposes of this report, the differences between MSL and MLLW (which represents the vertical datum for all National Ocean Service nautical charts of the Beaufort and Chukchi) 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 features 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).

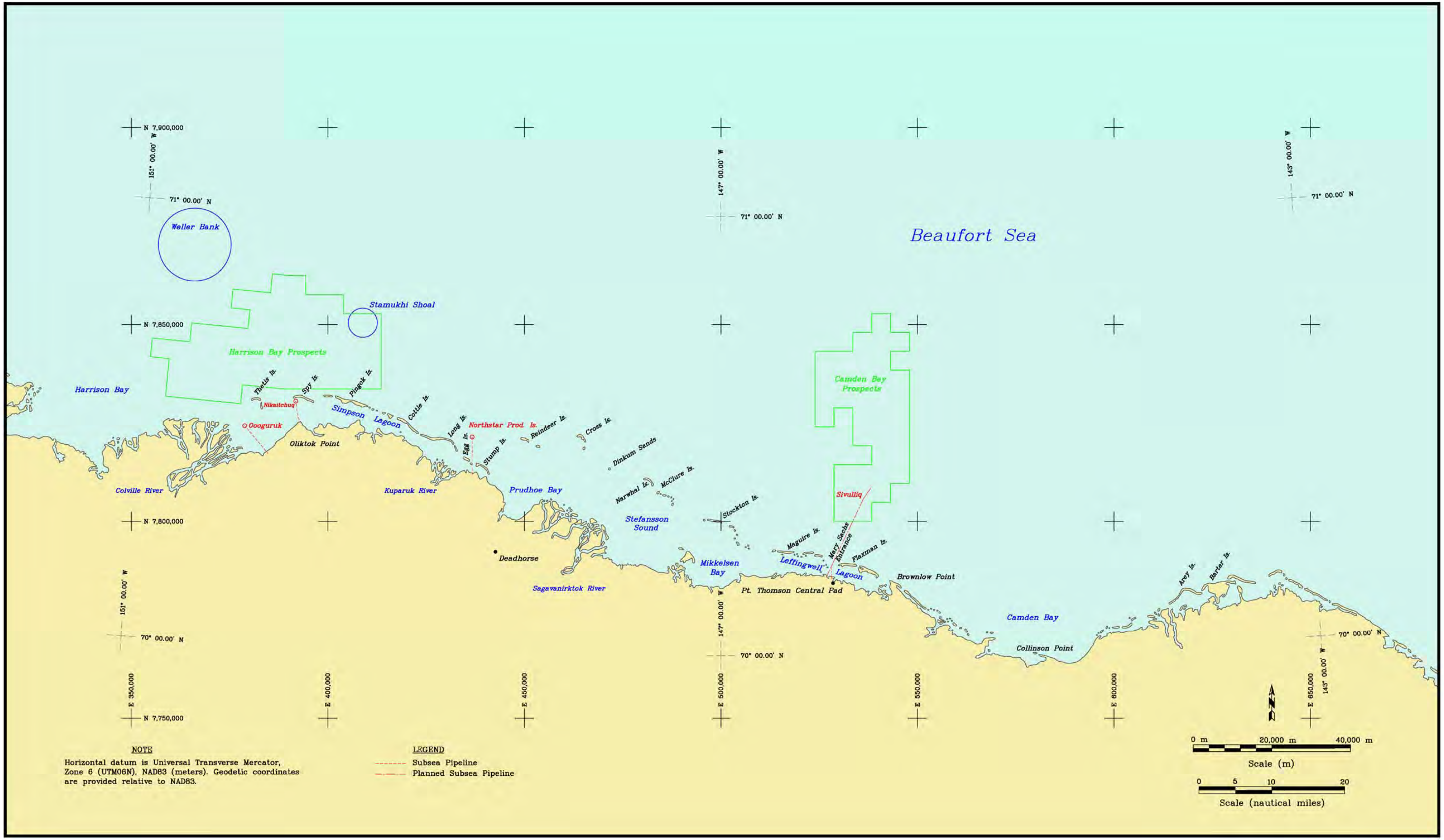


Figure 2. Geographic Points of Interest in Central Beaufort Sea

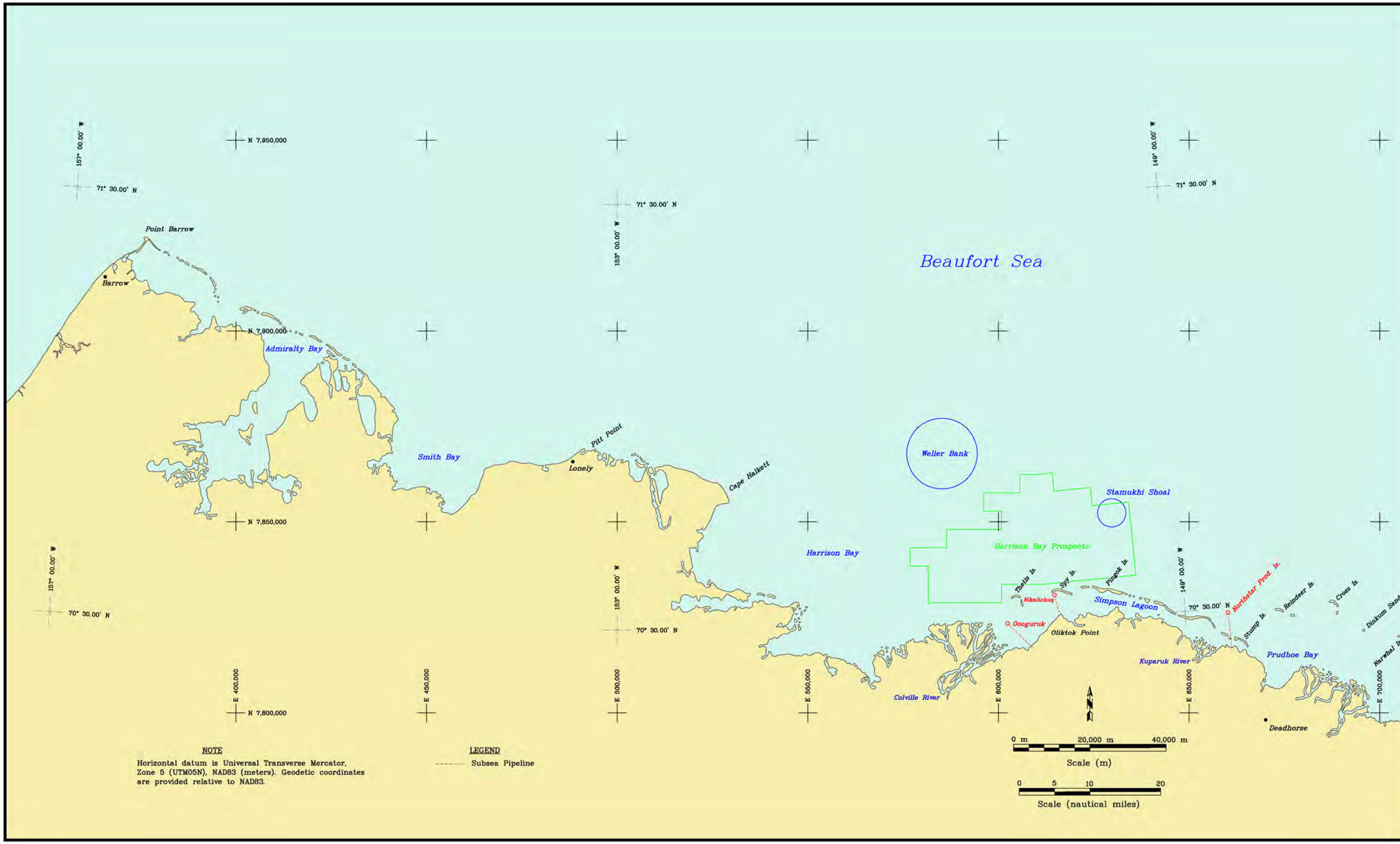


Figure 3. Geographic Points of Interest in Western Beaufort Sea

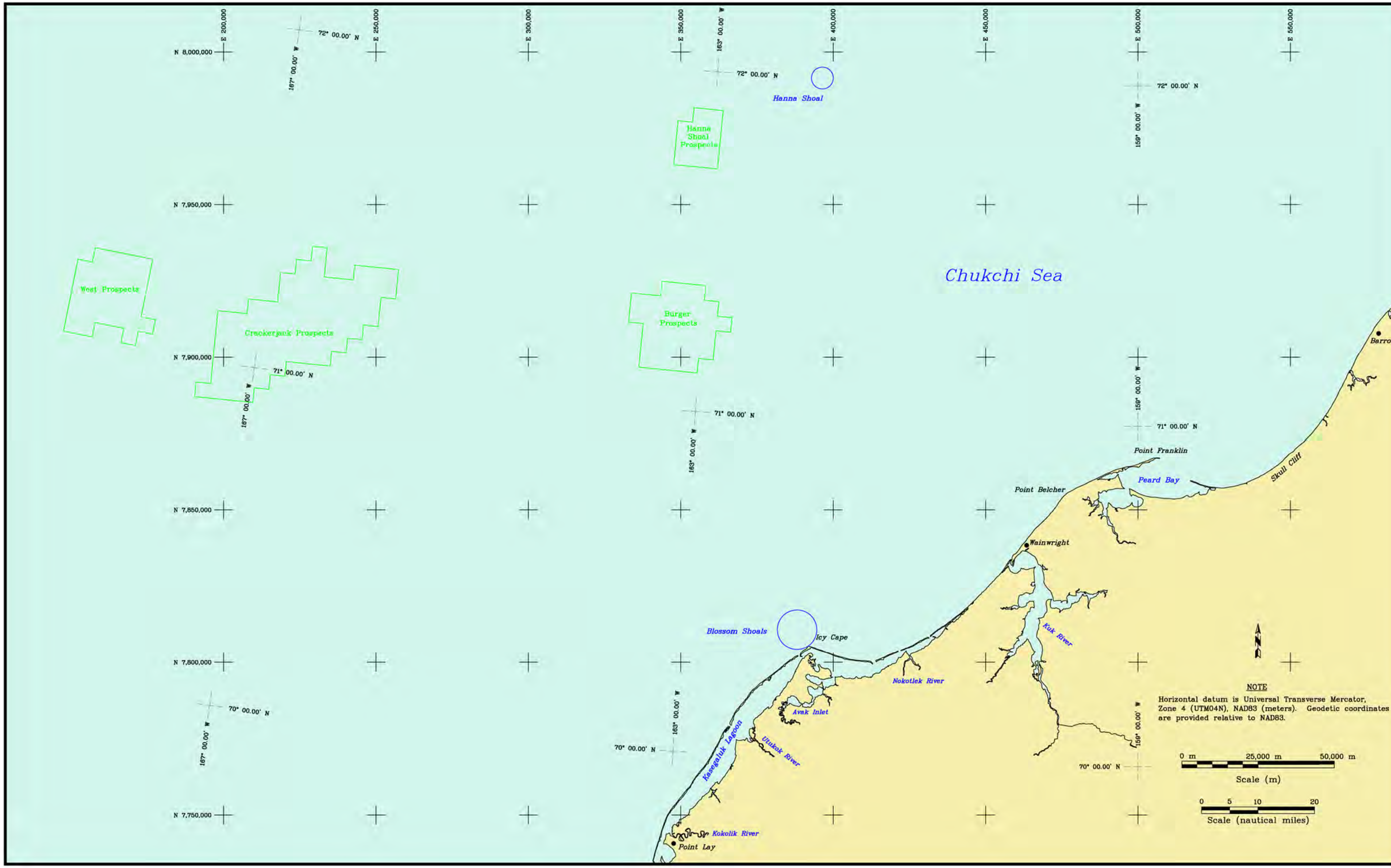


Figure 4. Geographic Points of Interest in Chukchi Sea

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). More recently, joint industry freeze-up studies were undertaken in 2009-10 and 2010-11 (Coastal Frontiers and Vaudrey, 2010; 2011). The methods and results of these eight prior studies are summarized in the subsections that follow.

2.1 1980s Freeze-Up Studies

The freeze-up studies conducted in the 1980s 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 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 reconnaissance flights continued to points east of Barter Island, sometimes 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, Barrow, and Barter Island.

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, 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, 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 of 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 well-established shear zones 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 in the Beaufort Sea. Several large rubble piles located 10 to 15 nm (19 to 28 km) northwest of Seal Exploration Island (the current location of Northstar Production Island) in water depths of 10 to 12 m were observed after a strong southwesterly in late December 1983.
- **Multi-Year Ice:** Multi-year ice was present in varying concentrations in the nearshore portion 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, when a concentration of 3- to 5-tenths occurred 2 to 3 nm (4 to 6 km) offshore of the barrier islands from Cross to Flaxman. In 1981, 1982 and 1984, multi-year ice was confined 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, storm reversals during the freeze-up season were found to cause shoreline pile-ups along the Chukchi coast, especially near Barrow and 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.

2.2 2009-10 Freeze-Up Study

The scope and methods of the 2009-2010 freeze-up study, which were adopted with only minor modifications for the 2010-11 and 2011-12 studies, are described in detail by Coastal Frontiers and Vaudrey (2010). Significant findings are as follows:

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 169°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.
- **Coastal Flaw Lead:** The distinctive flaw lead that forms off the Chukchi Sea coast opened and closed repeatedly in response to easterly (offshore) and westerly (onshore) winds. The width of the lead varied substantially, depending on the duration and intensity of the easterly winds. A maximum width of 40 to 50 nm (74 to 93 km) was noted during a 25-day period from mid-February to early March, and again during a 10-day period in late March.
- **Ice Pile-Ups:** Nineteen ice pile-ups were observed on the Chukchi Sea coast during the February reconnaissance flights, 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.

2.3 2010-11 Freeze-Up Study

Key findings of the 2010-11 freeze-up study (Coastal Frontiers and Vaudrey, 2011) are summarized below:

Beaufort Sea: 2010-11

- **Initiation of Freeze-Up:** Freeze-up in the nearshore portion of Beaufort Sea occurred during the second week in October.
- **Landfast Ice and Shear Zone Development:** 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. 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.
- **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 of the island's gravel-bag armor.
- **Multi-Year Ice:** 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. However, grounded fragments of old ice with diameters ranging from 1.0 to 5.5 m were observed on the 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.

Chukchi Sea: 2010-11

- **Initiation of 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 ice coverage in the region north of Cape Lisburne and east of the 169°W occurred during the first week in December.
- **Landfast Ice and Shear Zone Development:** 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. A 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.
- **Coastal Flaw Lead:** The coastal flaw lead 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.
- **Ice Pile-Ups:** Twenty seven ice pile-ups were observed on the Chukchi Sea coast in February 2011, representing eight more than in 2010. The piles were composed of blocks estimated to be 30 to 40 cm thick. 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.
- **Multi-Year Ice:** Large multi-year ice 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. Nevertheless, fragments of old ice embedded in first-year floes were observed in Shell's Burger Prospect in February 2011. They comprised less than 5% of the ice cover, while their maximum horizontal dimensions ranged from one hundred to several hundred meters.

3. DATA ACQUISITION AND ANALYSIS

As indicated in Section 1, the 2011-12 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 data files are provided on the CD that constitutes Appendix B.

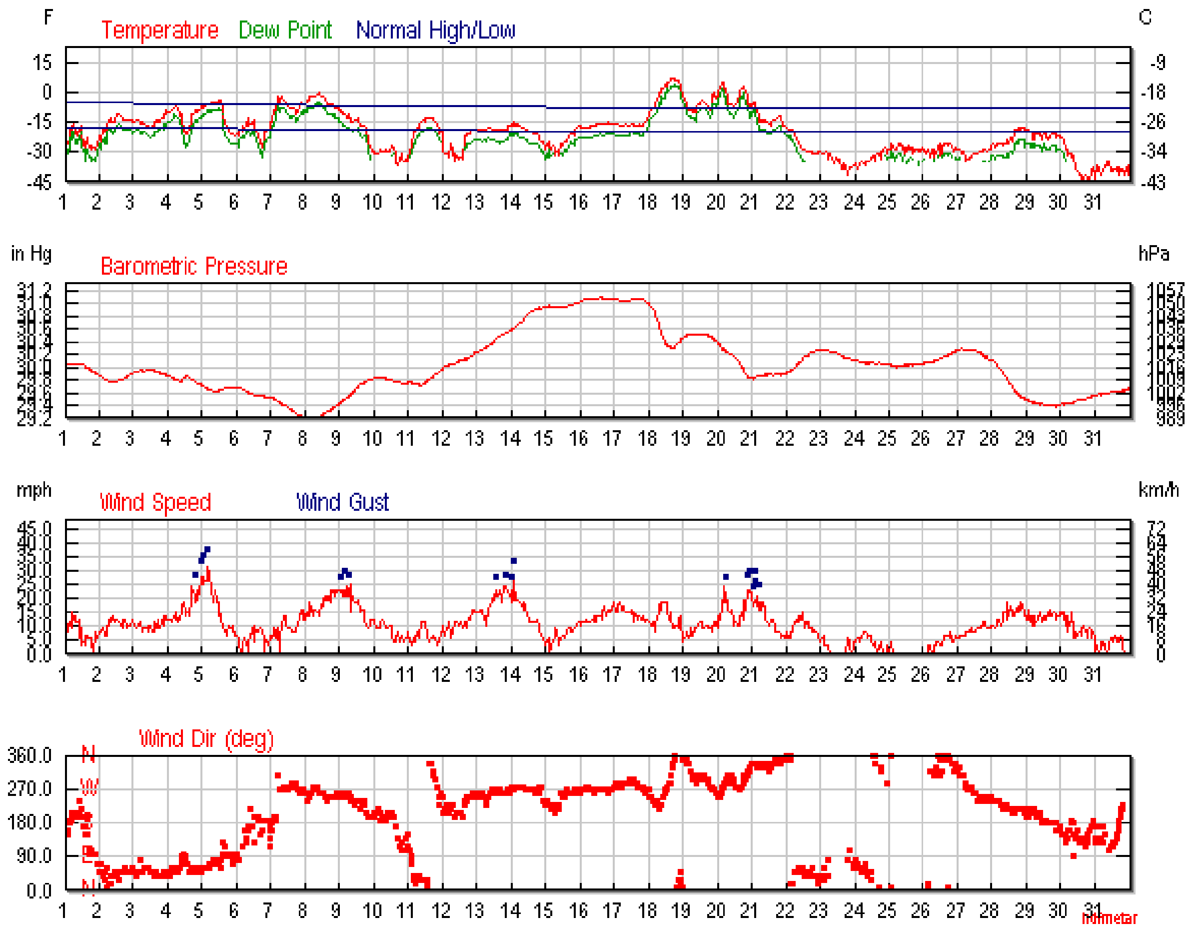
3.1 Meteorological Data

Meteorological data were obtained from two publicly-available sources: the Weather Underground (2012) and the National Ocean Service (2012). The following data were downloaded from the Weather Underground website for the Barrow and Deadhorse Airports covering the nine-month period from September 2011 through May 2012:

- Monthly tabulations of daily temperature, wind, dew point, humidity, barometric pressure, visibility, and precipitation data (compiled in an Excel spreadsheet in Appendix B);
- 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).

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 displaying the wind speeds in knots rather than miles per hour. These plots appear in the assessments of meteorological conditions 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; -2°C) 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 the Barrow and Deadhorse Airport sites are shown in Table 1.



Source: Weather Underground, 2012

Figure 5. Meteorological Data Recorded at Barrow Airport in January 2012

Table 1. Accumulated Freezing-Degree Days (<29°F) at Barrow and Deadhorse in 2011-12

Site	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Barrow	3	183	1059	2264	3814	5013	6588	7319	7556
Deadhorse	1	186	1231	2566	4253	5480	7290	8059	8275

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 Ocean Service website (2012) for the period from October 2011 through March 2012. 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”; 2012) and the National Ice Center (“NIC”; 2012). Although the charts from both organizations provide similar information, the CIS products incorporate greater detail by virtue of separate displays for ice concentration and stage of development. 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 six pairs of ice charts showing concentration and stage of development were obtained from the CIS for the period from October 3, 2011, through March 26, 2012. The charts, which were issued on a weekly basis, are provided as GIF files in Appendix B. A sample Stage-of-Development chart for October 24th, immediately prior to freeze-up in the nearshore region of the Alaskan Beaufort Sea, is included as Figure 6.

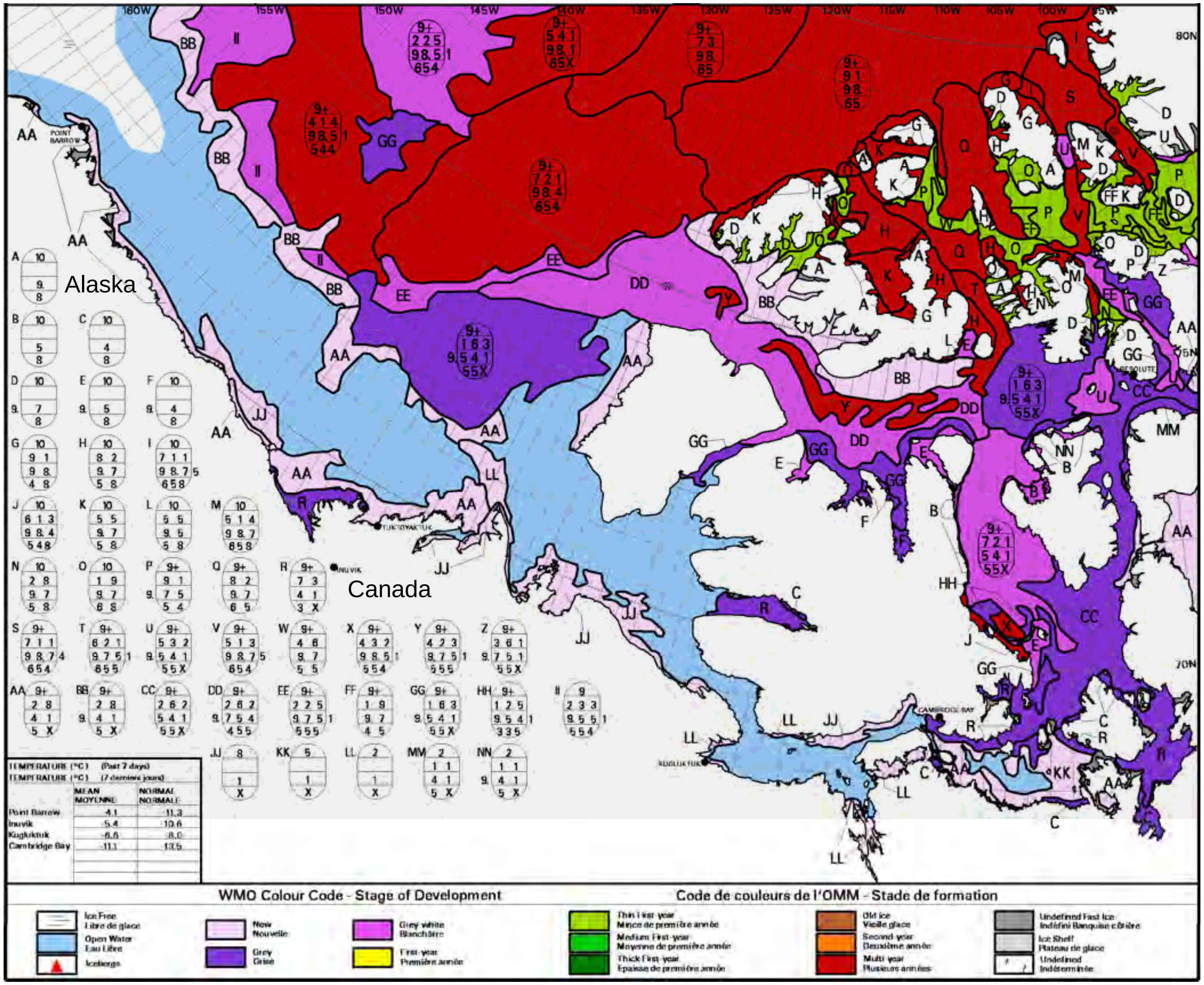
Seventy seven ice concentration charts covering the period from September 8, 2011, through March 26, 2012 were obtained from the NIC, consisting of thirty six Beaufort Sea charts and forty one Chukchi Sea charts. The charts typically were issued twice per week prior to the occurrence of complete ice cover in each basin, and once per week thereafter. A representative example that displays the Chukchi Sea on November 17th, when freeze-up was approaching in the nearshore region, 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

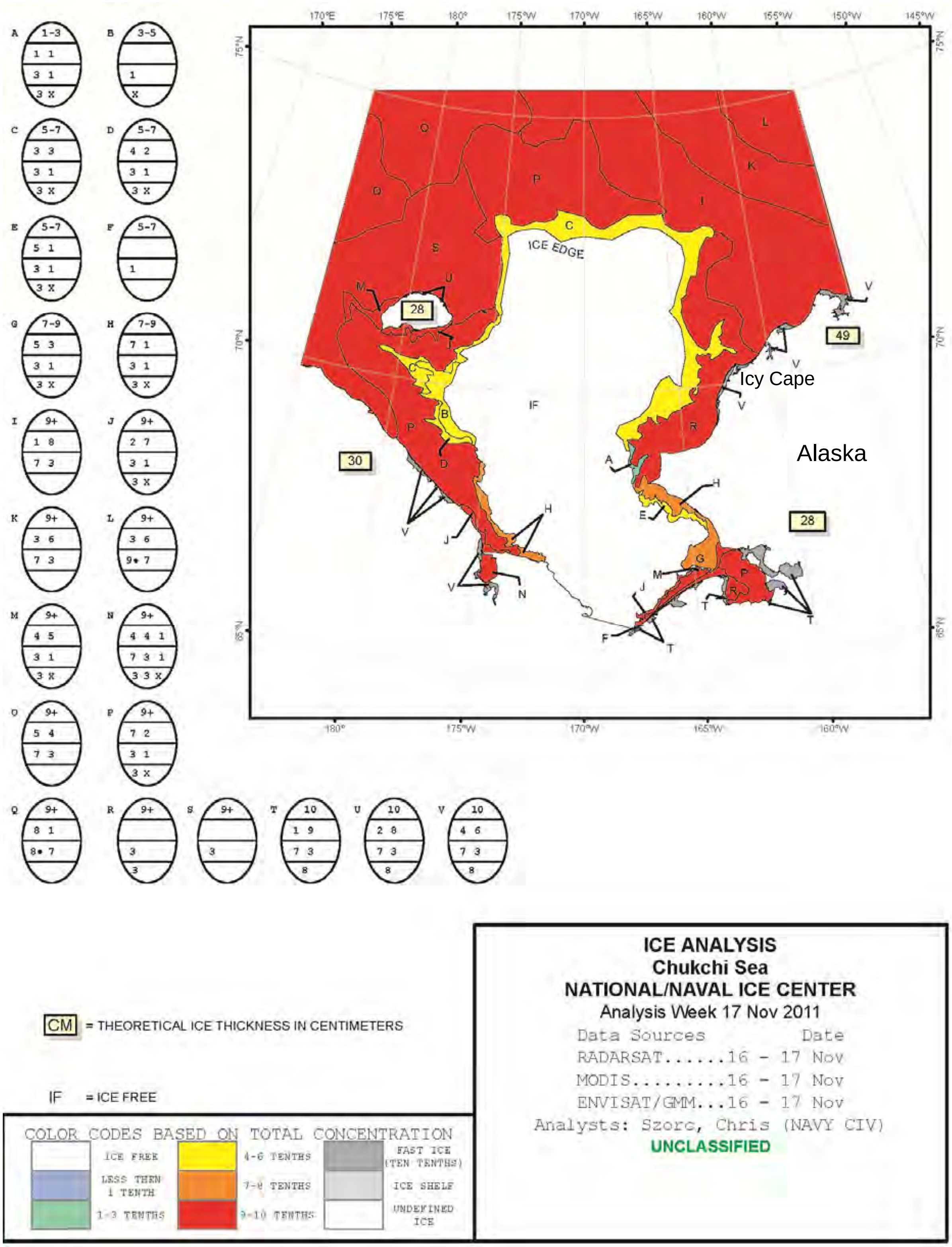
Three different types of satellite imagery were used to study the ice conditions that prevailed during the 2011-12 freeze-up season: RADARSAT-2, AVHRR (Advanced Very High Resolution Radiometer), and MODIS (Moderate Resolution Imaging Spectro-radiometer). The RADARSAT imagery served as the primary source of ice data, while the AVHRR and MODIS imagery played supplemental roles.

General information about the progress of freeze-up was obtained from twenty nine publicly-available RADARSAT mosaics compiled by the CIS (2012) for the period from



After: Canadian Ice Service, 2012

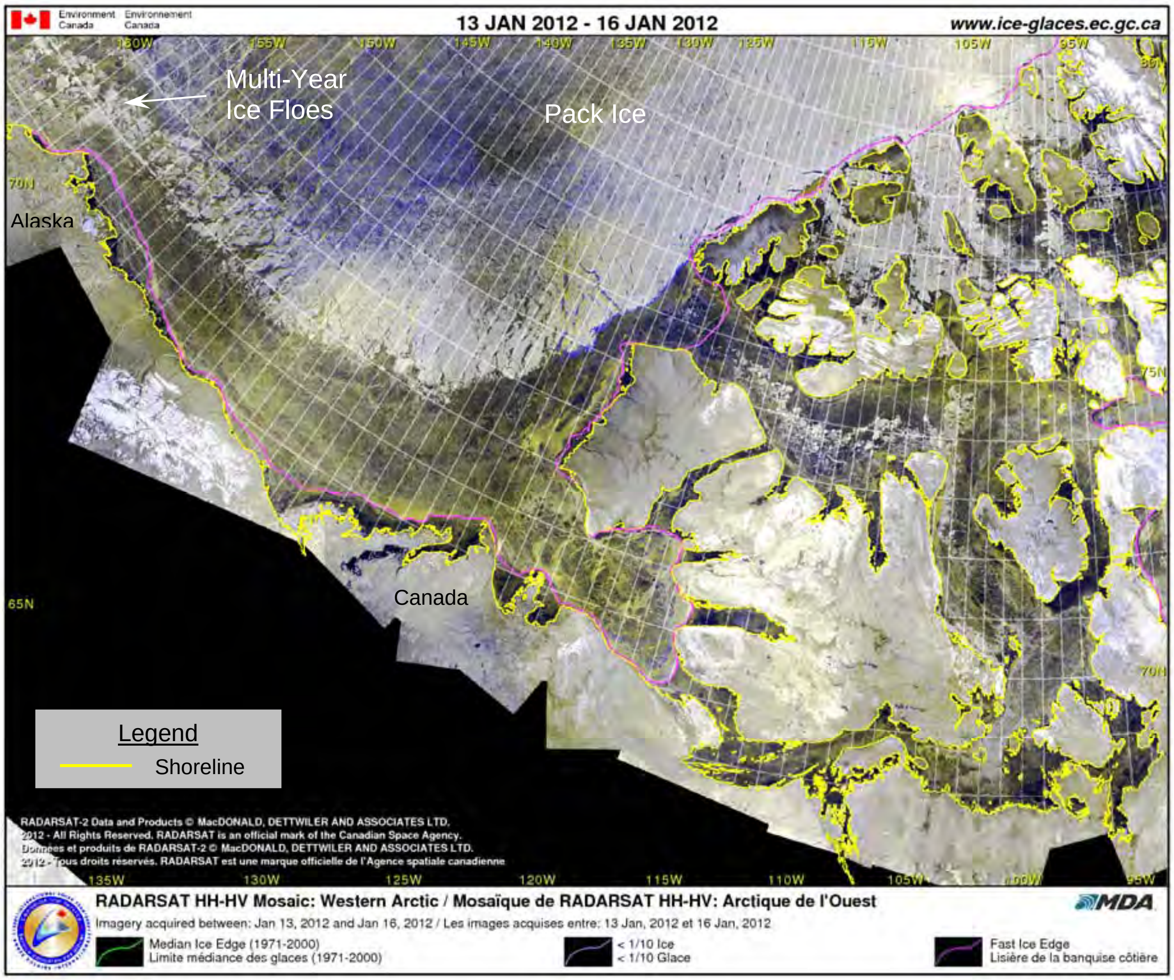
Figure 6. CIS Ice Chart of Beaufort Sea for October 24, 2011



After: National Ice Center, 2012

Figure 7. NIC Ice Chart of Chukchi Sea for November 17, 2011

September 12, 2011 through March 26, 2012. The mosaics, which were produced on a weekly basis, 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 shows a band of multi-year ice floes entering the Chukchi Sea in mid-January 2012 is provided in Figure 8.



After: Canadian Ice Service, 2012

Figure 8. CIS RADARSAT Image of Beaufort Sea for January 13-16, 2012

The most useful RADARSAT-2 images were provided by Shell, which supplied nineteen high-resolution, geo-referenced scenes of the Beaufort and seventeen of the Chukchi. The former were acquired between October 4, 2011, and March 14, 2012 while the latter were acquired between October 17th and March 15th. Most images were 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., 2012). These characteristics were sufficient not only to track the general evolution of the ice cover 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, leads, 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. Figure 9 provides a sample image of the northeast Chukchi Sea acquired on January 17th, immediately after the period covered by the CIS mosaic shown in Figure 8. A comparison of the two figures clearly illustrates the higher resolution of the ScanSAR Wide images.

Ninety five AVHRR images obtained between November 9, 2011 and March 28, 2012 were downloaded from the National Weather Service Alaska Region Headquarters (2012) to bridge the chronological gaps between RADARSAT scenes. The images are provided as JPG files in Appendix B. A representative scene in Figure 10 shows the landfast ice edge in the Beaufort along with an extensive flaw lead in the Chukchi on December 31, 2011.

The utility of the AVHRR imagery was limited by the sensor's 1-km resolution and inability to penetrate cloud cover. Notwithstanding these drawbacks, the high frequency of image capture (multiple scenes per day subject to suitable weather conditions) allowed large-scale changes in the ice canopy to be tracked on a short-term basis. The imagery was particularly useful in identifying periods when the coastal flaw lead opened in the Chukchi.

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 above 72°N. As a result, useful scenes were confined to two periods: (1) prior to the onset of darkness (October 11th to November 3rd) and (2) following the return of daylight (February 7th to March 28th). The thirty nine images that were downloaded from the MODIS Rapid Response website (NASA, 2012) are provided as JPG and TIF files in Appendix B. Figure 11 presents an image acquired on October 30th that shows newly-formed ice moving away from the coast in response to southwesterly winds.

3.4 Iridium Telemetry Buoys

On January 27, 2012, Shell installed seven Iridium telemetry buoys in the Beaufort Sea to document ice movement. Four of these buoys were located on the west side of Camden Bay, while three were located on the east side of Harrison Bay. The buoy positions were transmitted hourly via satellite and compiled on a proprietary website. Shell contributed the

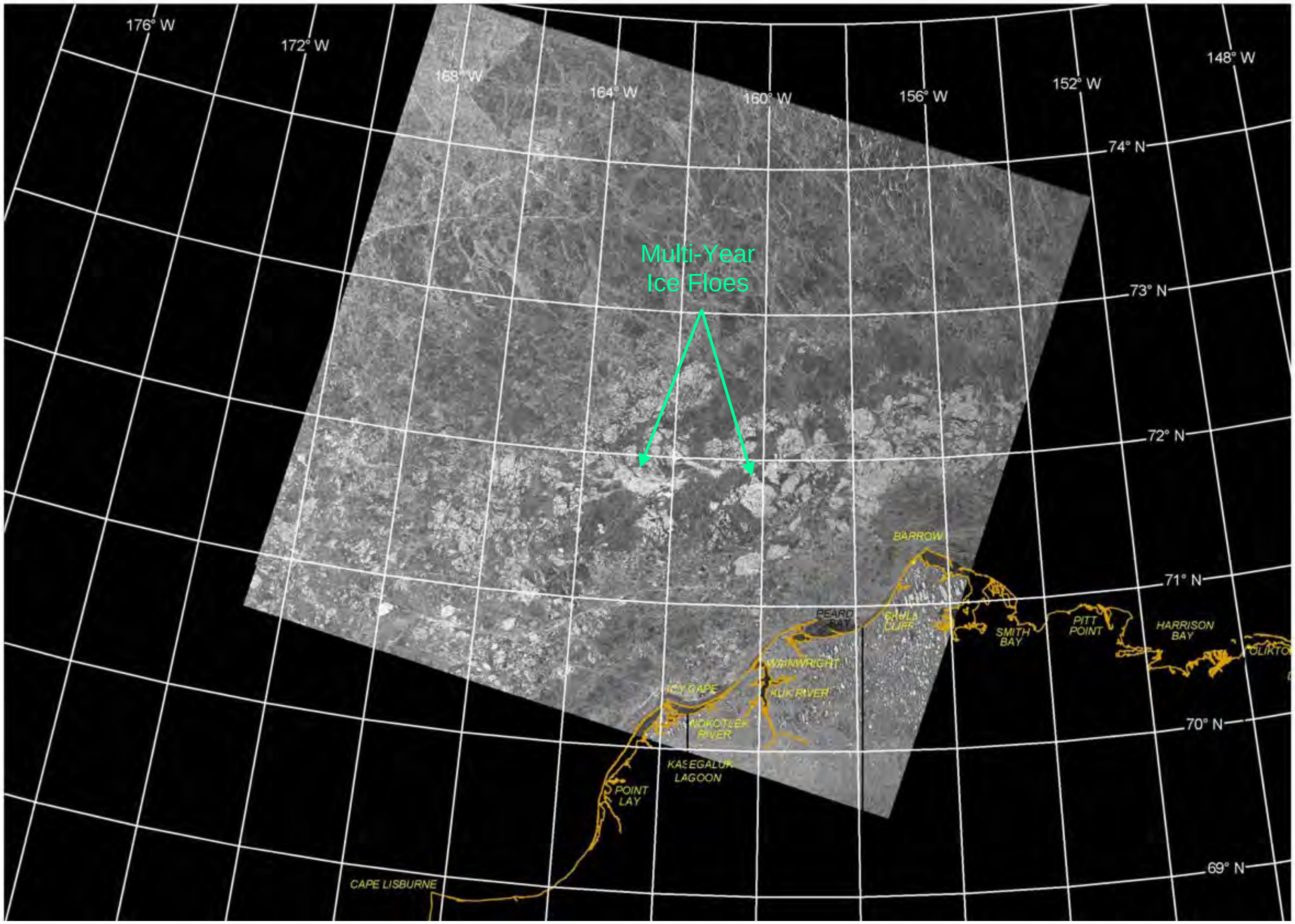
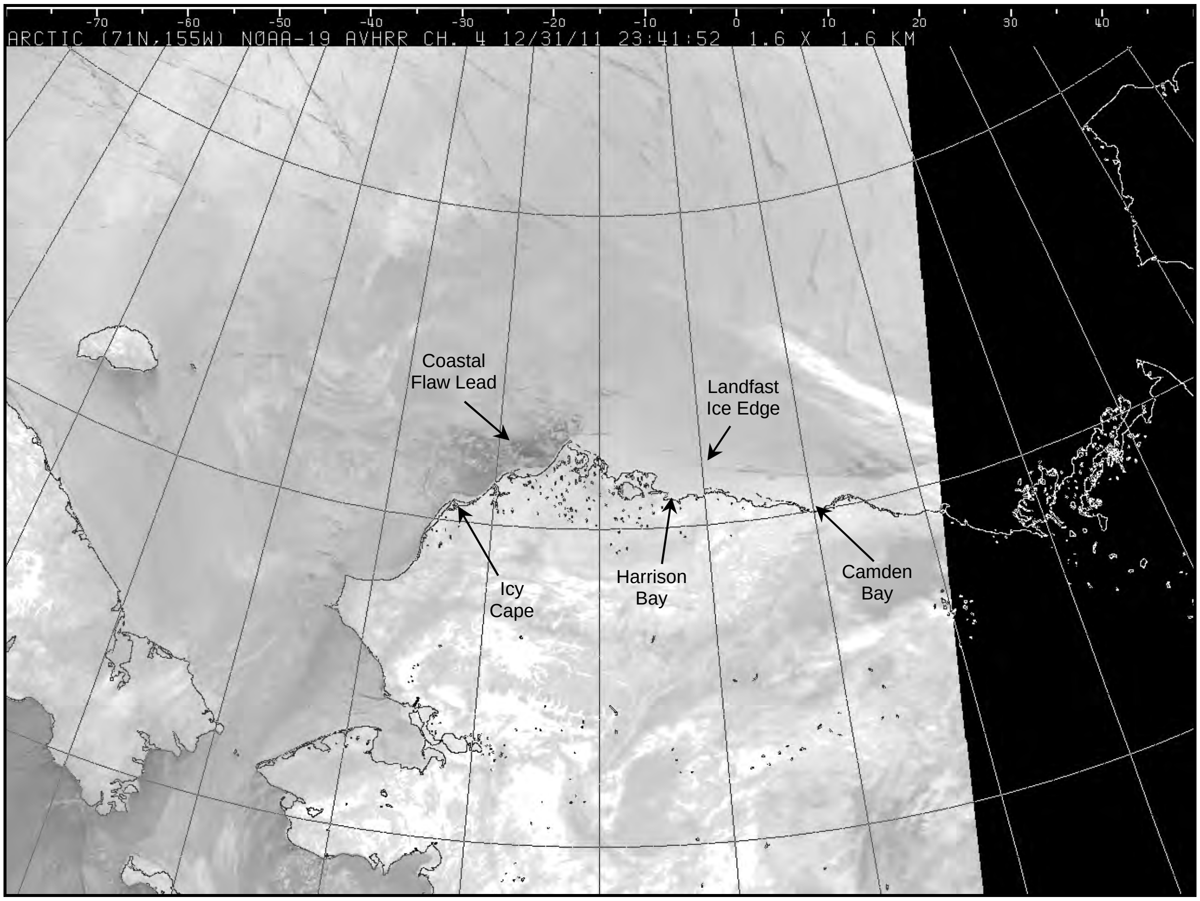
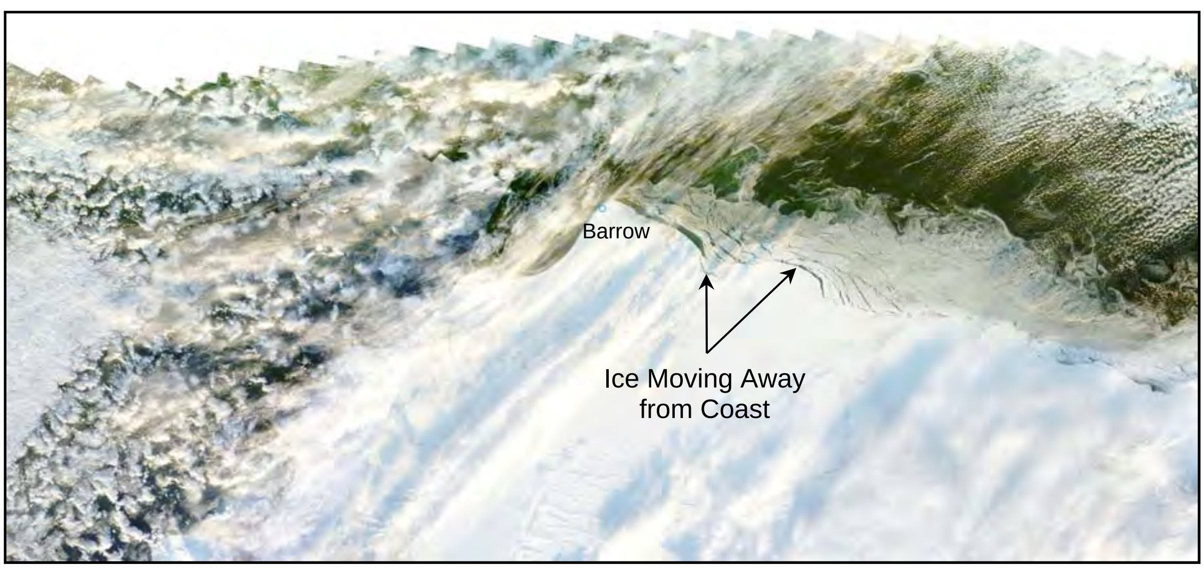


Figure 9. RADARSAT-2 Image of Chukchi Sea Acquired on January 17, 2012



Source: National Weather Service, 2012

Figure 10. AVHRR Image of Beaufort and Chukchi Seas Acquired on December 31, 2011



Source: NASA, 2012

Figure 11. MODIS Image of Beaufort and Chukchi Seas Acquired on October 30, 2011

data to this project in the interest of developing a more complete understanding of ice dynamics during the early-winter period (Hansen, 2010).

As shown in Figure 12, all three buoys in Harrison Bay and the southernmost buoy in Camden Bay remained essentially stationary from the time of deployment in January through the end of March. The three offshore buoys in Camden Bay followed coast-parallel trajectories, but the displacements were substantially smaller than those recorded by similar buoys in each of the past two years (Coastal Frontiers and Vaudrey, 2010; 2011).

The hourly position data for the seven Iridium buoys are tabulated in an Excel spreadsheet that appears in Appendix B. The information proved to be extremely useful in defining the boundary between stationary landfast ice and mobile pack ice, and also aided in correlating ice movement (or the lack thereof) with wind events.

Source: Joubeh Technologies, 2012; © Joubeh Technologies, 2008 – All Rights Reserved

Figure 12. Iridium Buoy Trajectories, January 27 - March 31, 2012

3.5 Aerial Reconnaissance Missions

Two aerial reconnaissance missions were conducted in late November 2011 followed by five in early February 2012 to supplement the remotely-sensed data obtained from other sources. The November flights were used to document the conditions that prevailed early in the freeze-up season, while the February flights were used to document the conditions at the end of the freeze-up season. 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 multi-year ice floes, leads and well-developed shear lines;
- Detect, investigate, and document small-scale ice features and processes 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.

Both of the missions in November and four of the five in February were conducted using a de Havilland Twin Otter (Plate 1). 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 in February was conducted using a Bell 412 helicopter (Plate 2), which provided invaluable opportunities to hover over and, if warranted, land at features of interest. The primary disadvantages of the helicopter were its limited range and high cost per flight hour.

Each flight path was mapped using a Garmin GPSMap 196. 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 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 flight paths in November are shown in Drawings CFC-863-01-001 and -002, while those in February are shown in Drawings CFC-863-02-001, -002, and -003 (Appendix A). The drawings display the locations of ice features observed during the flights as well as those of photographs and videos taken during the flights. In the case of the November flights, each photo has been assigned a unique identification number such as "B-35" and each video a unique identification number such as "C-V16". The first letter, "B" or "C", indicates whether the flight was conducted in the Beaufort or Chukchi; the number that follows indicates the order in which the photo or video was obtained during that flight. Hence, C-V16 designates the 16th video acquired during the sole Chukchi Sea reconnaissance flight conducted in November. The identification numbers for the February flights follow a similar format, except that a number has been added after "B" or "C" to

Plate 1. de Havilland Twin Otter at Barrow

Plate 2. Bell 412 Helicopter on Narwhal Island

indicate which flight was involved. For example, "B2-17" designates the 17th photograph acquired during the second Beaufort Sea reconnaissance flight conducted in February.

The photographs are provided in digital form in Appendix B, with the file names corresponding to the identification numbers shown on the drawings. 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
Crack	CRK
First-Year Ice	FY
Grounded Ice Feature (height, m)	GIF (_m)
Inactive Shear Line	ISL
Landfast Ice	LFI
Lead	LD
Multi-Year Ice (concentration)	MY (_%)
Nilas	NLS
Open Water	OW
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
Young Ice	YNG

Note: The prefixes "i" and "m" are used to indicate intermittent features and multiple features, respectively (*i.e.*, "iRBL" indicates intermittent rubble).

The objective and path of each flight are summarized below:

November 2011 Beaufort Sea Flight (Drawing CFC-863-01-001)

The first reconnaissance flight was undertaken with the Twin Otter on November 28th to observe the ice conditions in the central portion of the Alaskan Beaufort Sea early in the freeze-up season. The itinerary was as follows:

- Deadhorse Airport
- Barrier islands from Cross to Flaxman (heading east)
- Sivulliq Development prospective pipeline route
- Barrier islands from Alaska to Spy (heading west)
- Spy Island Drillsite
- Shell's Harrison Bay Prospects
- Harrison Bay
- Transit west in darkness
- Barrow Airport
- Flight time = 3.2 hr

November 2011 Chukchi Sea Flight (Drawing CFC-863-01-002)

A reconnaissance flight was undertaken with the Twin Otter on November 30th to observe the ice conditions in the northeast Chukchi Sea between the coast and Shell's Crackerjack Prospects. The flight path was as follows:

- Barrow Airport
- Transit west
- Shell's Burger Prospects
- Transit west
- Shell's Crackerjack Prospects
- Transit east
- Icy Cape
- Shoreline from Icy Cape to Point Franklin
- Barrow Airport
- Flight time = 3.7 hr

February 2011 Beaufort Sea Flight No. 1 ("B1" on Drawing CFC-863-02-001)

The first reconnaissance flight in February was undertaken with the Twin Otter on the 3rd to observe the ice conditions in the central Beaufort Sea at the end of the freeze-up season. The route is outlined below:

- Deadhorse Airport
- Prudhoe Bay West Dock Causeway
- Northstar Production Island
- Barrier islands from Long to Spy (heading west)
- Spy Island Drillsite
- Shell's Harrison Bay Prospects
- Stamukhi Shoal
- Transit east at distances of 15-25 nm (28-46 km) offshore)
- Shell's Camden Bay Prospects
- Transit east across northern Camden Bay
- Barter Island
- Transit west across Camden Bay
- Sivulliq Development prospective pipeline route
- Barrier islands from Alaska to Cross (heading west)
- Deadhorse Airport
- Flight time = 3.3 hr

February 2011 Beaufort Sea Flight No. 2 ("B2" on Drawing CFC-863-02-001)

The reconnaissance flight on February 4th, the sole helicopter mission, was undertaken to investigate features of interest noted during the prior Twin Otter flights in the Central Beaufort. The itinerary was as follows:

- Deadhorse Airport
- Barrier islands from Cross to Narwhal (heading east)
- Land at Narwhal Island to measure ice pile-up characteristics
- Barrier islands from Narwhal to Alaska (heading east)
- Sivulliq Development prospective pipeline route
- Mainland coast from Point Thomson to Bullen Point (heading west)
- Land on ice in Mikkelsen Bay to measure ice thickness
- Transit west in Stefansson Sound
- Endicott Project
- Deadhorse Airport
- Flight time = 2.3 hr

February 2011 Beaufort Sea Flight No. 3 ("B3" on Drawing CFC-863-02-002)

A reconnaissance flight was undertaken with the Twin Otter on February 5th to observe the ice conditions in the western Beaufort Sea. The flight proceeded in the manner outlined below:

- Deadhorse Airport
- Oooguruk flowline route and Offshore Drillsite
- Shell's Harrison Bay Prospects
- Weller Bank
- Transit west at distances of 15-35 nm (28-65 km) offshore
- Barrow Airport
- Flight time = 2.1 hr

February 2011 Chukchi Sea Flight No. 1 ("C1" on Drawing CFC-863-02-003)

A reconnaissance flight was undertaken with the Twin Otter on February 6th 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. The flight described the following path:

- Barrow Airport
- Coast from Barrow to Point Lay
- Transit north until 45 nm (83 km) off Point Lay
- Transit northeast over band of multi-year ice
- Barrow Airport
- Flight time = 3.1 hr

February 2011 Chukchi Sea Flight No. 2 ("C2" on Drawing CFC-863-02-003)

The final reconnaissance flight was undertaken with the Twin Otter on February 7th to observe the ice conditions in the offshore portion of the northeast Chukchi Sea. Primary emphasis was placed on visiting Hanna Shoal and four Shell prospects: Burger, Crackerjack, Hanna Shoal (which lies approximately 25 nm or 46 km to the southwest of Hanna Shoal itself; Figure 4), and West. This wide-ranging flight proceeded as follows:

- Barrow Airport
- Transit northwest over multi-year ice
- Hanna Shoal
- Transit southwest
- Shell's Hanna Shoal Prospects
- Transit west
- Northern portion of Shell's Crackerjack Prospects
- Transit west
- Shell's West Prospects
- Transit southeast

- Shell's Crackerjack Prospects
- Transit east
- Shell's Burger Prospects
- Transit east
- Barrow Airport
- Flight time = 4.2 hr

As in the case of the prior two freeze-up studies (Coastal Frontiers and Vaudrey, 2010; 2011), the reconnaissance flights conducted in support of the 2011-12 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. Specific operational lessons learned in 2011-12 are as follows:

1. The addition of reconnaissance flights in late November represented a significant enhancement to the scope of work. The flights not only provided insight into phenomena that occurred early in the freeze-up season, when the ice cover was mobile, but also fostered a realistic understanding of the conditions that might be encountered when responding to a drilling incident that occurred late in the open-water season.

2. Notwithstanding its crucial importance in acquiring synoptic-scale data in a cost-effective manner, remote sensing alone cannot be relied upon to provide all of the information needed for the design and operation of Arctic offshore structures. On-site observations, when used to complement remotely-sensed data, can aid in identifying local ice features and processes that otherwise might escape detection.

The importance of on-site observations was demonstrated during the February reconnaissance flights when two large grounded ice features were discovered off the Chukchi Sea coast. The larger of the two, estimated to be 80 m long, 40 m wide, and 20 m above sea level, was undetectable on the 100-m resolution ScanSAR Wide RADARSAT-2 images available to this study, and identifiable on a 2-m resolution RADARSAT-2 image only when the location mapped during the February reconnaissance flight was used to guide the search. A more complete discussion of the grounded ice features is provided in Section 5.6.9.

4. BEAUFORT SEA FREEZE-UP

Section 4.1 provides an overview of the 2011-12 freeze-up season in the Alaskan Beaufort Sea. Sections 4.2 through 4.7 then present a month-by-month analysis of the conditions that prevailed from October 2011 through March 2012.

4.1 Overview

Air Temperatures: In October and early November, the air temperatures at Deadhorse Airport tended to range from normal to above-normal. Colder-than-normal temperatures predominated thereafter, particularly during the second half of November, the second half of December, and the months of January and March.

Winds: Wind conditions during the 2011-12 freeze-up season are summarized in Table 3, which is based on the average daily speeds and directions recorded at Deadhorse Airport. Westerlies outnumbered easterlies by a ratio of three to two (60% vs. 40%). The average monthly speeds ranged from a maximum of 12 kt (6 m/s) in January to a minimum of 9 kt (5 m/s) in February and March.

Table 3. Beaufort Sea Wind Characteristics, October 2011 – March 2012

Month	Days		Average Speed (kt)
	Easterly	Westerly	
October	23	8	11
November	7	23	11
December	15	16	10
January	3	28	12
February	19	10	9
March	7	24	9
Total Days	74	109	n/a
Frequency (%)	40	60	n/a

Note: Table 3 is based on the average daily wind speeds and directions recorded at Deadhorse Airport.

Storms: The characteristics of all 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 2011 through March 2012. Of the fourteen events, eight were easterlies while six were westerlies. November and January were the stormiest months, with ten and eleven days of storm activity, respectively. February and March were relatively storm-free, with only one day of storm activity in the former and two in the latter, and with maximum sustained wind speeds less than or equal to 20 kt (10 m/s).

Table 4. Beaufort Sea Storm Characteristics, October 2011 – March 2012

Month	Day	Duration (days)	Maximum Wind Speed (kt)[2]	
			Easterly	Westerly
October	14-16	3	24	
	25-26	2	30	
November	Oct 31-Nov 2	3		18
	9-12[3]	4	18	
	14-15	2		19
	19	1		16
December	4	1	25	
	11-13	3	23	
	18	1	20	
January	7-9	3		19
	13-20[4,5]	8		23
February	14	1	16	
March	11	1		20
	24	1	16	
Total Duration		**34**		
Total Number of Events			**8**	**6**

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 13 kt on November 11 but freshened to 18 kt on November 12.

4 Daily average wind speed decreased to 10 kt on January 15 but freshened to 20 kt on January 16.

5 Daily average wind speed decreased to 12 kt on January 19 but freshened to 18 kt on January 20.

Ice Cover: Freeze-up began during the second week in October, when ice began forming adjacent to the coast. Complete ice coverage in the nearshore region occurred on October 26th, followed by complete coverage throughout the Alaskan Beaufort Sea on November 1st.

Ice Thickness: The thickness of undeformed first-year ice at the end of each month was estimated using the relationship of Lebedev (Bilello, 1960) in concert with the accumulated freezing degree days (FDD) at Deadhorse shown in Table 1. The relationship is as follows:

$$t = 0.94(\Sigma FDD)^{0.58} \tag{1}$$

where:

t	=	ice thickness in cm
ΣFDD	=	accumulated freezing-degree days relative to 29°F

(Although Lebedev originally calculated FDD relative to 32°F, ice thickness measurements in the Beaufort Sea obtained by Vaudrey indicated that Equation (1) would provide more accurate results if FDD were derived relative to 29°F.)

The computed values of ice thickness for the 2011-12 winter season are provided in Table 5, which indicates that undisturbed first-year ice attained a thickness of approximately 176 cm at the end of May.

Landfast Ice: The extent of the landfast ice zone varied according to the wind conditions, with expansion tending to occur during periods of easterly predominance and contraction during periods of westerly predominance. After a slow start in November, a month dominated by westerly winds, the landfast ice zone grew dramatically in December in response to three easterly storms. At the beginning of January, the zone extended past the 18-m isobath and exceeded 20 nm (37 km) in width over the entire region between Point Barrow and Barter Island. The return of westerly winds coupled with two westerly storms caused the landfast ice edge to retreat as the month progressed, but the ice remained firmly anchored on Weller Bank and Stamukhi Shoal. In February, easterly winds and an easterly storm triggered another period of expansion, particularly to the east of Prudhoe Bay. Contraction followed during the first half of March, with the greatest retreat (to the 11-m contour) occurring between Prudhoe Bay and Flaxman Island.

Ice Pile-Ups: As shown in Table 6, ten ice pile-ups occurred in central portion of the Alaskan Beaufort Sea during the 2011-12 freeze-up season. Nine were located on natural

Table 5. Beaufort Sea Computed Ice Thicknesses, October 2011 – May 2012[1]

Date	FDDs	Accumulated FDD	Ice Thickness[2] (cm)
31 October 2011	185	186	19
30 November 2011	1,045	1,231	58
31 December 2011	1,335	2,566	89
31 January 2012	1,687	4,253	120
29 February 2012	1,227	5,480	139
31 March 2012	1,810	7,290	163
30 April 2012	769	8,059	173
31 May 2012	216	8275	176

Notes:
1 Table 5 is based on the average daily temperature data recorded at Deadhorse Airport.
2 Ice thickness is computed from accumulated FDD using method of Lebedev (Bilelo, 1960).

Table 6. Ice Pile-Ups on Beaufort Sea Coast during 2011-12 Freeze-Up Season

No.	Location	Formation Date	Ice Block Thickness (cm)	Length[1] (m)	Height[2] (m)	Encroachment[3] (m)
1	No Name Is.	10/30/11	20	500	2	10
2	Narwhal Is.	10/30/11	20	300	4	5
3	Narwhal Is.	10/30/11	20	200	4	0
4	Narwhal Is.	10/30/11	20	200	3	3
5	Jeanette Is.	10/30/11	20	300	5	10
6	Karluk Is.	10/30/11	20	300	2	0
7	Narwhal Is.	11/13/11	30	1,200	7.6	20
8	Pole Is.	11/13/11	30	1,200	6	0
9	Pole Is.	11/13/11	30	1,100	8	20
10	Northstar Prod.	11/13/11	30	200	4	5

Notes:
1 "Length" indicates alongshore extent of pile-up.
2 "Height" indicates maximum height of pile-up relative to MSL.
3 "Encroachment" indicates distance ice advanced onto subaerial beach.

barrier islands and one on Northstar Production Island. The heights ranged from 2 to 7.6 m, the encroachment distances from 0 to 20 m (measured from the waterline), the alongshore lengths from 200 to 1,200 m, and the ice block thicknesses from 20 to 30 cm. It is likely that six of the pile-ups formed on October 30th, when the wind shifted from northeasterly to southwesterly. The other four were created on November 13th, when the wind shifted to the west following an easterly storm.

Multi-Year Ice: Patches of multi-year ice began entering the Alaskan Beaufort Sea from the Canadian Beaufort at the beginning of October. By the end of November, the ice had coalesced into a distinct band that extended from the vicinity of the 72°N parallel to the vicinity of the 73°N parallel. The band remained well offshore in the months that followed, with one exception: starting in mid-December and continuing through March, it turned to the southwest at the transition between the Beaufort and Chukchi, typically passing within 30 nm (56 km) of Point Barrow.

Ice Movement: The movements of eight multi-year ice floes were tracked using RADARSAT-2 images. In keeping with the westerly set of the Beaufort Gyre, all of the floes experienced net displacements to the west during freeze-up and early winter. This pattern was temporarily interrupted in January, however, when westerly winds pushed the floes toward the southeast. As shown in Table 7, the average floe speeds recorded during each month from November through February ranged from 1.6 to 6.5 nm/day (3.0 to 12.0 km/day). The average monthly value was 4.1 nm/day (7.6 km/day).

Table 7. Beaufort Sea Multi-Year Ice Floe Speeds, November 2011 - February 2012

Month	Monthly Speed (nm/day)[1]		
	Maximum	Minimum	Average[2]
November	6.4	5.4	6.0
December	8.3	4.9	6.5
January	1.7	1.6	1.6
February	3.1	2.0	2.4
Average			4.1

Notes:

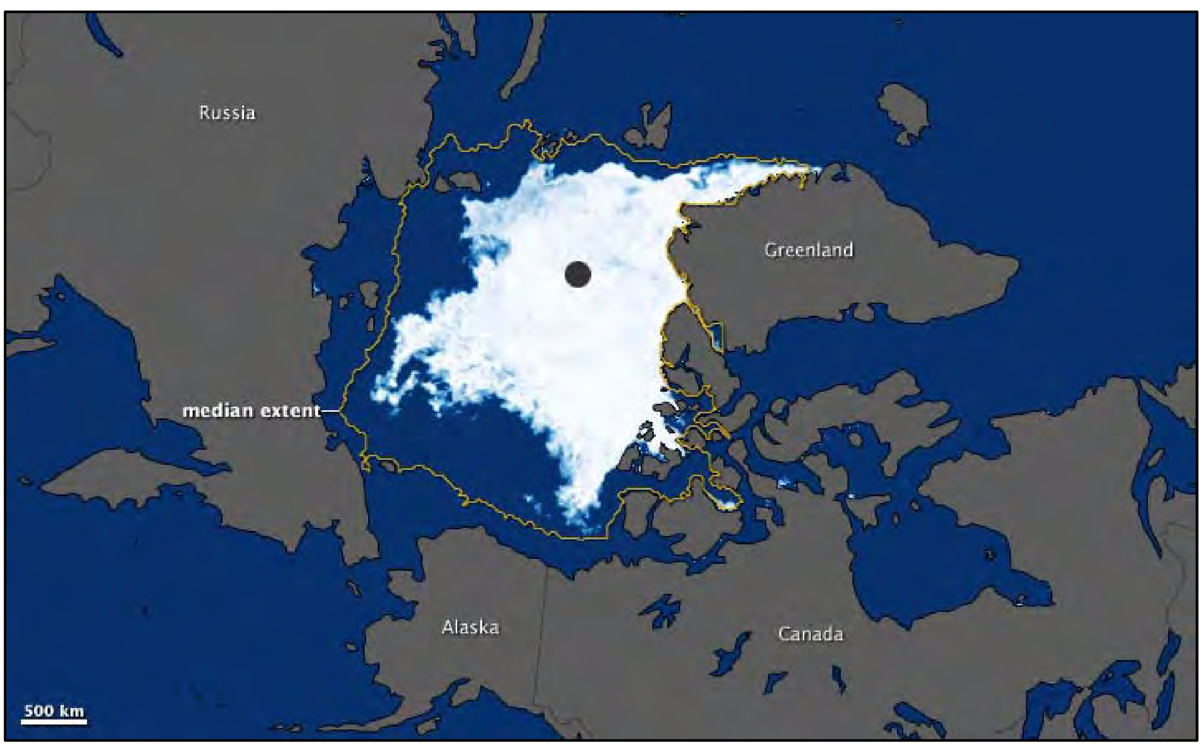
1 Monthly speeds are derived from periods ranging from 12 to 34 days (depending on data availability).

2 Average monthly speeds are derived from a minimum of 3 to a maximum of 7 floes.

4.2 Late Summer 2011

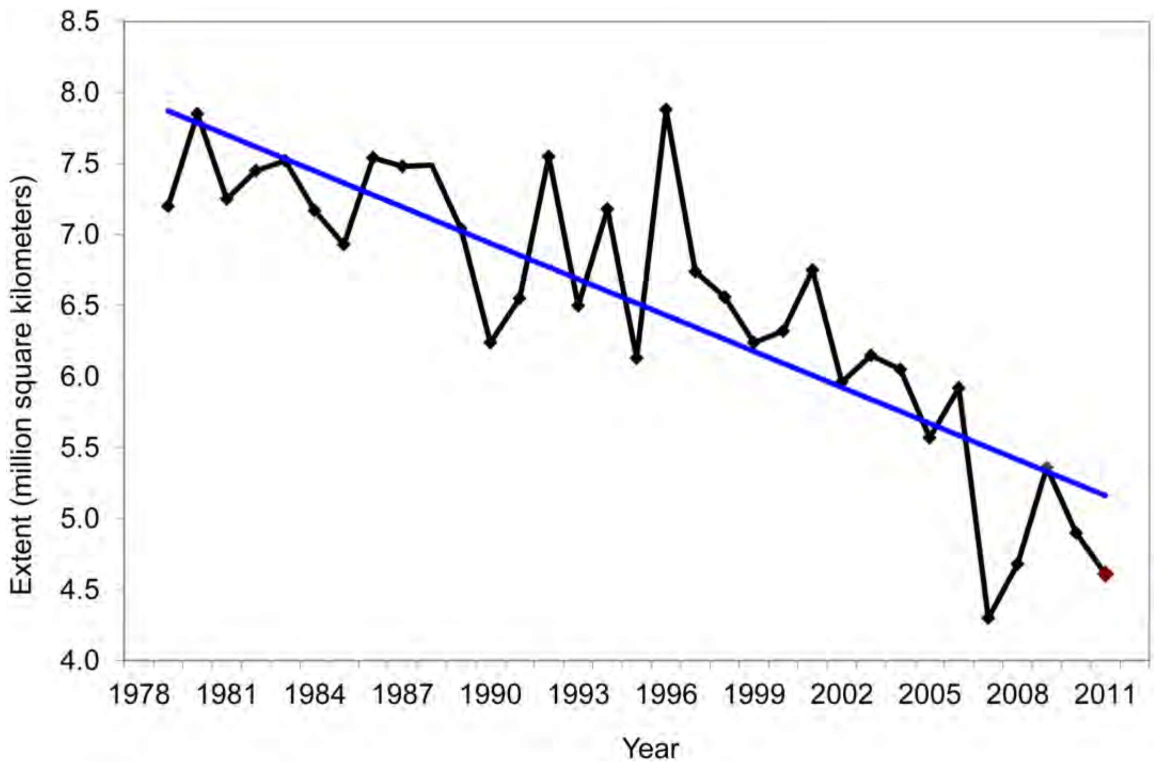
The ice cover in the Alaskan Beaufort Sea diminished throughout August and early September, due in part to melting in the nearshore zone and in part to the northward migration of the pack ice. According to the NIC ice chart for September 8th, the edge of the pack ice (where the ice concentration exceeded 0%) was located approximately 120 nm (222 km) off Barter Island and 225 nm (417 km) off Point Barrow (NIC, 2012). Unlike 2010, when a band of grounded ice persisted through freeze-up between Flaxman Island and Smith Bay, the last vestiges of nearshore ice disappeared from the Alaskan Beaufort in mid-August of 2011.

The minimum extent of the Arctic pack ice occurred on September 9th, ten days earlier than in 2010 and three days earlier than in 2009 (Figure 13; NASA, 2011). "Extent" refers to the area in which ice covers at least 15% of the ocean surface. The average extent in September 2011, 4.61 km^2, was the second lowest since record-keeping began in 1979 and only slightly larger than the all-time low of 4.30 million km^2 in 2007 (National Snow and Ice Data Center, 2011). As shown in Figure 14, the extent of the Arctic sea ice in September has declined at an average rate of 84,700 km^2/yr since 1979 (12% per decade relative to the 1979-2000 average).



Source: NASA, 2011

Figure 13. Sea Ice Minimum Extent on September 9, 2011



Source: National Snow and Ice Data Center, 2011

Figure 14. Average Sea Ice Extent in September, 1979-2011

Figure 13 illustrates the substantial disparity that existed between the minimum ice extent on September 9, 2011 and the median minimum extent for the period from 1979 through 2000. As in 2010, the shortfall was particularly large off the coasts of Alaska and eastern Siberia. At Point Barrow, for example, the line delineating ice concentrations greater than or equal to 15% lay more than 380 nm (704 km) north of the historical median location.

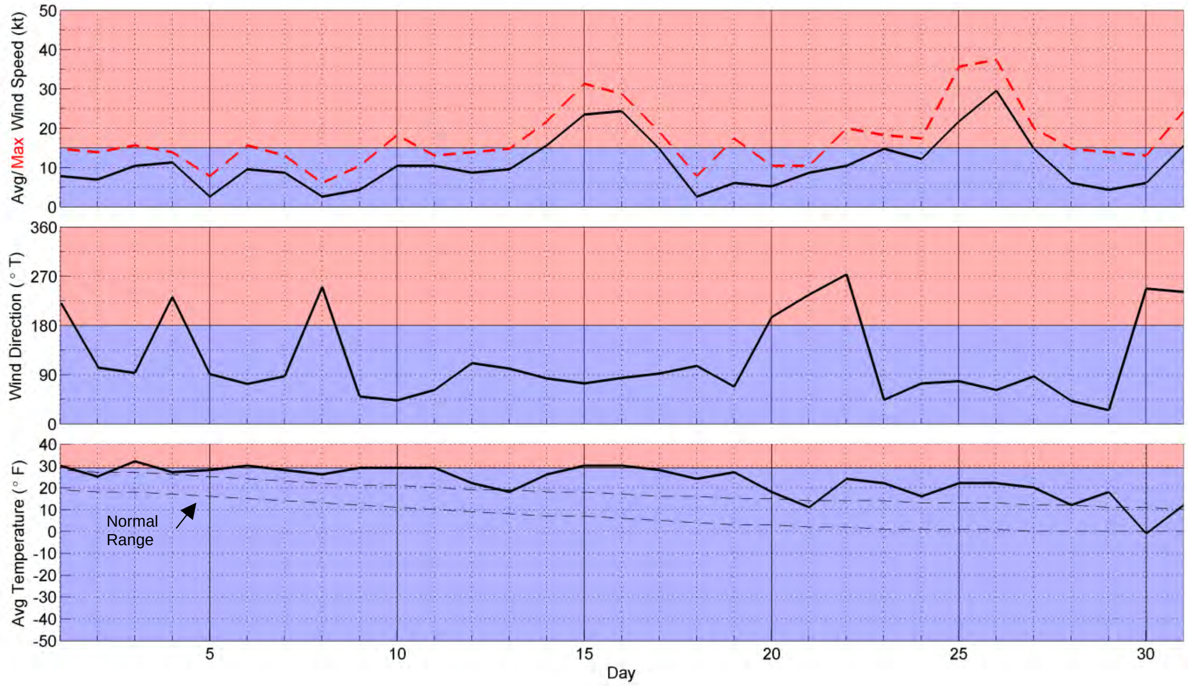
At the end of September, the ice edge (0% concentration) was located approximately 110 nm (204 km) off Barter Island and 240 nm (445 km) off Point Barrow.

4.3 Early Freeze-Up

4.3.1 October 2011

Meteorological Conditions: The daily values of average sustained wind speed, maximum sustained wind speed, average wind direction, and average air temperature at Deadhorse Airport are shown in Figure 15 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 8. Unless stated otherwise, the wind speeds discussed in the text refer to the daily average values rather than the daily maximum values.



Source: Weather Underground, 2012

Figure 15. Meteorological Conditions at Deadhorse Airport in October 2011

Table 8. Significance of Color Bands in Plots of Meteorological Conditions

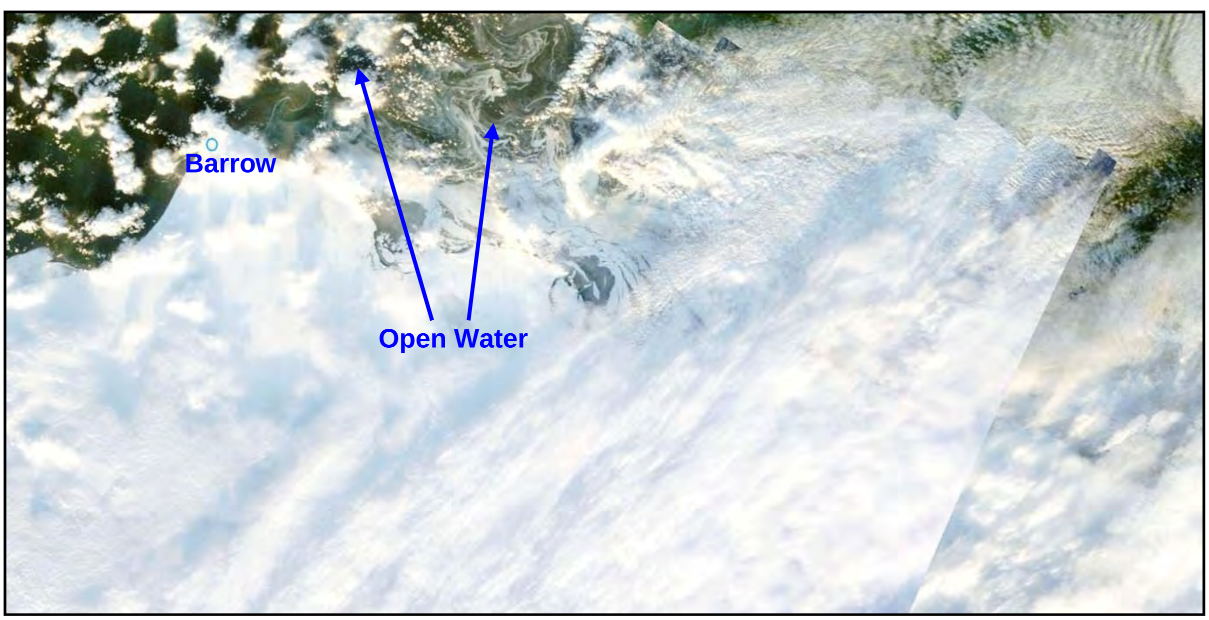
Parameter	**Band Color**	
	Blue	**Red**
Wind Speed	≤ 15 kt	> 15kt (Storm)
Wind Direction	Easterly	Westerly
Air Temperature	≤ 29°F (Freezing Point of Seawater)	>29°F

In a pattern reminiscent of that seen in October 2010, air temperatures remained higher than normal for most of the month. Easterly winds predominated, occurring nearly 75% of the time (23 of 31 days). Easterly storms took place on two occasions: October 14th-16th, and 25th-26th (Table 4). The latter was the most energetic of the entire freeze-up season, with the wind peaking at 30 kt (15 m/s) on October 26th. The sole westerly storm began on

October 31st and continued through November 2nd. The wind blew from the southwest for the entire duration of the event, attaining a maximum average daily speed of 18 kt on November 2nd.

Ice Cover: Freeze-up in the Alaskan Beaufort Sea began during the second week in October, when ice began to form in the brackish waters off river deltas and in shallow bays and lagoons. Although the ice charts prepared by the NIC (2012) and CIS (2012) both indicate that the nearshore region became ice-covered on or about October 24th, personnel at the Prudhoe Bay Seawater Treatment Plant reported that the ice remained broken and intermittent until the easterly storm on the 25th and 26th began to abate. Freeze-up in the nearshore region is assumed to have occurred on October 26th, concurrent with the accumulation of 102 freezing degree days (FDD) at Deadhorse Airport. By comparison, nearshore freeze-up in 2011 occurred on October 11th after the accumulation of 80 FDD. (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.)

On October 30th, the average daily air temperature plummeted to -1°F (-18°C). This substantial drop, coupled with light winds, produced rapid freezing in the 100-nm (185-km) wide band of open water that remained between the nearshore region and the pack ice. Nevertheless, a MODIS image obtained on October 31st suggests that small patches within the band remained unfrozen at month-end (Figure 16).



Source: NASA, 2012

Figure 16. MODIS Image Acquired on October 31, 2011

Ice Thickness: As indicated in Table 5, the computed thickness of undisturbed first-year ice was 19 cm at the end of October.

Ice Pile-Ups: Six ice pile-ups composed of 20-cm thick ice blocks were noted on the southwest sides of No Name, Narwhal, Jeanette, and Karluk Islands during the reconnaissance flights undertaken in November and February, including three on Narwhal. These features probably formed when the wind shifted from northeasterly to southwesterly on October 30th. Additional details are provided in Section 4.4.4

Multi-Year Ice: The CIS ice charts indicate that patches of multi-year ice began entering the Alaskan Beaufort Sea from the Canadian Beaufort at the beginning of October (CIS, 2012). The ice continued its westerly drift throughout the month, attaining the longitude of Point Barrow (156°30'W) prior to month-end. The southern boundary of the multi-year ice remained well offshore, typically in the vicinity of 72°30'N.

4.3.2 November 2011

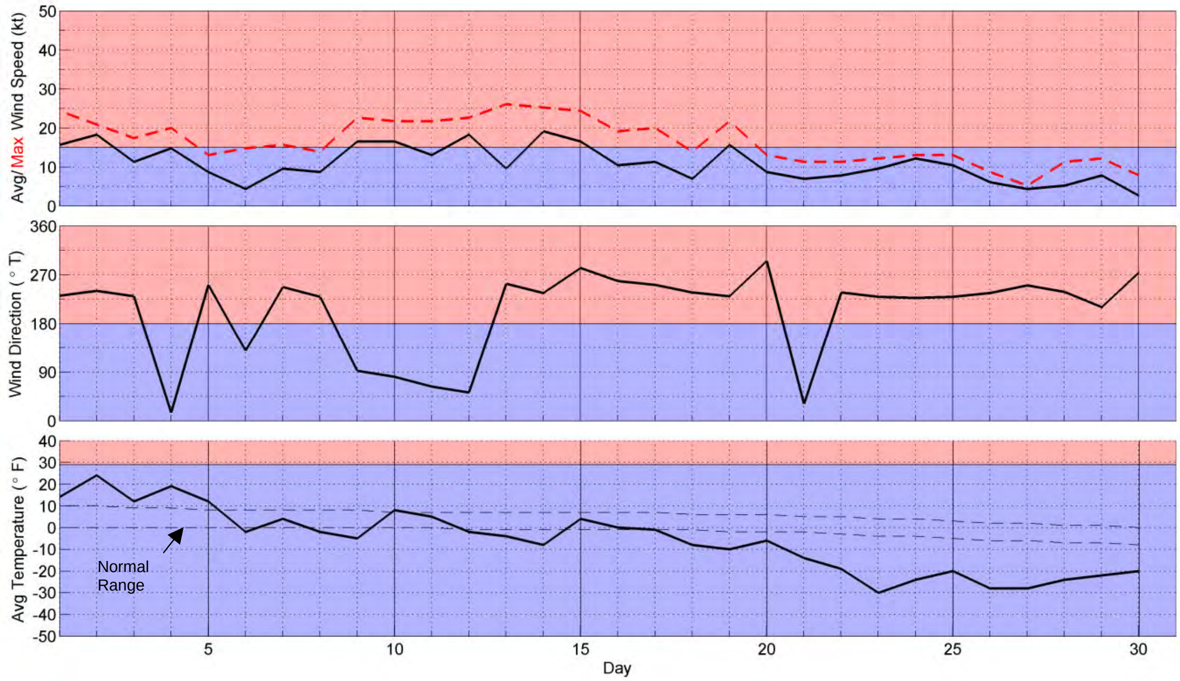
Meteorological Conditions: The meteorological conditions that prevailed at Deadhorse Airport in November are shown in Figure 17. After ranging from slightly above to slightly below normal from the 1st through the 17th, the air temperatures dropped to well below normal for the remainder of the month. In contrast to October, westerly winds prevailed more than 75% of the time (23 of 30 days).

The southwesterly storm that ran from October 31st through November 2nd was followed by three additional storm events (Table 4):

- a four-day easterly with a maximum wind speed of 18 kt (9 m/s) from the 9th through 12th;
- a two-day westerly with a maximum wind speed of 19 kt (10 m/s) on the 14th and 15th; and
- a one-day westerly with a wind speed of 16 kt (8 m/s) on the 19th.

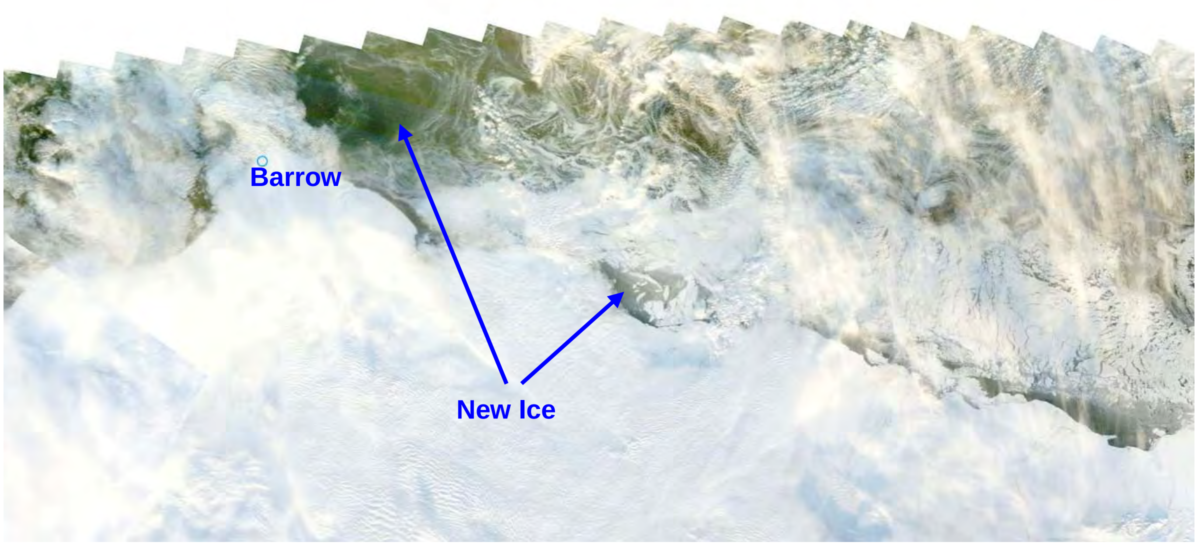
Ice Cover: Ice charts compiled by the NIC and CIS for October 31st, coupled with a MODIS image obtained on November 1st (Figure 18), indicate that complete freeze-up in the Alaskan Beaufort Sea occurred on or about the 1st. The temperature data recorded at Deadhorse Airport through this date produced an accumulated total of 201 FDD.

The NIC ice chart for November 3rd and a RADARSAT-2 image obtained on November 4th (Figure 19) indicate that the southwesterly storm at the beginning of the month created a narrow tongue of open water extending northeast from Point Barrow and



Source: Weather Underground, 2012

Figure 17. Meteorological Conditions at Deadhorse Airport in November 2011



Source: NASA, 2012

Figure 18. MODIS Image Acquired on November 1, 2011

two small areas of incomplete ice cover (7-8 tenths concentration) in Camden Bay and east of Barter Island. The next NIC ice chart, dated November 7th, shows complete ice cover for the entire Alaskan Beaufort Sea. During the remainder of the month, despite one easterly and two westerly storms (Table 4), the nascent ice canopy remained intact.

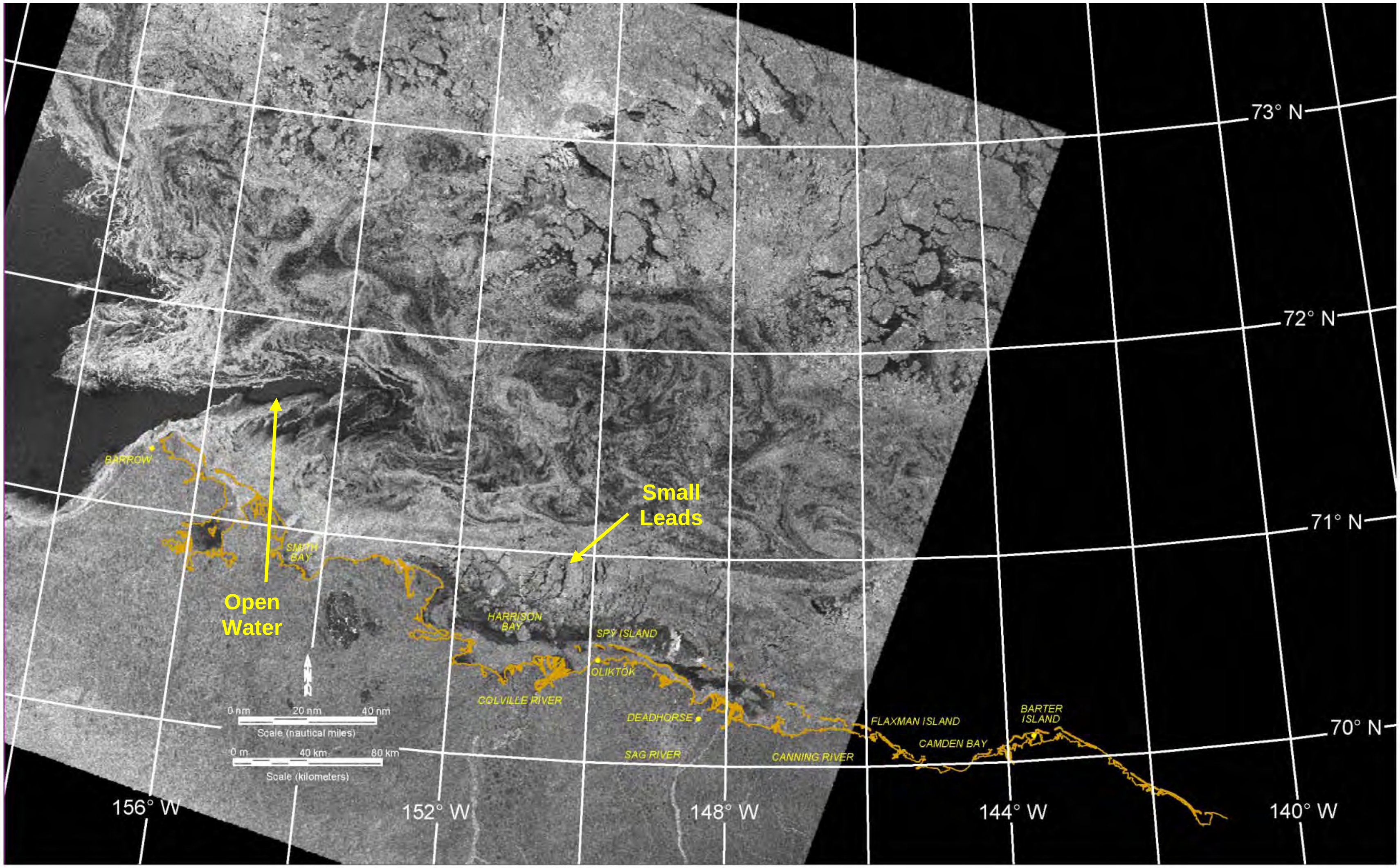


Figure 19. RADARSAT-2 Image of Beaufort Sea Acquired on November 4, 2011

Ice Thickness: The calculated thickness of undisturbed first-year ice increased from 19 cm at the beginning of the month to 58 cm at the end (Table 5).

Landfast Ice: The successive locations of the landfast ice edge as interpreted from RADARSAT-2 images obtained on November 4th, 11th, 18th, and 25th, and December 2nd, are shown in Figure 20. Narrow strips of landfast ice were present on November 4th, with the greatest accumulation in Harrison Bay. The landfast ice edge registered a substantial seaward advance during the next week, when the prolonged easterly storm on the 9th through 12th drove the ice against the coast to initiate the formation of a grounded shear zone. On November 11th, the landfast ice zone encompassed the semi-protected waters behind the barrier islands from Thetis and Flaxman, but remained narrow and poorly-developed in exposed areas that included Smith, Harrison, and Camden Bays. This situation is consistent with the modest ice thickness that prevailed at the time (approximately 30 cm), and that impeded the development of rubble with sufficient mass and strength to become firmly grounded.

With the exception of Smith Bay, the width of the landfast zone remained essentially unchanged after November 11th. This lack of growth may be explained by a strong predominance of westerly winds and complete absence of easterly storms (Figure 17). Unlike easterlies, which tend to create grounded rubble, westerlies inhibit shear zone formation by driving the ice offshore. In Smith Bay, the landfast ice edge moved seaward by up to 10 nm (19 km) between the 11th and 25th.

Ice Pile-Ups: Four ice pile-ups composed of 30-cm thick ice blocks that appeared to have arrived from the northwest were noted during the reconnaissance flights undertaken in November and February (Section 3.5). Two were located on the north side of Pole Island, one on the north side of Narwhal Island, and one on the north side of Northstar Production Island. The pile-ups were created when the wind shifted to westerly on November 13th following the four-day easterly storm that ended a day earlier. Additional details are provided in Section 4.4.4

Leads: The November 4th RADARSAT-2 image (Figure 19) shows numerous small leads oriented perpendicular to the coast in the nearshore region between Cape Halkett and Cross Island. The leads, which tended to range from 5 to 15 nm (9 to 28 km) in length and 0.25 to 1 nm (0.5 to 2 km) in width, probably resulted from the southwesterly storm that ended on the 2nd. The next RADARSAT-2 image, acquired on November 11th, contains a dense concentration of small leads and polynyas within 40 nm (75 km) of the coast from

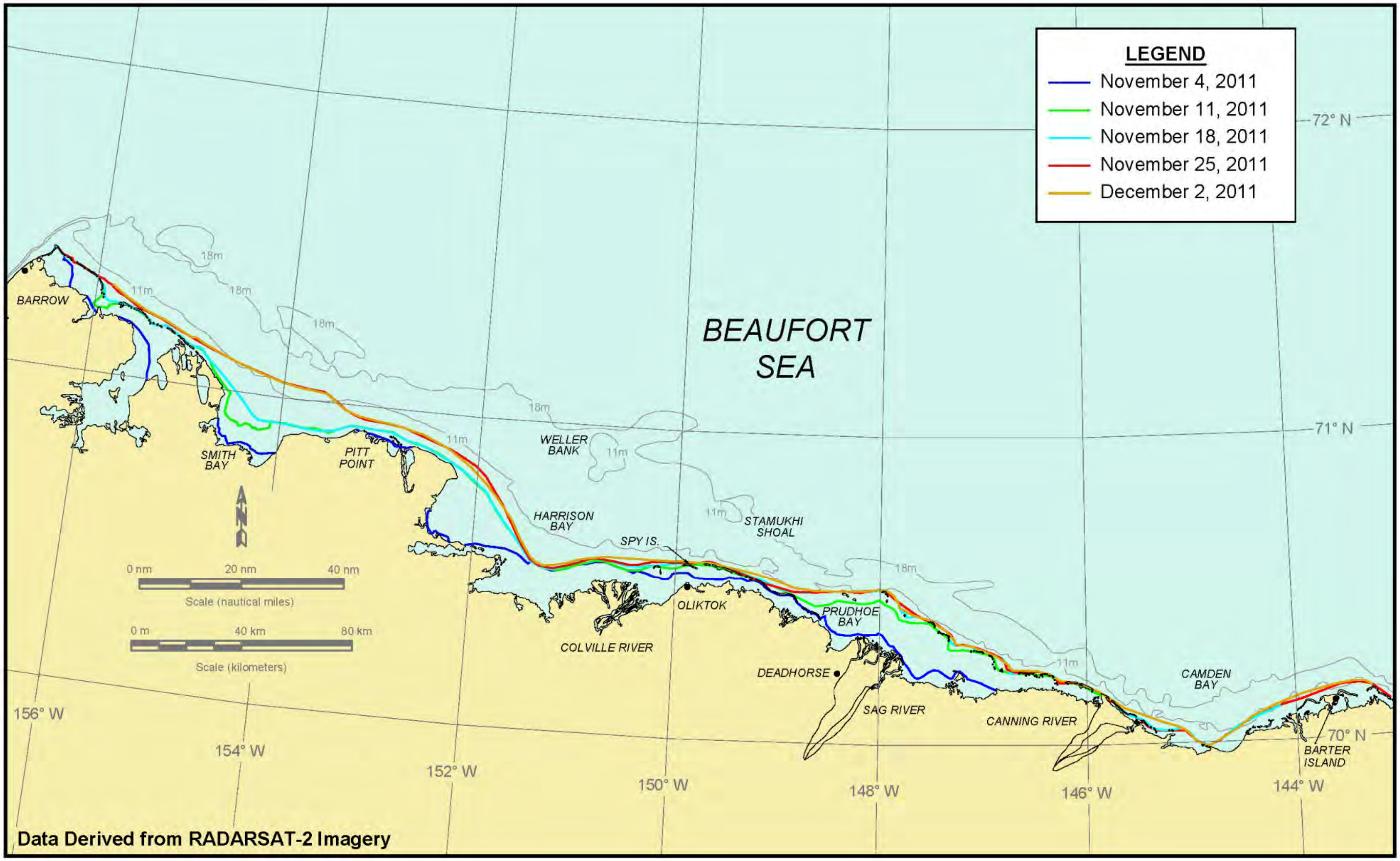


Figure 20. Beaufort Sea Landfast Ice Edge in November 2011

Point Barrow to Camden Bay (where the image ends). The disturbed condition of the ice appears to have been caused by the easterly storm that began on the 9th and continued through the 12th (Table 4). The small leads and polynyas are absent from the November 18th image, which instead contains a long, sinuous lead typically less than 1 nm (2 km) wide that runs parallel to the coast from Point Barrow to Long Island (a distance approaching 150 nm or 278 km; Figure 21). This feature closed prior to the acquisition of the next image on November 25th, at which time no significant leads were present in the region south of 72°N.

Multi-Year Ice: Large multi-year ice floes as indicated by bright returns on the RADARSAT-2 images remained absent from the nearshore region of the Beaufort Sea throughout the month of November. The southern boundary of the multi-year ice varied between 72°N and 72°30'N off Camden Bay, and between 71°40'N and 73°N off Point Barrow (Figure 21). By the end of the month, the multi-year ice had coalesced into a distinct band that extended from the vicinity of the 72°N parallel to the vicinity of the 73°N parallel.

Ice Movement: Ice movement rates in the band of the multi-year ice were quantified by tracking the progress of selected floes in successive RADARSAT-2 images. As shown in Figure 22, Floe A was identified in two images (November 11th and 18th) before moving into the Chukchi Sea, Floe B was identified in four images (November 11th, 18th, and 25th, and December 2nd), and Floes C, D, and H were identified in three images (November 18th and 25th, and December 2nd). The diameters of these floes ranged from 6 to 26 km.

All five floes described clockwise arcs that trended first toward the southwest and then toward the west at speeds that ranged from 4.2 to 13.3 nm/day (7.8 to 24.6 km/day) between successive RADARSAT images. The highest rate occurred between November 11th and 18th, a period that began with the prolonged easterly storm from the 9th through 12th (Table 4). In addition, the floe (Floe A) was relatively unconstrained by virtue of its separation from other large, multi-year floes and the minimal thickness of the first-year ice sheet.

In the case of the four floes (B. C. D, and H) for which the period of record equaled or exceeded twelve days between November 11th and December 2nd (Figure 22), "monthly speeds" were computed from the first and last positions. As shown in Table 7, the values were found to range from 5.4 to 6.4 nm/day (10.1 to 11.9 km/day) with an average of 6.0 nm/da y (11.1 km/day).

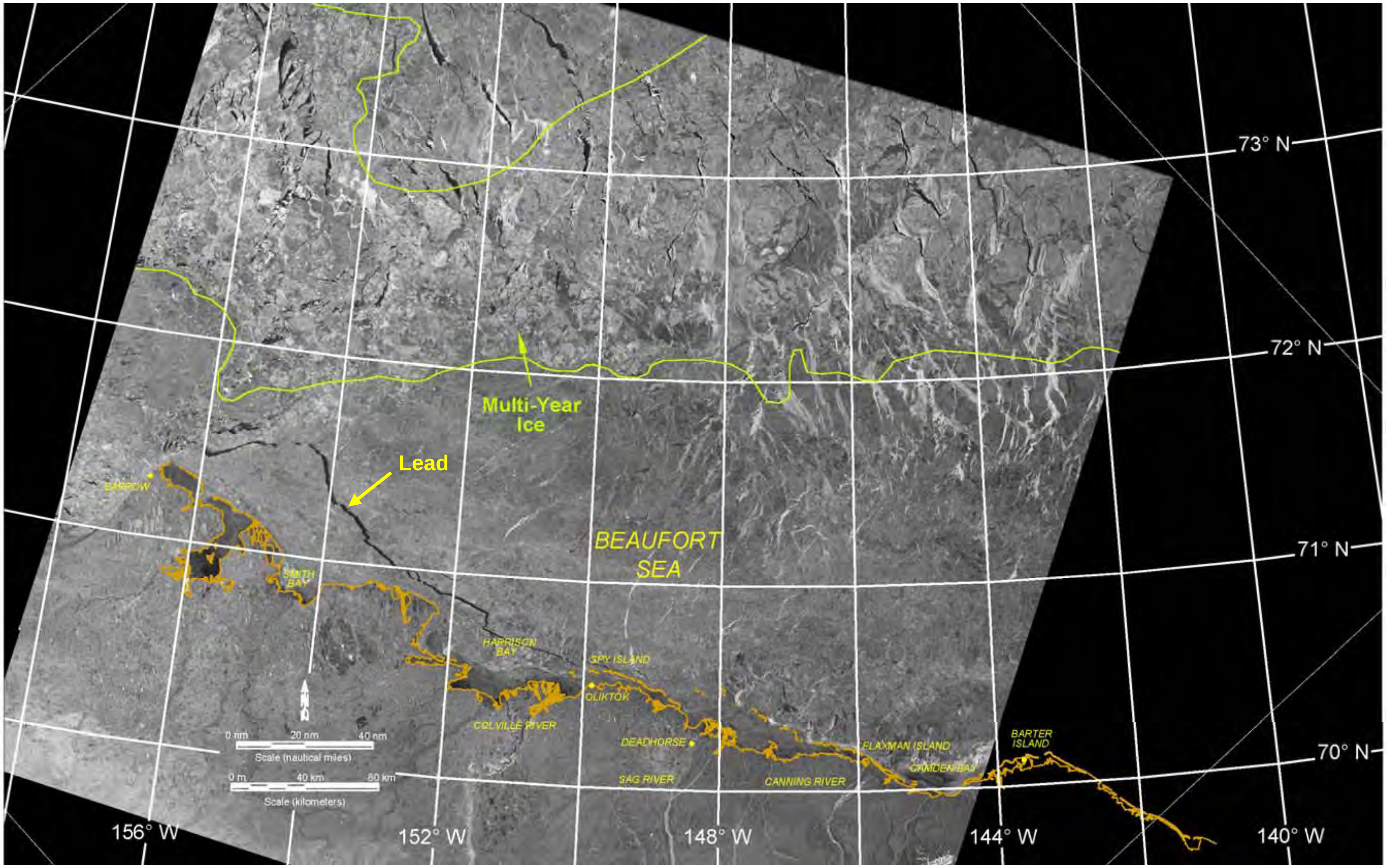


Figure 21. RADARSAT-2 Image of Beaufort Sea Acquired on November 18, 2011

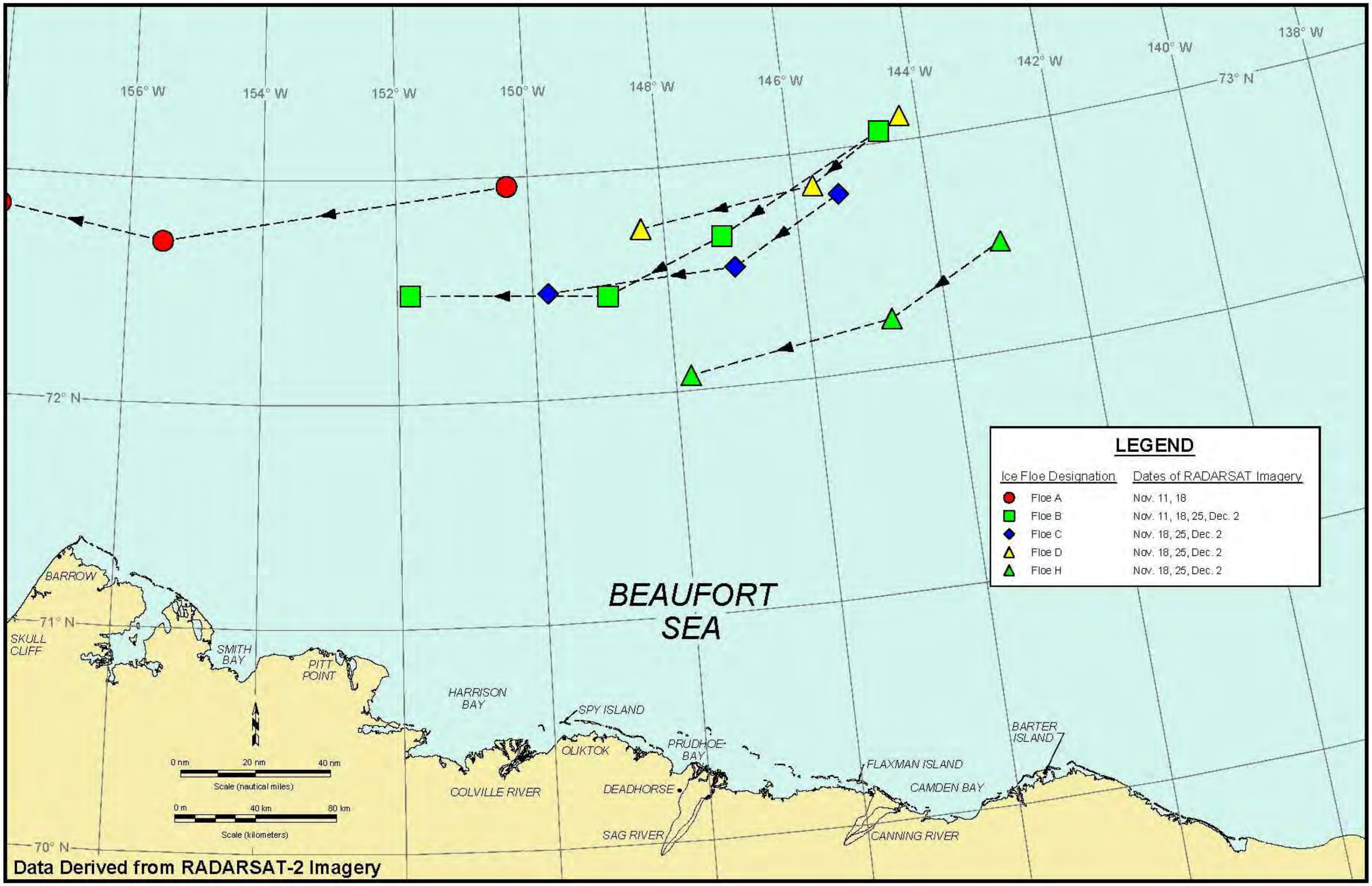


Figure 22. Beaufort Sea Multi-Year Ice Floe Displacements in November 2011

4.4 November Reconnaissance Flights

As discussed in Section 3.5, an aerial reconnaissance mission was undertaken on November 28th to observe the ice conditions that prevailed early in the freeze-up season in the central portion of the Alaskan Beaufort Sea. The flight path, which stretched from Flaxman Island on the east to Cape Halkett on the west, is shown in Drawing CFC-863-01-001. Although both still and video images were acquired throughout the flight, photography were hampered by limited daylight and intermittent clouds and fog.

4.4.1 Lagoon Ice

The nearshore ice in the semi-protected lagoons behind the barrier islands was found to be primarily flat and featureless (Plate 3). Scattered rubble fields were noted in Stefansson Sound, however, with rubble heights to 1 m in the central portion and 2 m in the northern portion. The rubble probably formed when the wind shifted from northeasterly to southwesterly on October 30th, pushing the ice against the barrier islands that define the northern boundary of the Sound (Figure 11).

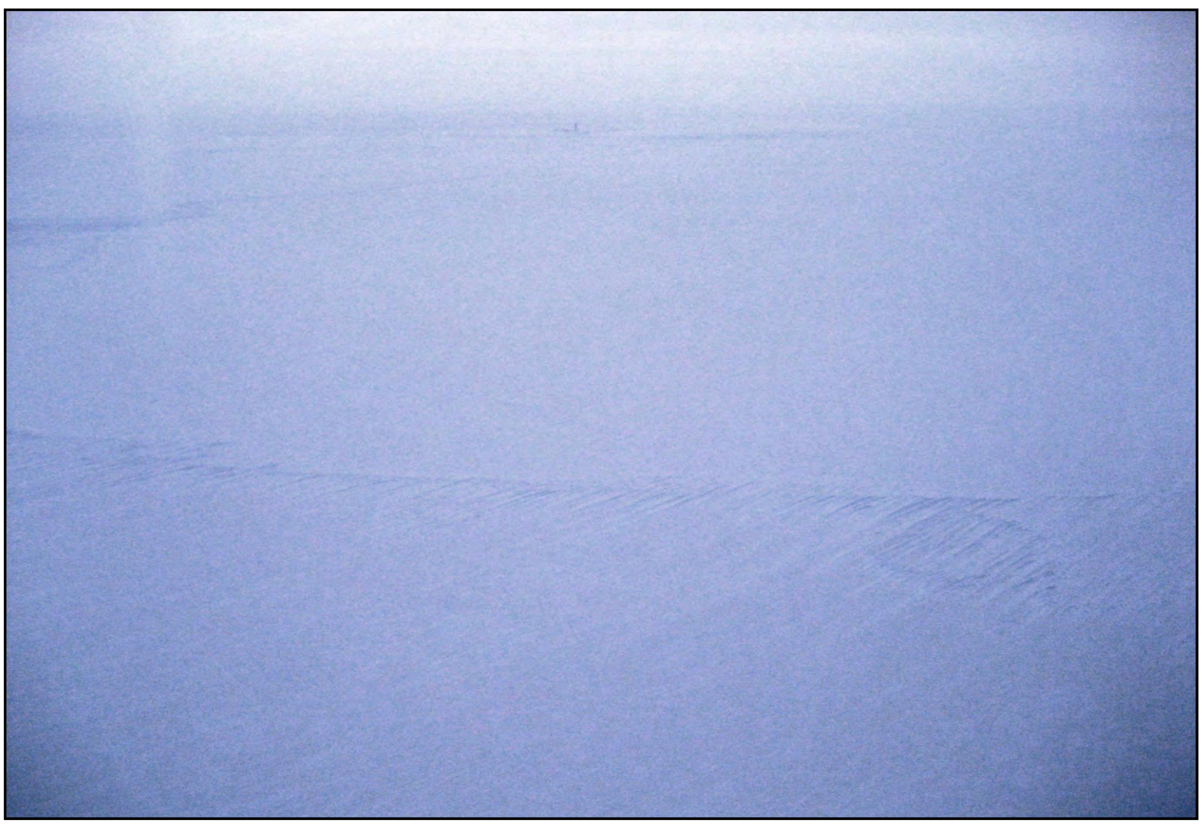


Plate 3. Flat, Featureless Ice in Mikkelsen Bay (November 28, 2011)

4.4.2 Landfast Ice and Shear Zone

The landfast ice zone observed during the November 28th reconnaissance flight closely resembled that noted in the RADARSAT-2 image obtained three days earlier (Figure 20). The seaward edge tended to follow the 5-m bathymetric contour in Harrison Bay, and to lie just north of the barrier islands from Thetis to Flaxman. The shear zone on the north side of the barrier islands was narrow and poorly-developed in most areas, with rubble heights typically ranging from 3 to 5 m and widely-scattered ridges to 5 m (Plate 4). The most striking exception occurred at Cross Island, where well-grounded, 8-m high rubble was noted more than a kilometer north of the shoreline (Plate 5).

4.4.3 Leads

Large leads and polynyas were conspicuously absent from the central portion of the Alaskan Beaufort Sea during the flight. Small refreezing leads were noted in Harrison Bay.

4.4.4 Ice Pile-Ups

Seven ice pile-ups were observed during the November 28th reconnaissance flight, with block thicknesses ranging from 20 to 30 cm. Three additional pile-ups with similar block thicknesses were discovered during the reconnaissance flights conducted in early February. It is likely that these features existed at the time of the November flight but were overlooked due to the poor visibility that prevailed. The characteristics of all ten pile-ups are provided in Table 6.

The first six pile-ups listed in Table 6 were composed of 20-cm thick ice blocks and located on the southwest sides of natural barrier islands. As indicated in Section 4.3.1, these features probably formed when the wind shifted from northeasterly to southwesterly on October 30th. The remaining four pile-ups, consisting of three on natural barrier islands and one on Northstar Production Island, were composed of 30-cm thick ice blocks that had been pushed ashore from the northwest. They appear to have been created on November 13th when the wind shifted to the west following a four-day easterly storm.

The maximum heights of the pile-ups varied from 2 to 7.6 m above MSL, while the lengths varied from 200 to 1,200 ft alongshore. Seven of the ten pile-ups extended past the waterline onto the subaerial beach, with encroachment distances ranging from 3 to 20 m. The largest pile-up, with a height of 7.6 m, length of 1,200 ft, and encroachment of 20 m, occurred on the western end of Narwhal Island on November 13th. This feature is shown in Plate 6 along with a smaller, 4-m high pile-up that formed previously on October 30th.

Plate 4. Intermittent, 3-m Rubble off Alaska Island (November 28, 2011)

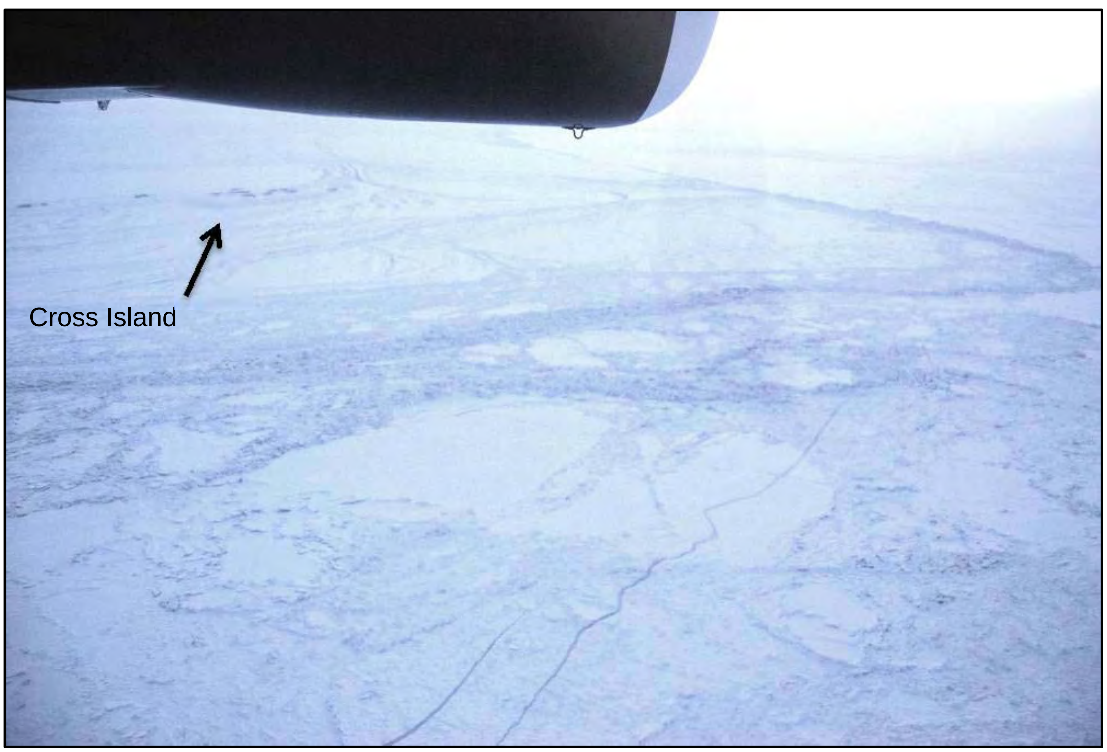


Plate 5. Well-Grounded, 8-m Rubble off Cross Island (November 28, 2011)

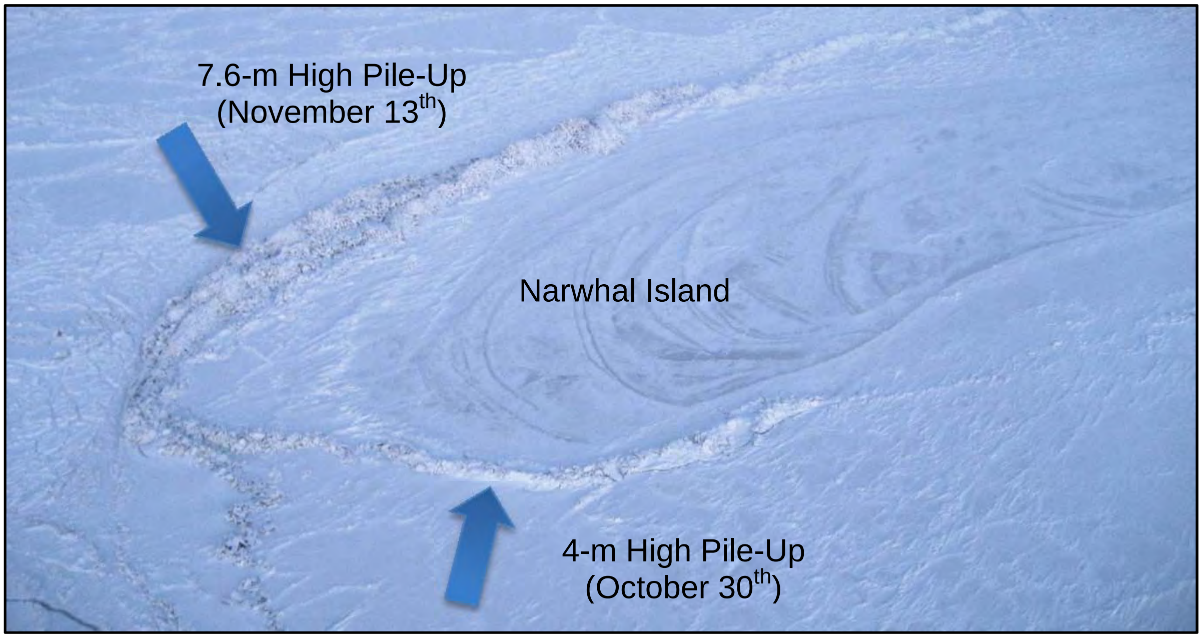


Plate 6. Two Ice Pile-Ups on West End of Narwhal Island (November 28, 2011)

4.4.5 Ice Conditions in Shell Prospects

In Shell's Sivulliq Development, the ice cover on the prospective pipeline route was found to be flat and featureless on the 2-nm (4-km) stretch in Leffingwell Lagoon (Drawing CFC-863-01-001). Farther north, from Mary Sachs Entrance to a distance of 10 nm (19 km) off the barrier islands, intermittent rubble with heights of 2 to 4 m was present (Plate 7). The rubble transitioned into relatively flat ice with only modest deformation on the seawardmost 2 nm (4 km) of the route (Plate 8).

The Harrison Bay Prospects contained large pans of flat, first-year ice interspersed with refreezing leads (Plate 9). Scattered rubble and ridges were present with heights to 3 m. The ice appeared to be ungrounded and highly mobile.

4.5 Late Freeze-Up

4.5.1 December 2011

Meteorological Conditions: The wind and temperature data recorded at Deadhorse Airport in December 2011 are provided in Figure 23. After ranging from normal to above normal from the 1st through the 13th, the air temperatures remained below normal for the remainder of the month.

The wind direction changed frequently in December, resulting in a near-equal split between easterlies (15 days) and westerlies (16 days). The three storm events consisted of a

Plate 7. Intermittent, 3-m Rubble off Mary Sachs Entrance (November 28, 2011)

Plate 8. Flat Ice with Scattered Rubble at Seaward End of Sivulliq Pipeline Route (November 28, 2011)

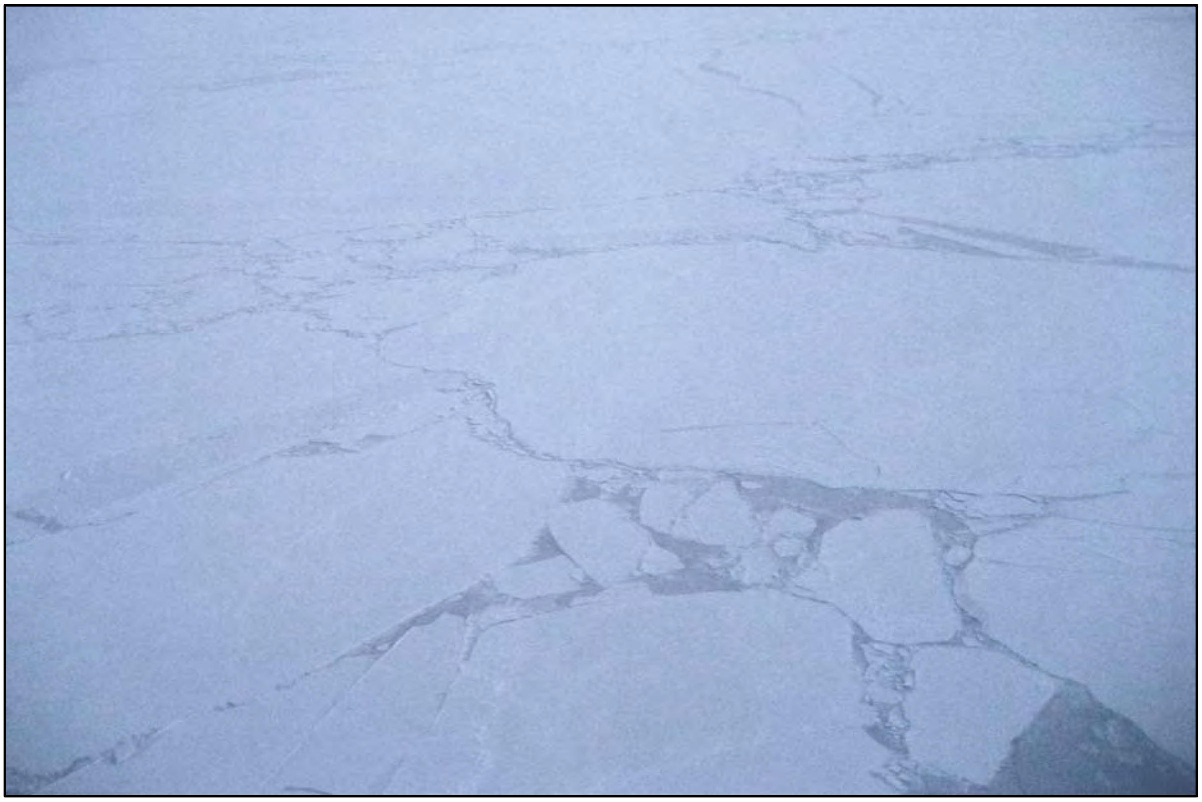
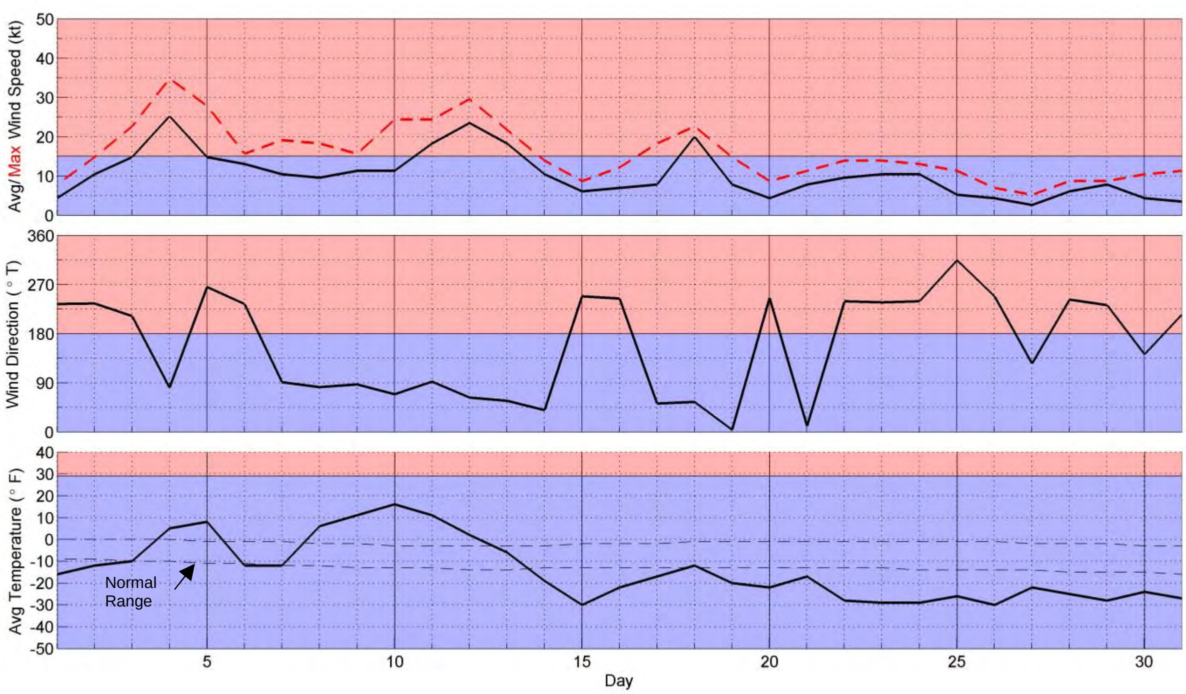


Plate 9. Large Pans of Flat, First-Year Ice Interspersed with Refreezing Leads (November 28, 2011)



Source: Weather Underground, 2012

Figure 23. Meteorological Conditions at Deadhorse Airport in December 2011

25-kt (13-m/s) easterly on the 4th, a 23-kt (12-m/s) easterly from the 11th through 13th, and a 20-kt (10 m/s) easterly on the 18th (Table 4). From the 19th through month-end, the average daily wind speed never exceeded 10 kt (5 m/s).

Ice Thickness: The calculated thickness of undisturbed first-year ice increased by 31 cm over the course of the month, from 58 to 89 cm.

Landfast Ice: The locations of the landfast ice edge were estimated from RADARSAT-2 images obtained on December 2nd, 9th, and 16th, and January 5th. The results are presented in Figure 24.

The occurrence of three easterly storms, coupled with a complete absence of westerly storms, caused a dramatic increase in the width of the landfast ice zone over the course of the month. Between December 2nd and 9th, a period that included the first of the three easterly storms, the landfast ice edge remained virtually unchanged to the east of Cross Island but moved seaward of the 11-m isobath to the west. The storm of December 11th-13th caused another substantial advance, in this case encompassing the entire length of the coast between Smith Bay and Barter Island. Finally, between December 16th and January 5th, the easterly storm of December 18th coupled with the light winds that followed prompted a third major advance. On January 5th, the landfast ice zone extended past the 18-m isobath and exceeded 20 nm (37 km) in width over the entire region between Point Barrow and Barter Island.

Leads: The RADARSAT-2 images obtained on December 2nd, 9th, and 16th show few leads in the ice canopy. On December 2nd, the most significant feature was located on an apparent shear line that paralleled the coast between Harrison Bay and the Stockton Islands. It was approximately 70 nm (130 km) long, up to 1.5 nm (2.8 km) wide, and located well north of the 71°N parallel. A week later, on December 9th, the only leads of consequence lay north and east of Barter Island. The leads were relatively small, typically measuring 10 to 20 nm (19 to 37 km) in length and up to 1 nm (1.8 km) in width. No leads were present on December 16th, when the final image of the month was acquired.

Multi-Year Ice: The band of multi-year ice that was located well north of the Beaufort Sea coast at the end of November persisted throughout December. On the 16th, the southern edge varied in a narrow range between 71°40’ and 72°N over the entire 110-nm (204-km) stretch between Barter Island and Smith Bay (Figure 25). Soon thereafter, multi-year ice approached within 30 nm (56 km) of Point Barrow and began streaming southwest into the Chukchi – a pattern that persisted through March.

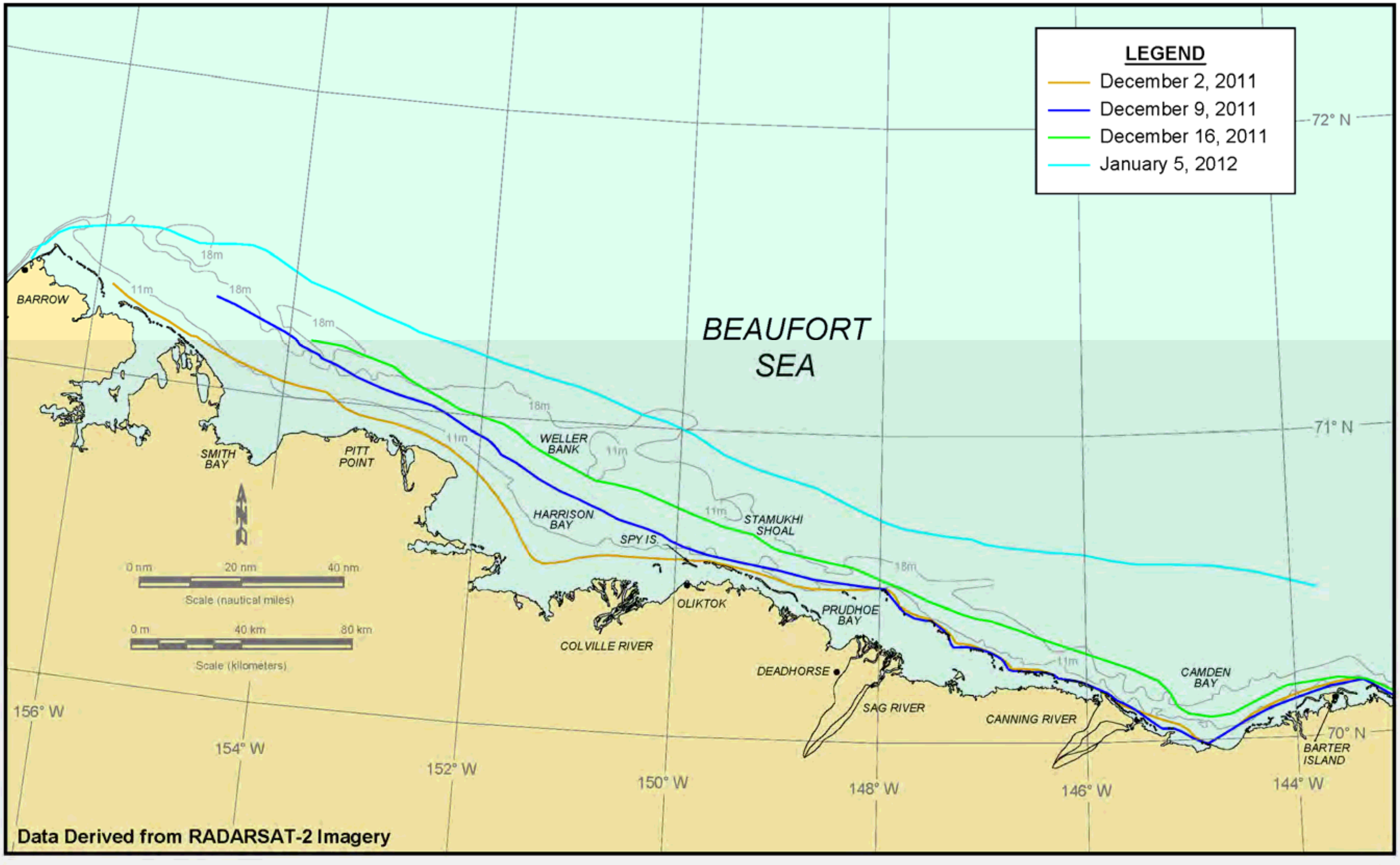


Figure 24. Beaufort Sea Landfast Ice Edge in December 2011

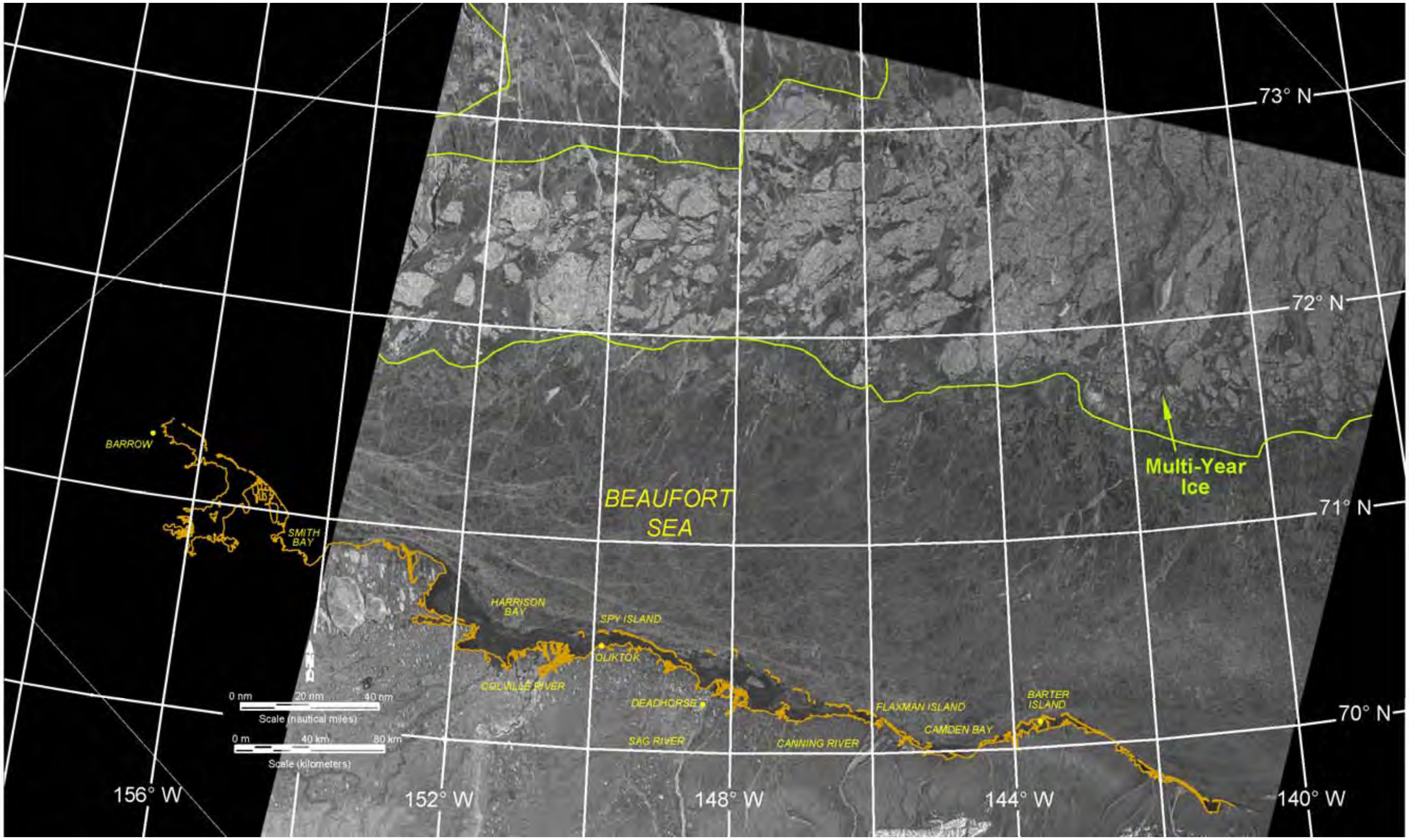


Figure 25. RADARSAT-2 Image of Beaufort Sea Acquired on December 16, 2011

Ice Movement: Velocities in the band of multi-year ice were quantified by comparing the positions of seven floes over various periods bracketed by RADARSAT-2 images obtained on December 2, 2011, and January 5, 2012. Four of the floes (B, C, D, and H) had been tracked in November, while three new floes were added in December (Floes E, F, and G, with diameters ranging from 4 to 20 km). The tracking period for each floe was determined by the extent to which it could be identified in the December 2nd and January 5th images as well as intermediate scenes obtained on December 7th, 9th, 14th and 16th. In the case of Floes B, C, and H, whose trajectories lay primarily in the Chukchi after December 14th, the tracking period for the Beaufort Sea was terminated on that date. 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, 9.3 nm/day (17.2 km/day), was attained by Floes B, C, and H between December 7th (Floe B) or 9th (Floes C and H) and December 14th (all three floes). Not surprisingly, these periods included the three-day easterly storm that prevailed from the 11th through the 13th. The lowest rate of 4.9 nm/day (9.1 km/day) was recorded by Floe F between December 16th and January 5th, when westerly winds predominated despite the occurrence of a one-day easterly storm on December 18th.

A monthly speed was computed for each of the floes for which the period of record in the Beaufort Sea equaled or exceeded twelve days. The values, which were derived from a comparison of the first and last floe positions recorded between December 2nd and January 5th, ranged from 4.9 to 8.3 nm/day (9.1 to 15.4 km/day; Table 7). The average monthly speed, 6.5 nm/day (12.0 km/day) was slightly higher than that in November (6.0 nm/day or 11.1 km/day). This finding indicates that the occurrence of three easterly storms (Table 4) more than compensated for the greater degree of confinement to which the multi-year floes were subjected by virtue of the progress of freeze-up.

4.5.2 January 2012

Meteorological Conditions: Figure 27 presents the wind and temperature data recorded at Deadhorse Airport in January 2012. Continuing a trend that began in mid-December, the air temperatures remained below normal through mid-January. After a brief warm spell, the temperatures dropped sharply to -48°F (-44°C) on the 23rd and remained below normal for the rest of the month.

Westerly winds predominated throughout January, occurring with a frequency of 90% (28 of 31 days). The storm pattern reflected this westerly predominance, with two westerly and no easterly events (Table 4). The first storm ran from the 7th through the 9th with a

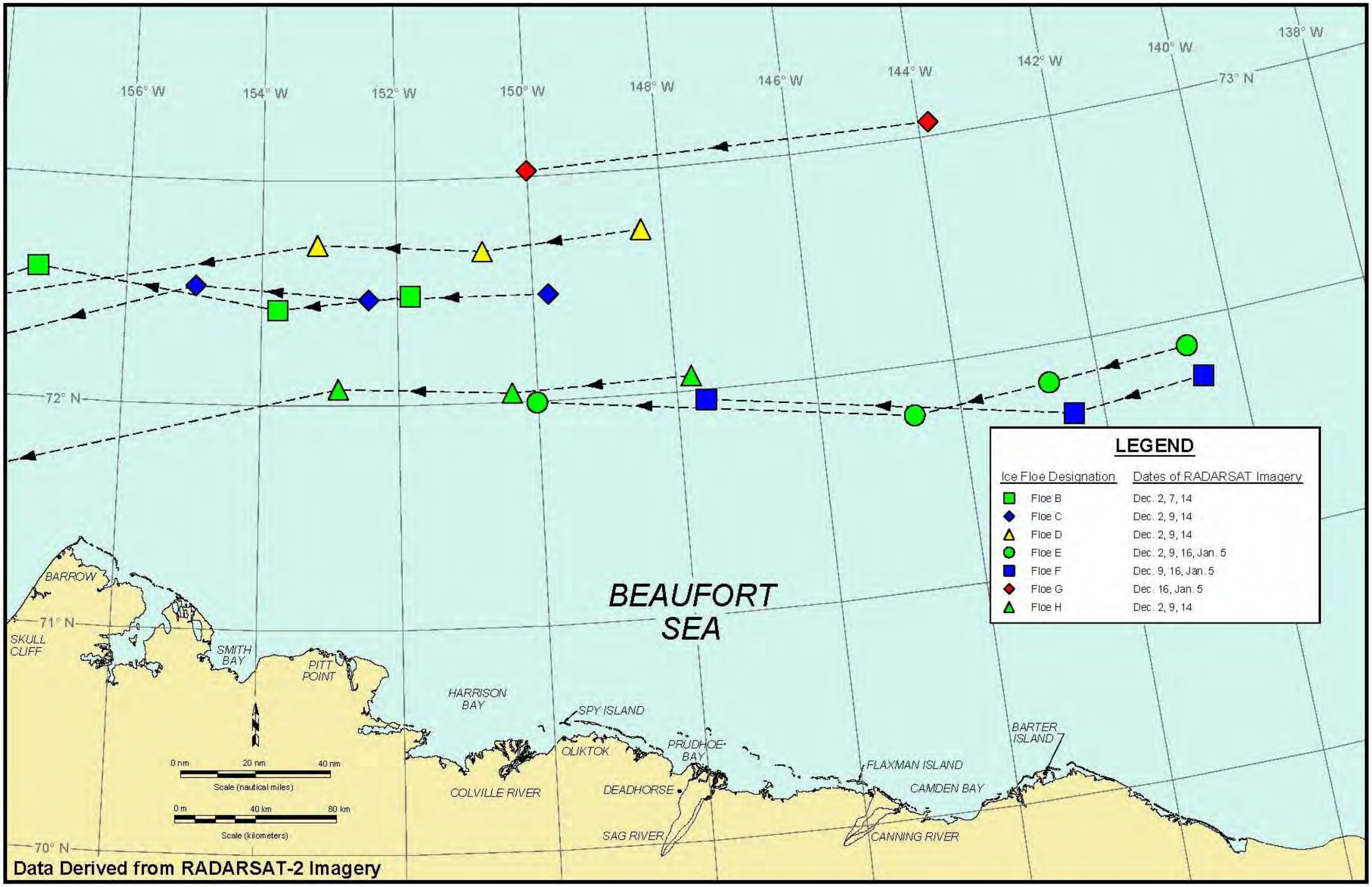
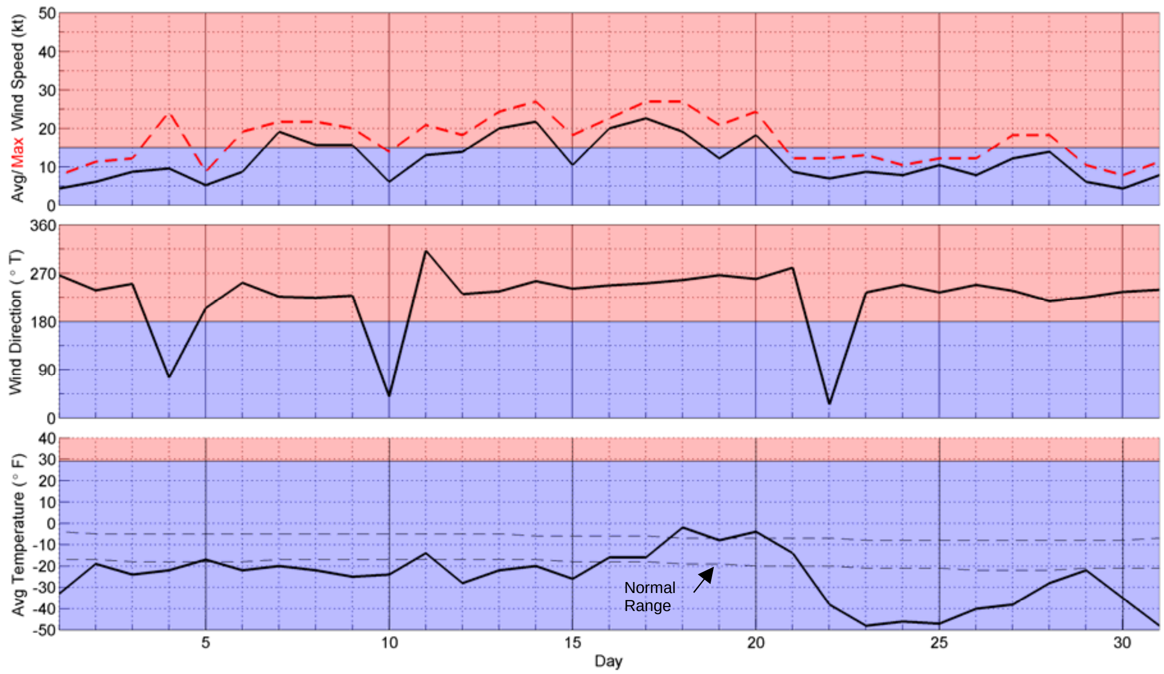


Figure 26. Beaufort Sea Multi-Year Ice Floe Tracks in December 2011



Source: Weather Underground, 2012

Figure 27. Meteorological Conditions at Deadhorse Airport in January 2012

maximum wind speed of 19 kt (10 m/s). The second persisted for eight days, from the 13th through the 20th, with a maximum speed of 23 kt (12 m/s).

Ice Thickness: The calculated thickness of undisturbed first-year ice increased from 89 cm at the beginning of January to 120 cm at the end, a gain of 31 cm.

Landfast Ice: Figure 28 illustrates the locations of the landfast ice edge derived from RADARSAT-2 images obtained on January 5th, 19th, and 29th. In keeping with the predominance of westerly winds and storms, the width of the landfast ice zone declined precipitously over the course of the month. Between January 5th and 19th, the landfast ice edge remained stable in the western Beaufort but retreated to the 11-m isobath in the region east of Weller Bank. The loss was greatest off Camden Bay, where the width of the landfast ice decreased by up to 30 nm (56 km).

During the 10-day period between January 19th and 29th, the landfast ice zone remained stable to the east of Weller Bank but narrowed by up to 22 nm (41 km) to the west. The retreat was greatest off Smith Bay, where the ice edge moved inshore of the 11-m isobath.

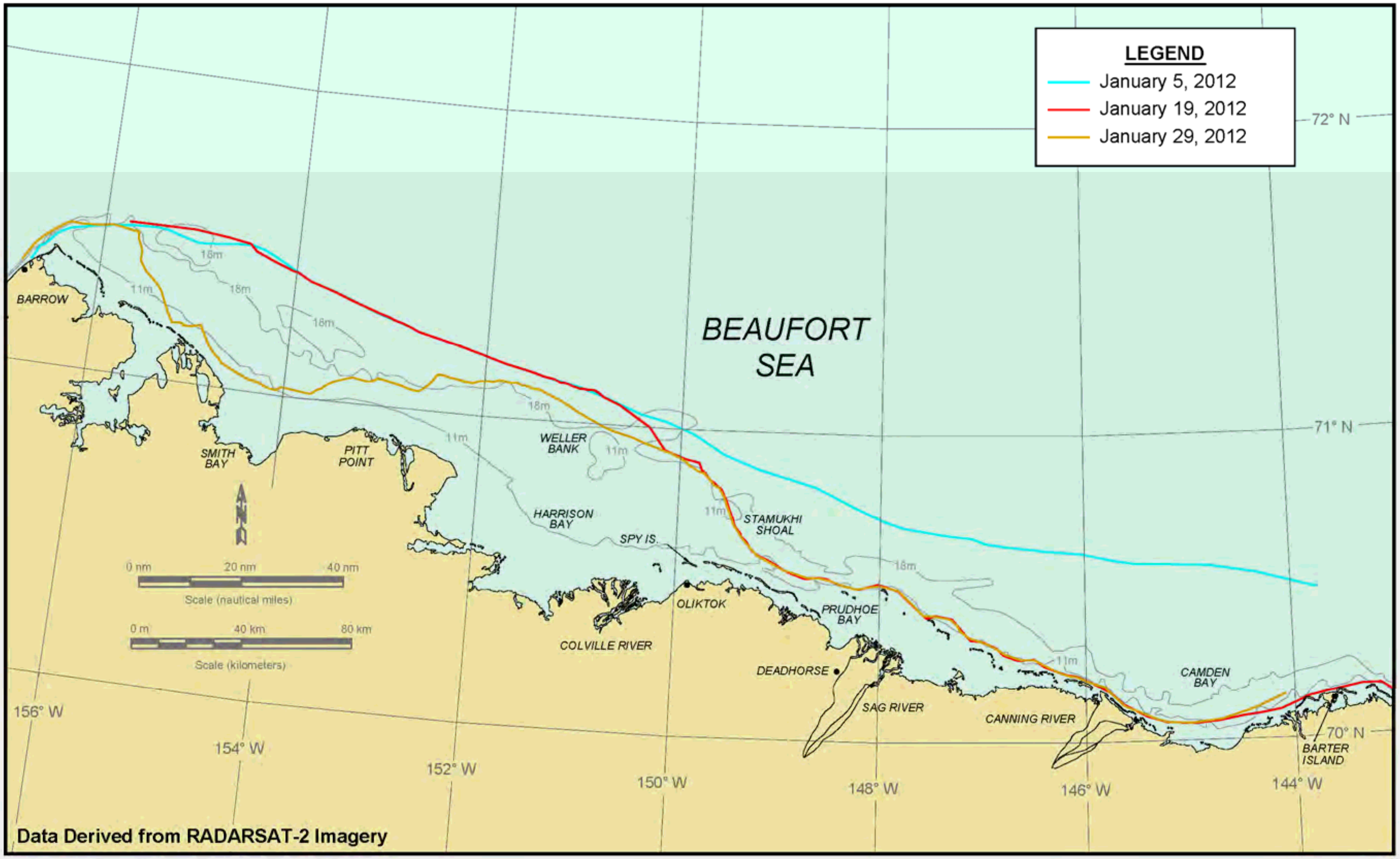


Figure 28. Beaufort Sea Landfast Ice Edge in January 2012

Notwithstanding the substantial losses that transpired in January, the landfast ice edge remained anchored on Weller Bank and Stamukhi Shoal at month-end. This outcome indicates that the ice rubble created by the easterly storms in December was sufficiently well-grounded on these features to resist displacement by the offshore winds that followed.

<u>Leads</u>: The RADARSAT-2 image from January 5th shows a relatively small, intermittent lead extending along the landfast ice edge between the Sagavanirktok and Canning River mouths. The lead width varied from negligible to 1 nm (2 km). No other leads were present at this time, and none were present when the next image was acquired on January 19th.

The January 29th image shows a series of long, serpentine leads extending from Point Barrow to Camden Bay (Figure 29). These features, which tended to follow the landfast ice edge to the west of Stamukhi Shoal, and to deviate farther offshore to the east, were created by offshore displacement of the ice sheet in response to westerly winds. The maximum width, 2.5 nm (4.6 km) occurred in two locations: just east of Point Barrow, and just east of Stamukhi Shoal.

<u>Multi-Year Ice</u>: The band of multi-year ice identified in November and December (Figures 21 and 25) moved south but remained well offshore in January except off Point Barrow (Figure 29). The southern edge was located about 90 nm (167 km) off Flaxman Island and 30 nm (56 km) off Point Barrow on January 5th, versus 65 nm (120 km) and 20 nm (37 km), respectively, on the 29th.

<u>Ice Movement</u>: Three of the multi-year floes identified in December (Floes E, F, and G) were used to investigate ice movement rates in January based on the RADARSAT-2 images obtained on the 5th, 19th, and 29th. Their trajectories are shown in Figure 30.

Unlike November and December, when all of the multi-year floes under surveillance moved to the west, Floes E, F, and G each experienced a net displacement of about 20 nm (37 km) to the southeast between January 5th and 19th. This change in direction, indicating that the westerly set of the Beaufort Gyre had been overcome by the predominance of westerly winds, was followed by a period of negligible net displacement between the 19th and 29th.

The monthly speeds computed for the three floes on the basis of their positions on January 5th and 29th were extremely small: 1.6 nm/day (3.0 km/day) for Floe E and 1.7 nm/day (3.2 km/day) for Floes F and G (Table 7). The highest speed between successive positions, 2.9 nm/day (5.4 k/day), was attained by Floes F and G from the 5th to the 19th.

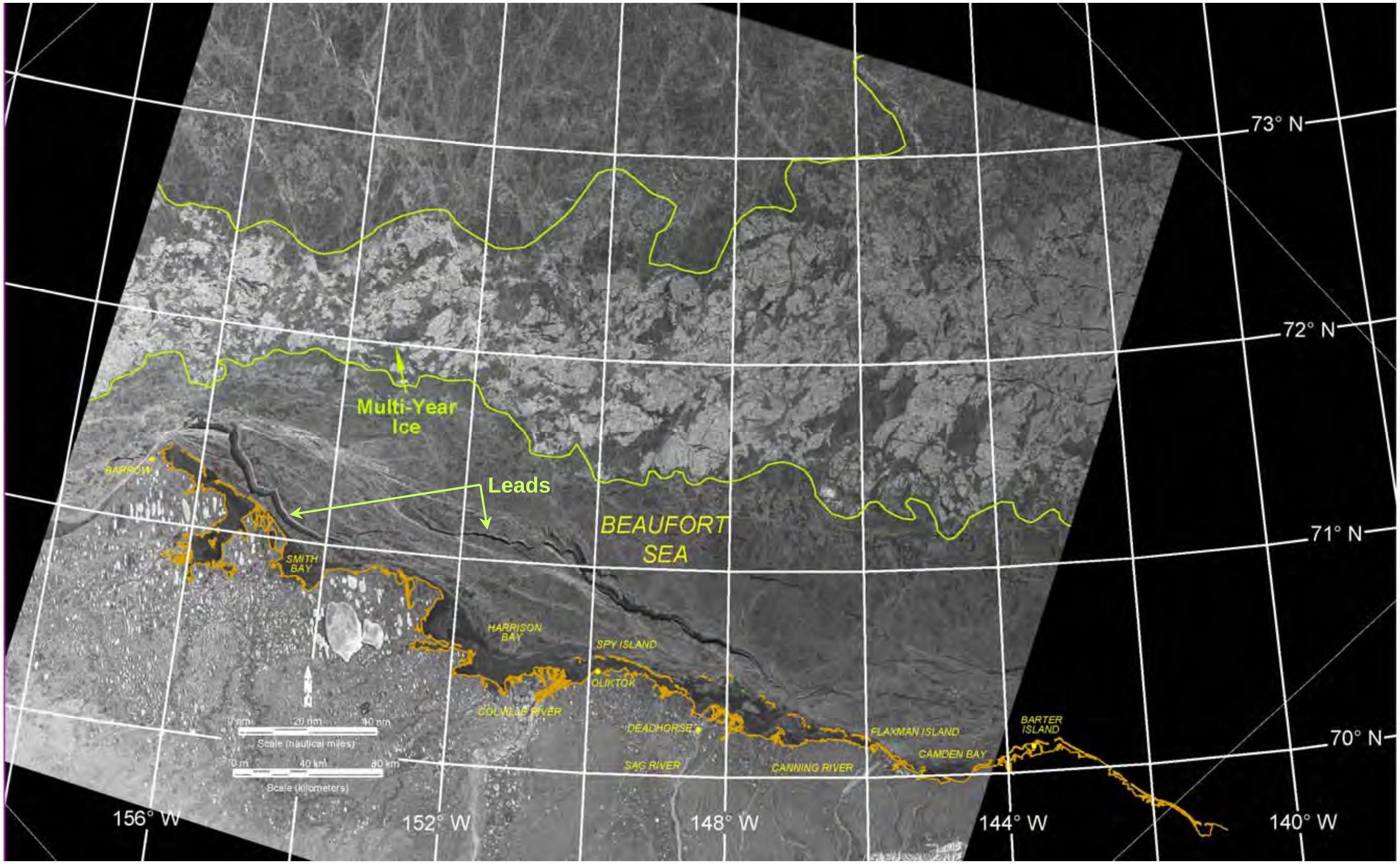


Figure 29. RADARSAT-2 Image of Beaufort Sea Acquired on January 29, 2012

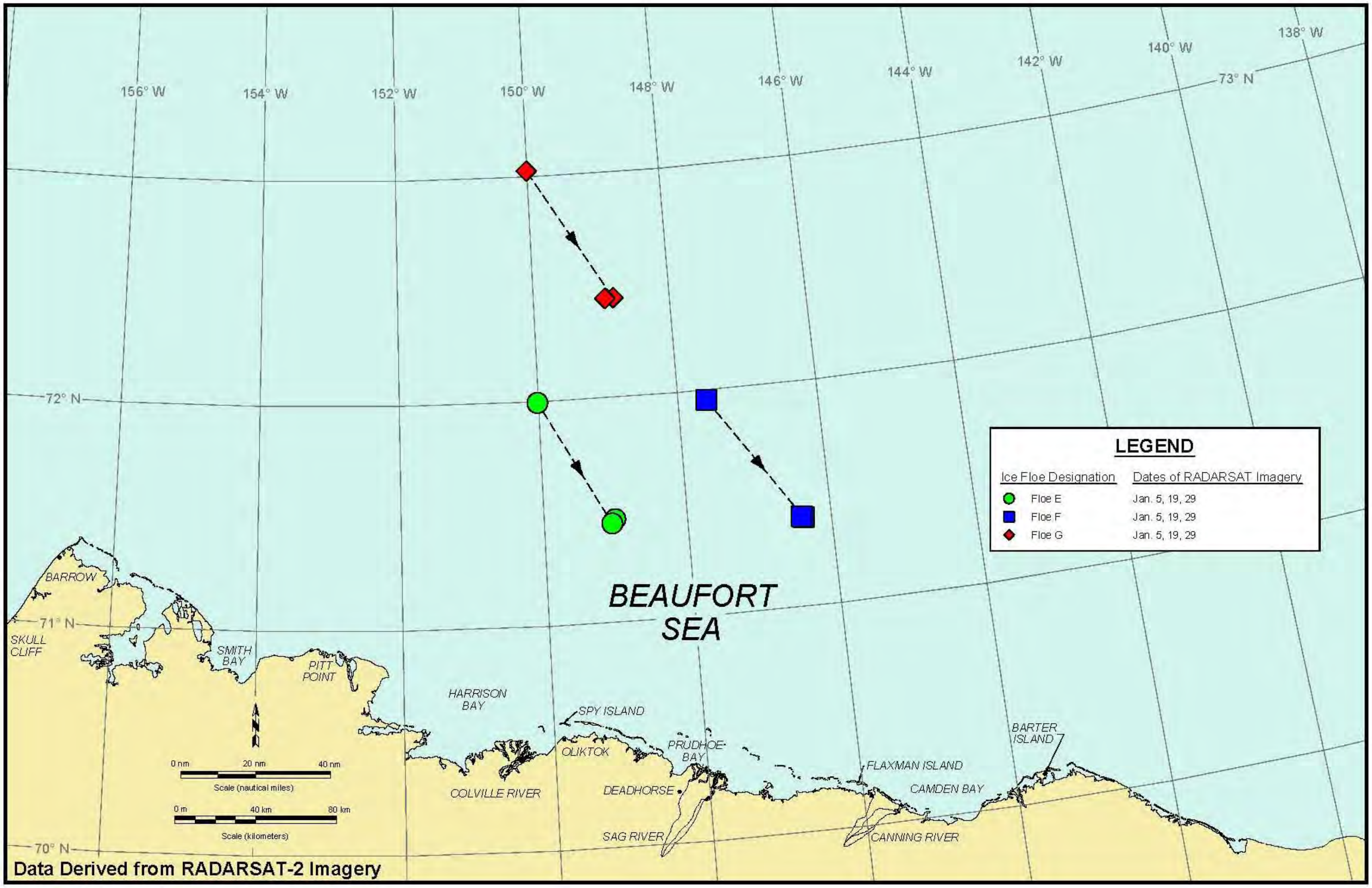


Figure 30. Beaufort Sea Multi-Year Ice Floe Tracks in January 2012

The lowest speed, a meager 0.1 nm/day (0.2 km/day), was logged by Floes E and F from the 19^{th} to the 29^{th}.

Per Section 3.4, Shell installed four Iridium telemetry buoys on the west side of Camden Bay and three on the east side of Harrison Bay on January 27, 2012, to document ice movement. As shown in Figure 31, which displays the position of each buoy at midnight on each day, Buoys A, B, and C were located inside the landfast ice edge in Harrison Bay and remained stationary for the remainder of the month. Buoys 1, 2, and 3 each moved less than 0.2 nm (0.4 km) to the northeast in Camden Bay. Buoy 4, the seawardmost buoy in Camden Bay, initially moved to the northeast but then reversed course and headed west from the 29^{th} through 31^{st}. The net displacement between the 27^{th} and 31^{st} was 2.2 nm (4.1 km) to the west, while the maximum average daily speed was 0.07 kt (0.04 m/s) on the 29^{th}. As westerly winds prevailed at Deadhorse Airport throughout this period, the east-to-west movement of Buoy 4 may have resulted from a different wind regime in Camden Bay, or, alternatively, from an eddy as the ice sheet moved offshore.

4.6 February Reconnaissance Flights

The second set of Beaufort Sea aerial reconnaissance missions was undertaken on February 3^{nd}, 4^{rd}, and 5^{th}. Beaufort Sea Flight Nos. 1 and 2 (Flights "B1" and "B2" on Drawing CFC-863-02-001) focused on ice conditions in the central Beaufort, while Beaufort Sea Flight No. 3 (Flight "B3" on Drawing CFC-863-02-002) was used to observe ice conditions in the western Beaufort Sea.

4.6.1 Lagoon Ice

The nearshore ice in the semi-protected lagoons behind the barrier islands was found to resemble that observed in November: primarily flat and featureless (Plate 10) with scattered rubble fields in Stefansson Sound. The most noteworthy change was the presence of several small thermal cracks in Stefansson Sound between the Sagavanirktok River Delta and Tigvariak Island (Drawing CFC-863-02-001).

As discussed in the 2010-11 Freeze-Up Study report (Coastal Frontiers and Vaudrey, 2012), thermal cracks tend to form when a rapid drop in air temperature precedes 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 at Deadhorse Airport, the cracks and associated ridges noted during the aerial reconnaissance missions may have

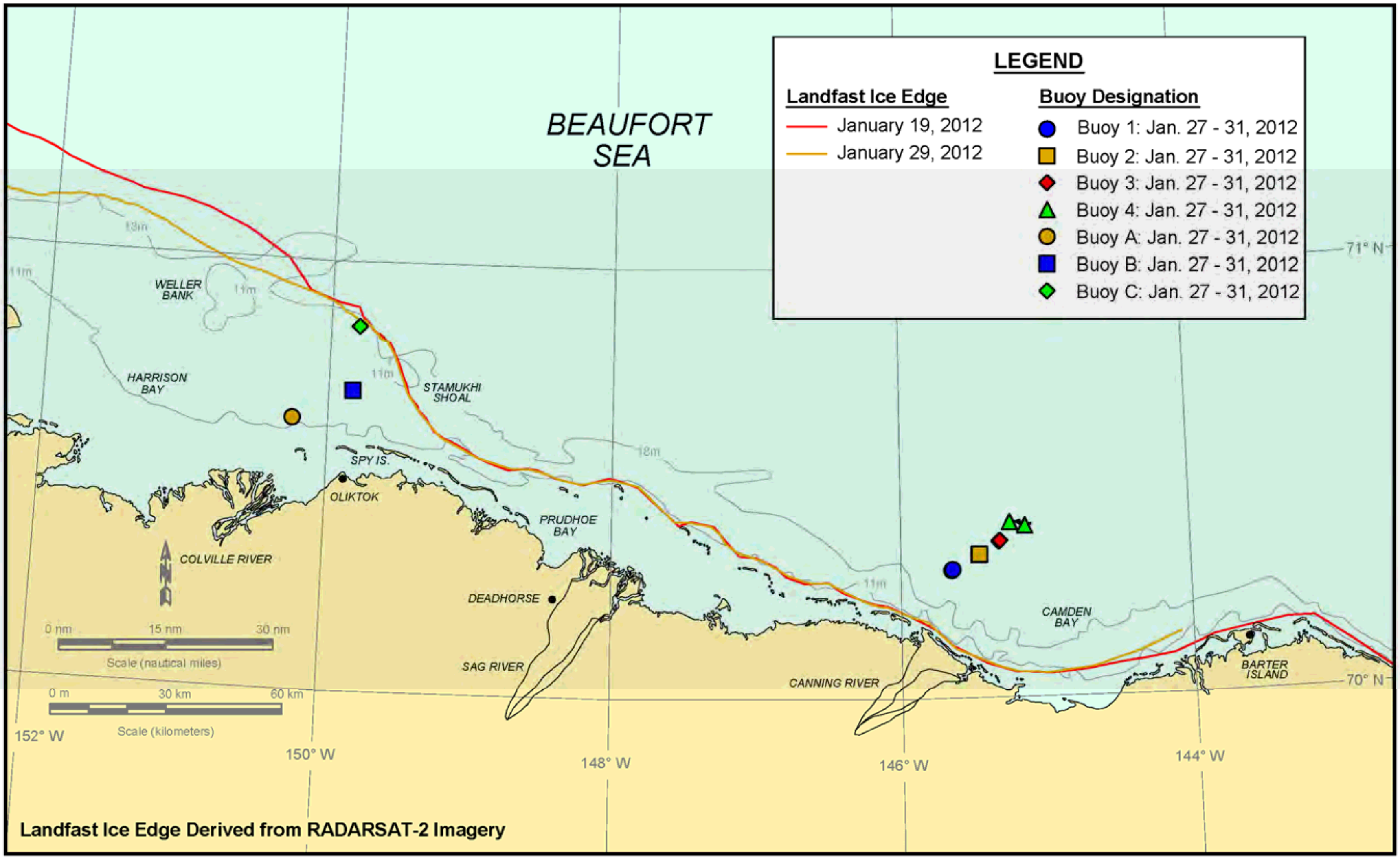


Figure 31. Beaufort Sea Iridium Buoy Tracks in January 2012

Plate 10. Flat Ice Cover in Mikkelsen Bay North of Badami Development (February 4, 2012)

formed between December 5th and 8th. During this three-day period, the average daily temperature dropped from +8 to -12°F (-13 to -24°C) before rebounding to +6°F (-14°C).

The thermal cracks observed in 2012 were located in the same region as similar features discovered a year earlier, in February 2011. The cracks were smaller and fewer in number in 2012, however, with ridge heights typically less than 50 cm (Plate 11). Thermal cracks also 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).

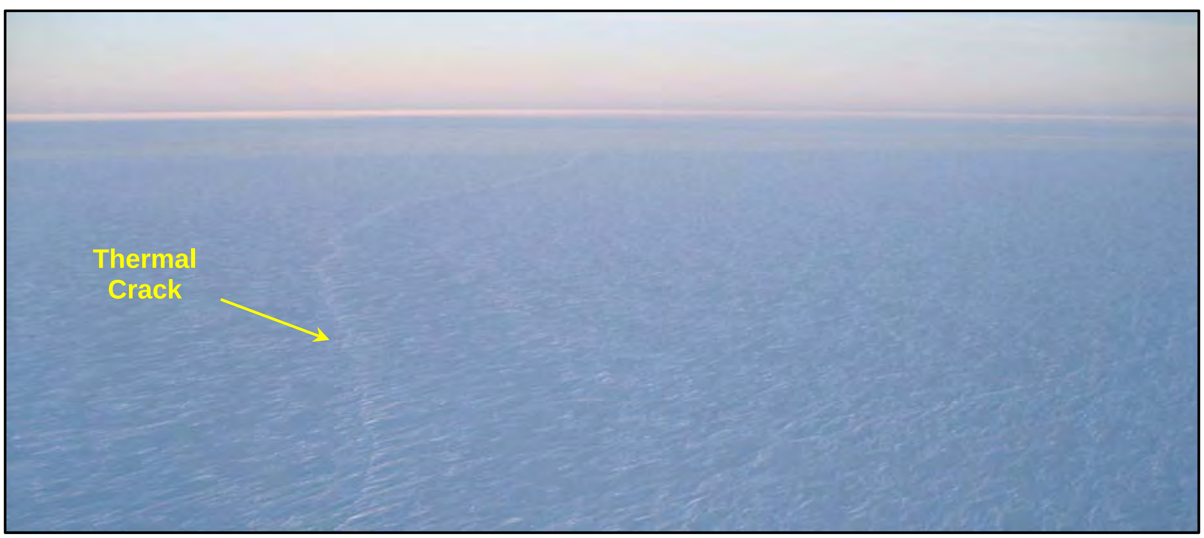


Plate 11. Small Thermal Crack with Extruded Ridge in Stefansson Sound (February 4, 2012)

4.6.2 First-Year Ice Growth

As indicated in Section 3.5, the field crew landed in Mikkelsen Bay to measure the thickness of undisturbed first-year ice during the helicopter flight on February 4th (Plate 12). The objective was to provide a basis for verifying or refining the ice thickness computations developed using the method of Bilello (1960; Section 4.1). Two independent measurements yielded values of 124 and 127 cm, both of which compare extremely well with the predicted value of 123 cm.

Plate 12. Ice Thickness Measurement in Mikkelsen Bay (February 4, 2012)

4.6.3 Landfast Ice and Shear Zone

The extent of the landfast ice zone observed during the 2012 reconnaissance flights closely resembled that derived from the RADARSAT-2 image of January 29th (Figure 28) and also resembled that noted during the flights conducted a year earlier in February 2011 (Figure 32). In both years, the landfast ice edge tended to follow the 11-m isobath off

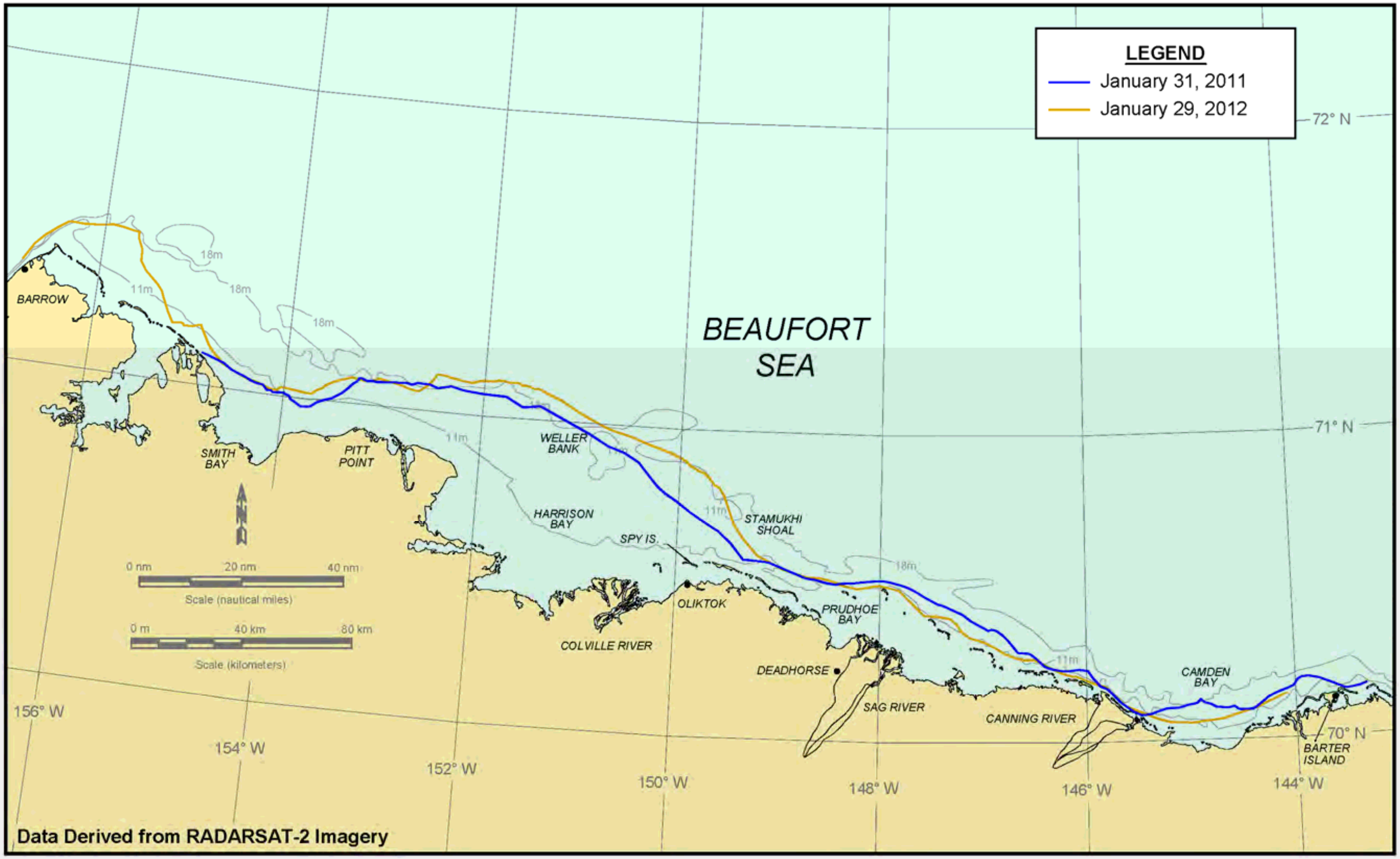


Figure 32. Beaufort Sea Landfast Ice Edge on January 31, 2011 and January 29, 2012

Admiralty and Smith Bays, bulge offshore to the 18-m isobath off Harrison Bay, and retreat back to the 11-m contour from the vicinity of Prudhoe Bay to the eastern side of Camden Bay. The bulge off Harrison Bay reflects the stabilizing influence of Weller Bank and, in 2012, Stamukhi Shoal, both of which tend to serve as anchor points for grounded rubble.

Notwithstanding the similarity between the two landfast ice zones in terms of areal extent, the shear zone at the offshore boundary was found to be better-developed and more securely grounded in 2012. This circumstance is consistent with the occurrence of three easterly, rubble-generating storms in December 2011 versus only one in December 2010. The colder temperatures during the 2011-12 freeze-up season also aided the process of shear zone development through the creation of thicker, stronger ice. The difference between the two years is illustrated in Plates 13 and 14, which show modest rubble and poorly-defined shear lines in 2011 in contrast to substantial rubble and well-defined shear lines in 2012.

Regional characteristics of the landfast ice zone observed during the reconnaissance flights are summarized below:

- ***Harrison Bay:*** The landfast ice edge was secured by extensive grounded rubble on Weller Bank (Plate 14) and Stamukhi Shoal. The rubble heights typically ranged from 2 to 4 m but values as high as 7 m were observed.
- ***Barrier Islands:*** The region immediately north of the barrier islands in the central Beaufort Sea experienced extensive ridge and rubble formation during the period between the November and February reconnaissance flights. The deformation was greatest between Cross Island and the Stockton Island chain, where the grounded rubble attained heights to 10 m (Plates 15 and 16). Farther east, from Challenge Island to Point Brownlow, rubble heights ranged from 2 to 4 m.
- ***Camden Bay:*** The landfast ice in the western portion of Camden Bay, although confined to a narrow strip, appeared to be more stable than in either of the past two years.

4.6.4 Leads

Numerous leads oriented roughly parallel to the coast were observed during the Beaufort Sea reconnaissance flights. As in the case of those noted in the January 29th RADARSAT-2 image (Figure 29), the leads appeared to reflect offshore displacement of the ice in response to the westerly winds that prevailed in late January (Figure 27). The leads tended to be relatively narrow, with widths typically less than 1 nm (2 km). Some were open, while others displayed various degrees of refreezing.

Plate 13. Poorly-Developed Shear Zone East of Weller Bank in February 2011 (Coastal Frontiers and Vaudrey, 2012)

Plate 14. Well-Developed Shear Zone with 4-m Grounded Rubble East of Weller Bank in February 2012

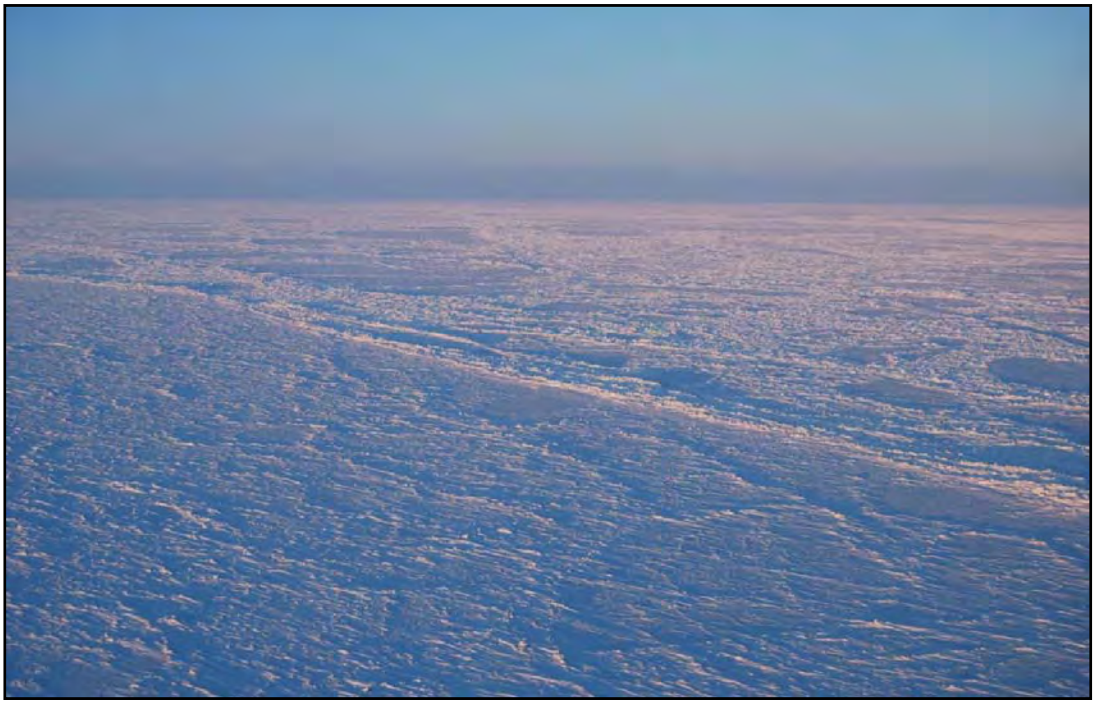


Plate 15. Shear Line and 10-m Grounded Rubble Field off Cross Island (February 4, 2012)

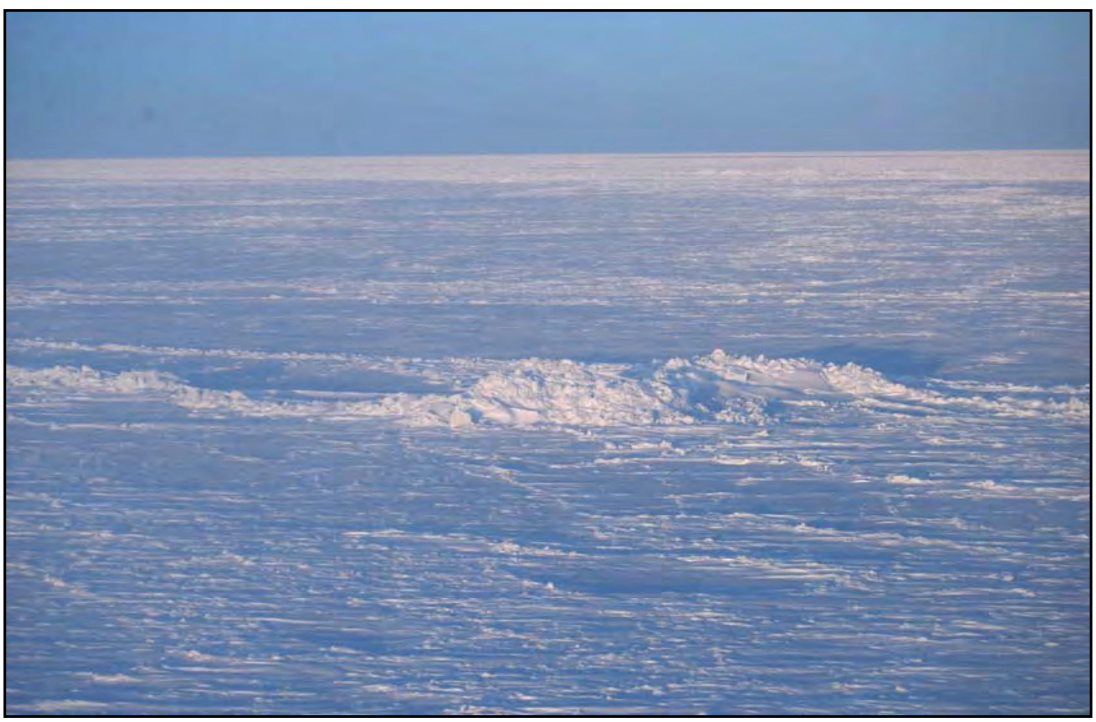


Plate 16. 10-m Grounded Rubble Pile off Pole Island (February 4, 2012)

The largest lead observed during the flights, with an estimated average width of 1 nm (2 km), extended 15 nm (28 km) east of Stamukhi Shoal (Plate 17; Drawing CFC-863-02-001). Considerable refreezing was noted, suggesting that the feature is identical to that which appears at this location in the January 29th RADARSAT-2 image (Figure 29). Other areas with prominent leads included Camden Bay (Plate 18), the region to the northwest of Weller Bank (Plate 19), and the region between Smith Bay and Point Barrow (Plate 20).

4.6.5. Ice Pile-Ups

Ten ice pile-ups were observed in the Alaskan Beaufort Sea during the February reconnaissance flights, consisting of the seven noted previously in November and three discovered for the first time. As discussed in Section 4.4.4, the ice block thicknesses (20-30 cm) imply that the three newly-discovered features existed at the time of the November flight but were overlooked due to poor visibility. The characteristics of the ten pile-ups, all of which appear to have formed between late October and mid-November, were presented previously in Table 6.

The helicopter flight on February 4th afforded an opportunity to land on the west end of Narwhal Island: where a 4-m high pile-up on October 30th was followed by a 7.6-m high pile-up on November 11th (Plate 6). As discussed in Section 4.4.4, the latter was the largest such feature observed in the Beaufort Sea, with a length of 1,200 ft and encroachment of 20 m onto the subaerial beach. The 7.6-m height was measured with a hypsometer, while the 30-cm block thickness was measured with a scale. Representative photographs are provided in Plates 21 and 22.

4.6.6 Ice Conditions in Shell Prospects

When the prospective pipeline route for Shell's Sivulliq Development was inspected on February 3rd and 4th, the ice was found to be more stable than in either of the past two years. The landfast ice edge appeared to lie more than 1 nm (2 km) north of Mary Sachs Entrance, in the vicinity of the 9-m isobath.

As shown in Plate 23, the ice in Leffingwell Lagoon was found to be flat and smooth. Proceeding north from Mary Sachs Entrance, extensive rubble with heights of 3 to 4 m prevailed for about 2.5 nm (4.6 km; Plate 24) before transitioning into intermittent rubble and occasional ridges with similar heights. Farther offshore, from 8 nm (15 km) north of Mary Sachs Entrance to the end of the pipeline route, the ridge and rubble heights increased to as much as 6 m (Plate 25). In contrast to February 2010 and 2011, when numerous leads and broken ice were observed outside the barrier islands, the only significant features of this kind in 2012 were located at the extreme offshore end of the route (Plate 26).

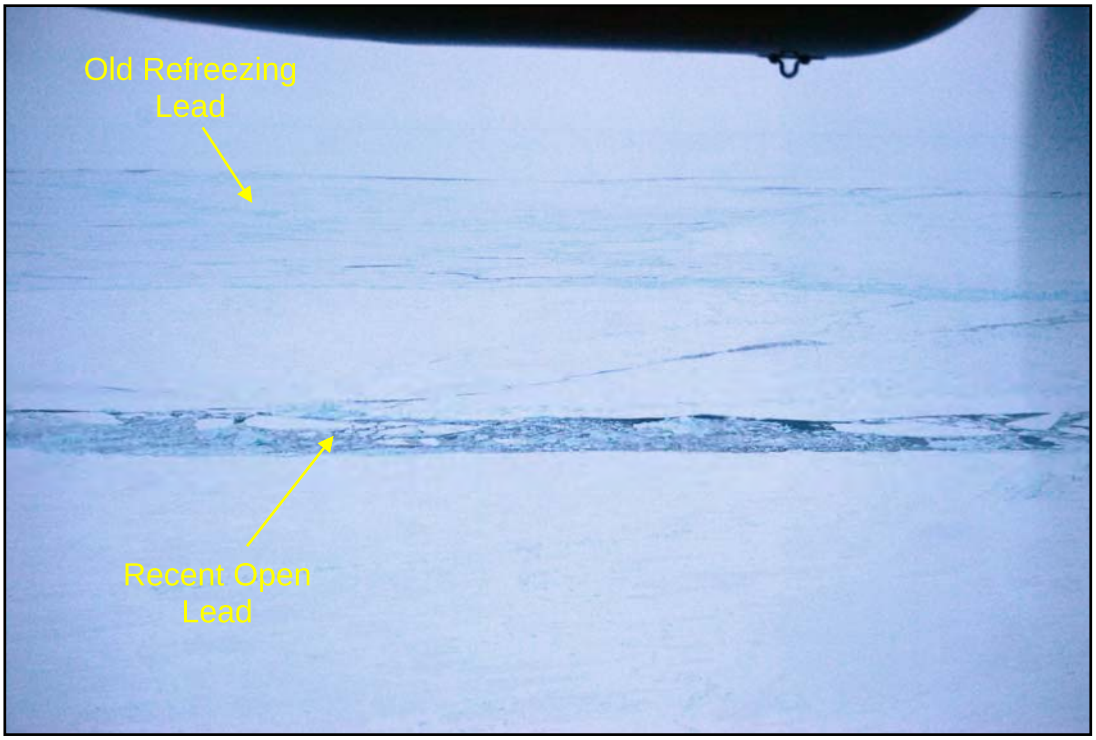


Plate 17. Old Refreezing Lead and Recent Open Lead East of Stamukhi Shoal (February 3, 2012)

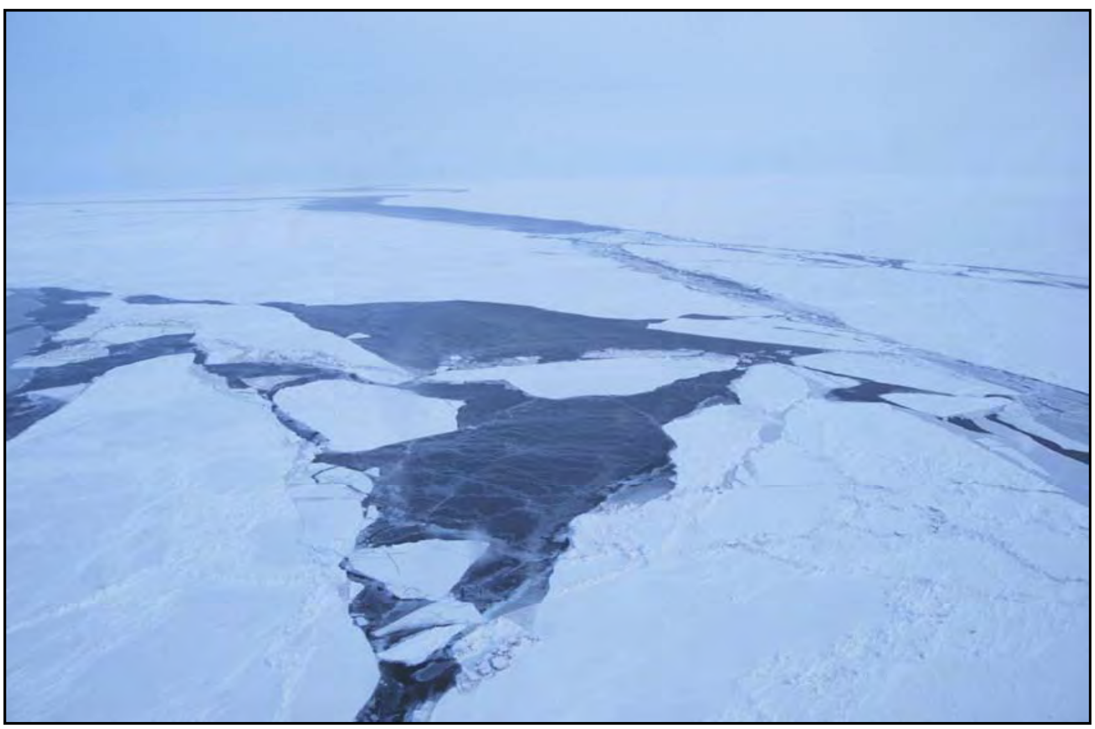


Plate 18. Open Lead 25 nm Offshore in Central Camden Bay (February 3, 2012)

Plate 19. Open Lead 17 nm Northwest of Weller Bank (February 5, 2012)

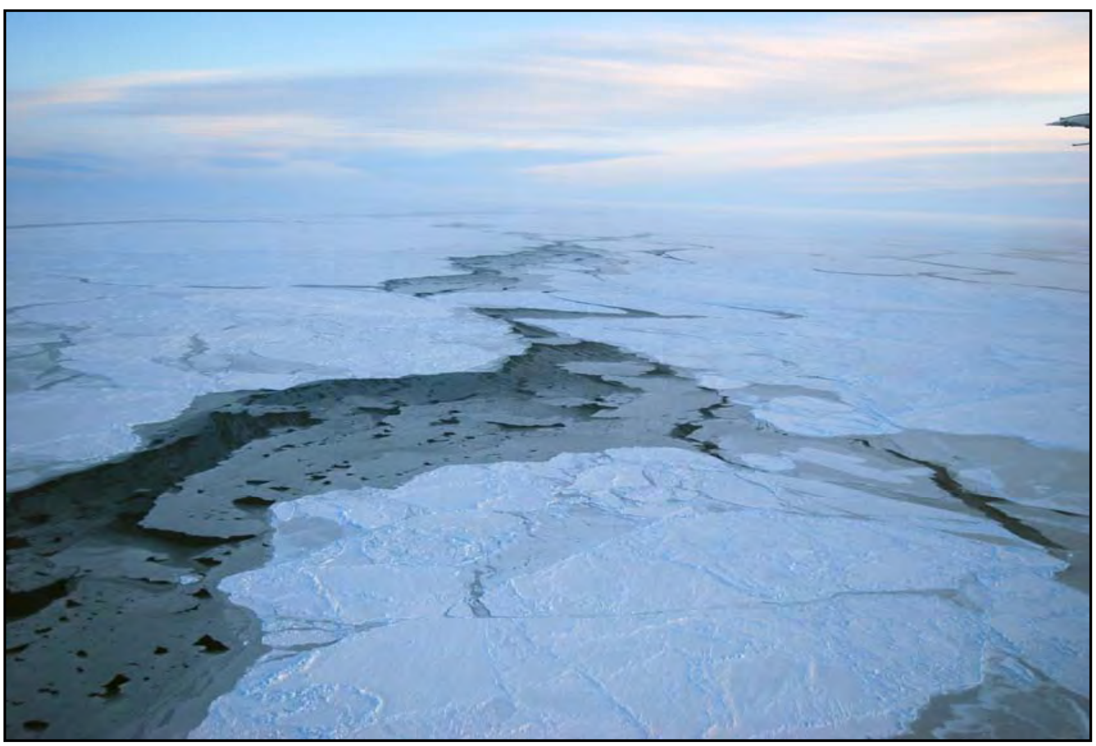


Plate 20. Refreezing Lead 20 nm off Point Barrow (February 5, 2012)

Plate 21. 7.6-m High Ice Pile-Up on Narwhal Island (February 4, 2012)

Plate 22. 30-cm Thick Ice Blocks Comprising 7.6-m Pile-Up on Narwhal Island (February 4, 2012)

Plate 23. Flat, Smooth Ice on Sivulliq Pipeline Route in Leffingwell Lagoon (February 4, 2012)

Plate 24. Extensive Rubble with Heights to 4 m on Sivulliq Pipeline Route 2 nm North of Mary Sachs Entrance (February 4, 2012)

Plate 25. Ridges and Rubble with Heights to 6 m on Sivulliq Pipeline Route 10 nm North of Mary Sachs Entrance (February 4, 2012)

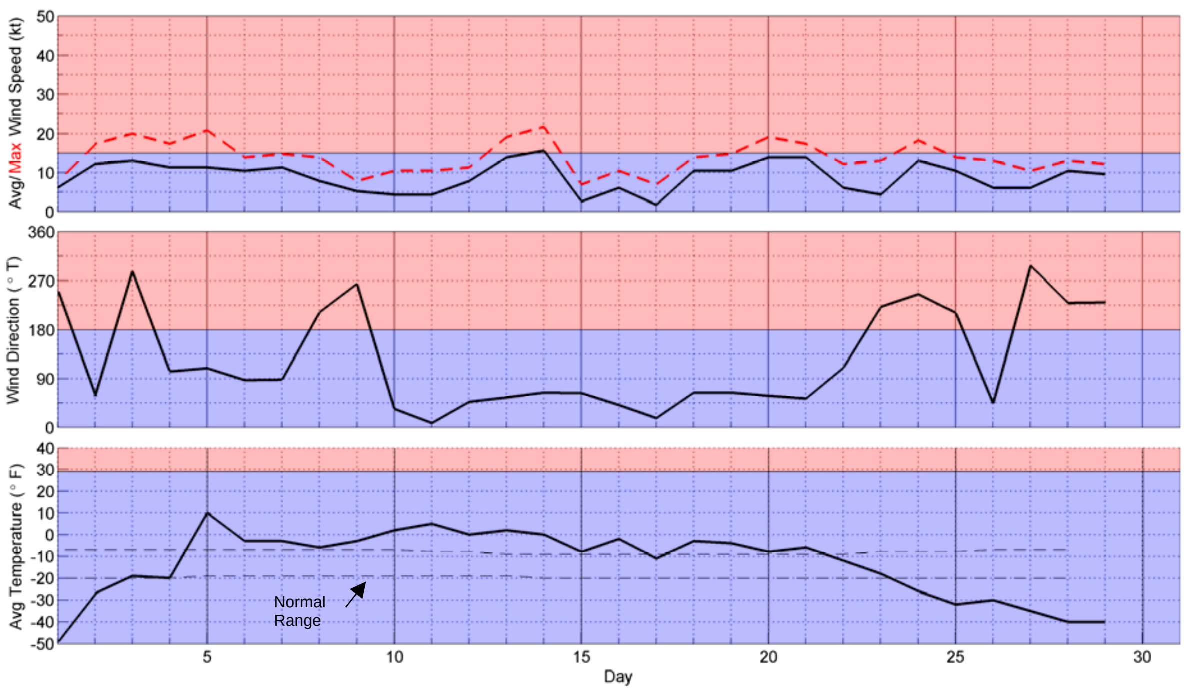
Plate 26. Substantial Lead and Broken Ice at Offshore End of Sivulliq Pipeline Route (February 3, 2012)

Shell's Harrison Bay Prospects were located inside the landfast ice zone at the time of the February reconnaissance flights. As indicated in Drawings CFC-863-02-001 and -002 and show in Plates 27 and 28, the ice cover was unremarkable and relatively uniform with ridge and rubble heights typically ranging from 2 to 3 m. Neither leads nor broken ice were observed in this region during the flights, which were conducted on the 3rd and 5th.

4.7 Mid-Winter

4.7.1 February 2012

Meteorological Conditions: The meteorological conditions recorded at Deadhorse Airport in February are displayed in Figure 33. The average daily temperature increased from below normal at the start of the month to above normal on the 5th, remained above normal through the 21st, and decreased steadily thereafter. Easterly winds predominated, occurring on 19 of 29 days including an uninterrupted stretch of 13 days in mid-month.



Source: Weather Underground, 2012

Figure 33. Meteorological Conditions at Deadhorse Airport in February 2012

Storm activity was limited to a one-day easterly on February 14th (Table 4). The average daily wind speed was 16 kt (8 m/s), the minimum value necessary to qualify as a storm event under the definition adopted for this study.

Plate 27. Intermittent Rubble with Heights to 3 m in Central Portion of Harrison Bay Prospects (February 3, 2012)

Plate 28. 3-m Rubble in Western Portion of Harrison Bay Prospects (February 5, 2012)

Ice Thickness: The calculated thickness of undisturbed first-year ice increased by 19 cm, from 120 to 139 cm.

Landfast Ice: Figure 34 presents the locations of the landfast ice edge derived from RADARSAT-2 images obtained on January 29th and February 8th, 12th, and 29th. Between January 29th and February 8th, a period that contained five days of easterly winds with average speeds of 10 to 13 kt (5 to 7 m/s), the landfast ice edge moved seaward in virtually all areas of the central and western Beaufort Sea. The advances were greatest to the west of Weller Bank and east of Stamukhi Shoal, in the regions that had experienced substantial retreat during the prior period of westerly winds (Figure 28). As a result, the landfast ice edge on February 8th tended to lie on or seaward of the 18-m isobath over the entire stretch of coast from Point Barrow to Camden Bay.

The extent of the landfast ice zone remained virtually unchanged between February 8th and 12th, a period of light winds. Thereafter, from the 12th to the 29th, the width grew modestly between Smith Bay and Harrison Bay, and also off Stamukhi Shoal. As in the case of the much larger gains seen earlier in the month, these changes reflect a predominance of easterly winds including the one-day storm that occurred on the 14th (Figure 34).

Leads: The RADARSAT-2 image obtained on February 8th displays a number of small leads just outside the landfast ice zone along with a polynya in the central portion of Camden Bay measuring 16 nm long by up to 3 nm wide (30 x 6 km). These features probably formed when the wind shifted from easterly to southwesterly on the day the image was acquired.

On February 12th, the only significant lead radiated to the northeast from vicinity of Point Barrow. The feature was 100 nm (185 km) long and typically ranged from 0.25 to 1.5 nm (0.5 and 2.8 km) in width. No leads were present on February 29th, when the final image of the month was obtained (Figure 35).

Multi-Year Ice: In the central Beaufort, the southern boundary of the multi-year ice band fluctuated only slightly over the course of the month and remained about 65 nm (120 km) north of Flaxman Island at month-end (Figure 35). The situation was markedly different off Point Barrow, however, where the southern boundary lay 20 nm (37 km) offshore on January 29th, 35 nm (65 km) offshore on February 8th, and only 3 nm (6 km) off the coast on February 29th (Figure 35).

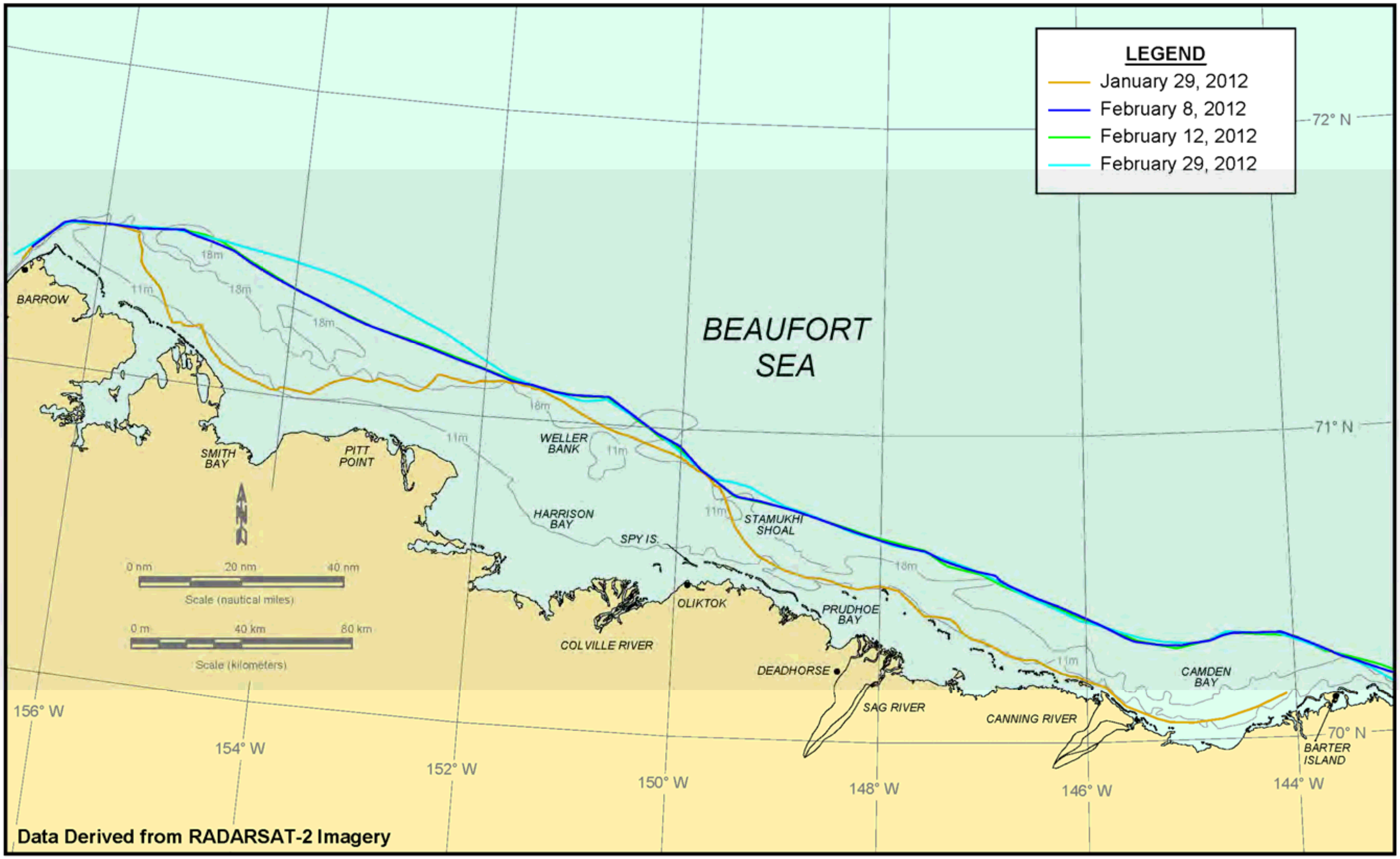


Figure 34. Beaufort Sea Landfast Ice Edge in February 2012

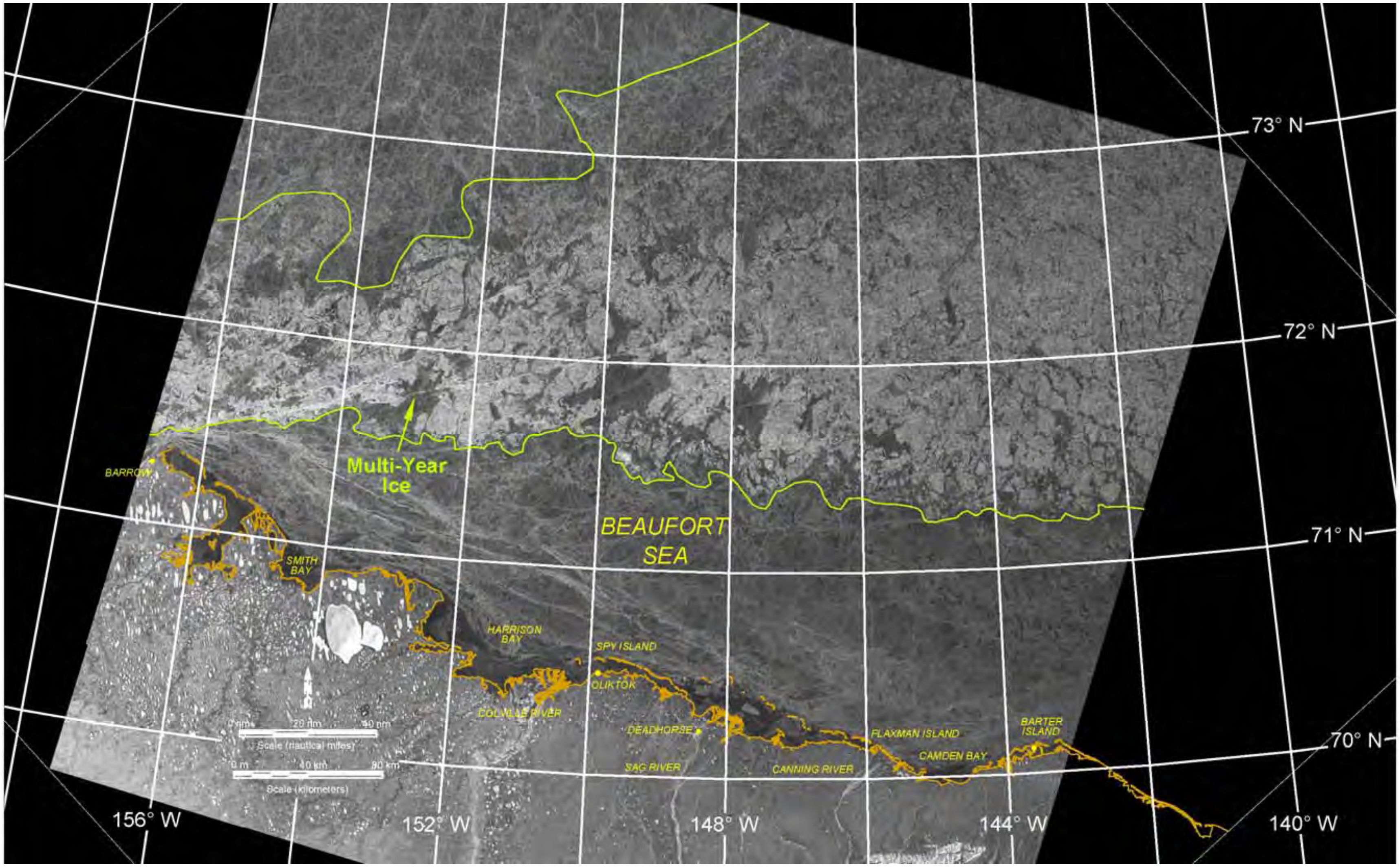


Figure 35. RADARSAT-2 Image of Beaufort Sea Acquired on February 29, 2012

Ice Movement: Ice movement rates in February were investigated using the same three multi-year floes (Floes E, F, and G) and seven Iridium buoys (Buoys 1 through 4 and A through C) tracked in January. The three floes were identified in the RADARSAT-2 images obtained on January 29th and February 8th, 12th, and 29th. In the case of the buoys, hourly position data were available for the entire month.

The resurgence of easterly winds in February (Figure 33) led to the re-establishment of the Beaufort Gyre. Drift speeds remained low, however, due in part to the dearth of easterly storm events and in part to the confinement provided by the mid-winter ice canopy. As shown in Figure 36, the three multi-year floes moved to the west at speeds that averaged 2.0 to 3.1 nm/day (3.7 to 5.7 km/day) over the course of the month. The mean monthly speed was 2.4 nm/day (4.4 km/day). Short-term speeds between successive positions varied from a minimum of 0.4 nm day (0.7 km/day; Floe E between the 12th and 29th) to a maximum of 5.7 nm/day (10.6 km/day; Floe G between the 8th and 12th).

The tracks described by the seven Iridium buoys during the month of February are displayed in Figure 37 based on the positions reported at midnight of each day. The three buoys in eastern Harrison Bay (Buoys A, B, and C) were located within the landfast ice zone, and therefore remained stationary.

The four buoys in western Camden Bay moved to the west by amounts that increased with distance offshore. The net displacements were relatively small, however, ranging from a near-negligible 0.3 nm (0.6 km) over the course of the month for the inshore buoy (Buoy 1) to 18.4 nm (34.0 km) for the offshore buoy (Buoy 4).

Figure 38 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. The plots indicate that nearly all of the buoy movement occurred during the first ten days of the month, when the winds remained light while alternating between east and west on five occasions. It thus appears that the motion resulted from the ice losing confinement rather than from a strong motive force such as a sustained easterly storm.

In keeping with the light-to-moderate wind speeds that predominated in February, the calculated buoy speeds were unexceptional. The maximum daily speed of 0.36 kt and maximum hourly speed of 1.31 kt were attained by Buoy 4 on the 7th, when easterly winds prevailed with a daily average speed of 11 kt and maximum sustained speed of 15 kt (Figure 33).

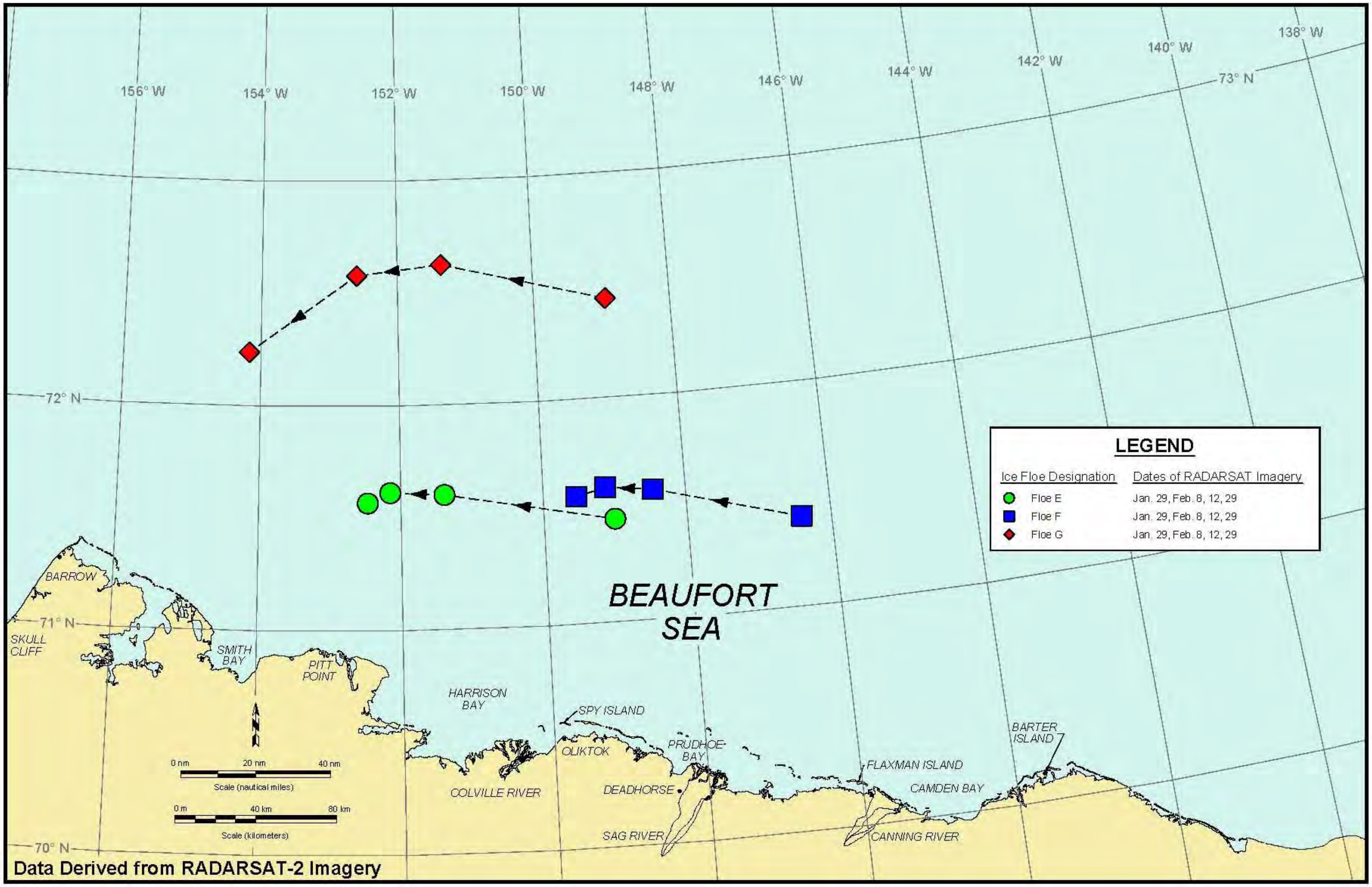


Figure 36. Beaufort Sea Multi-Year Ice Floe Tracks in February 2012

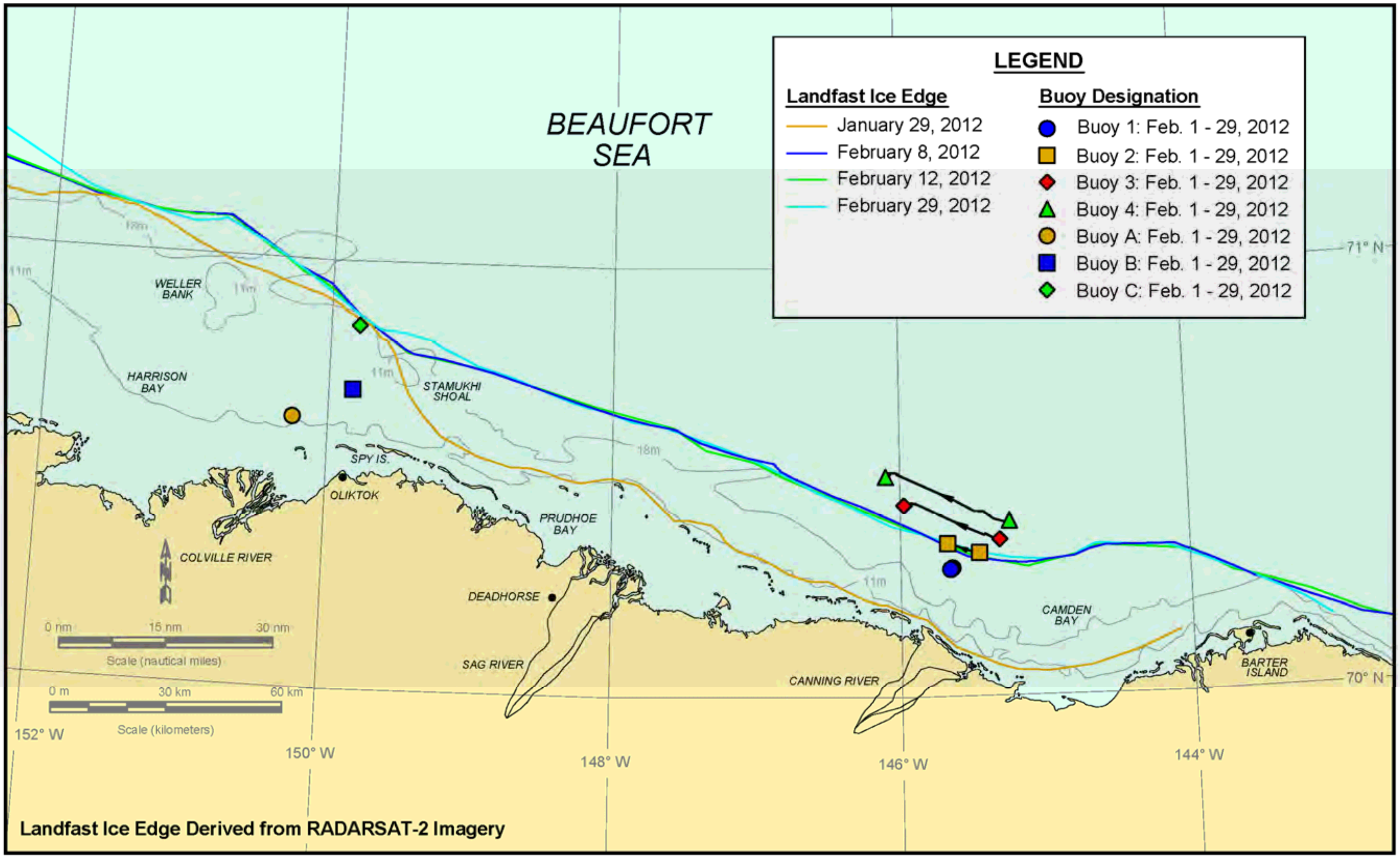


Figure 37. Beaufort Sea Iridium Buoy Tracks in February 2012

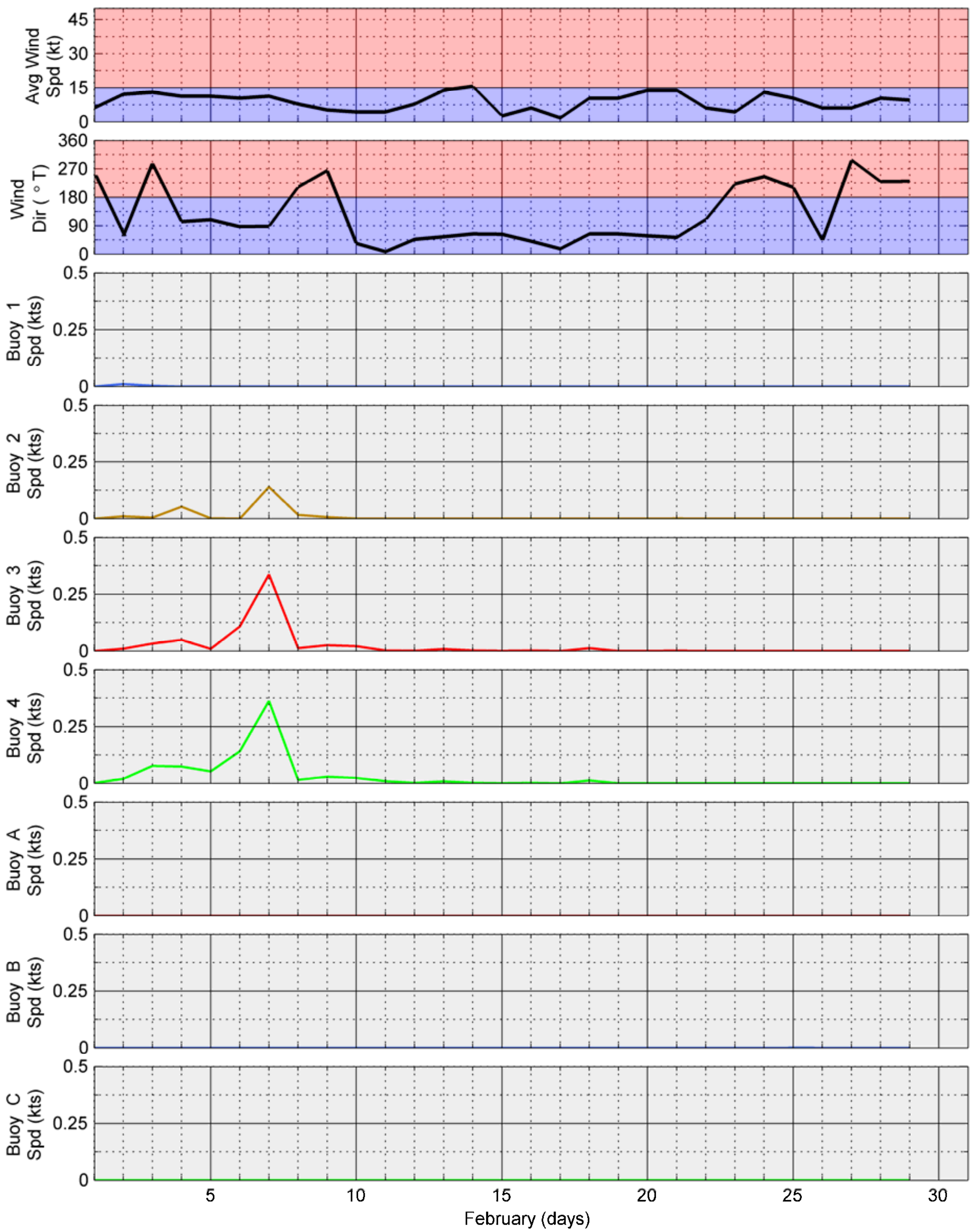
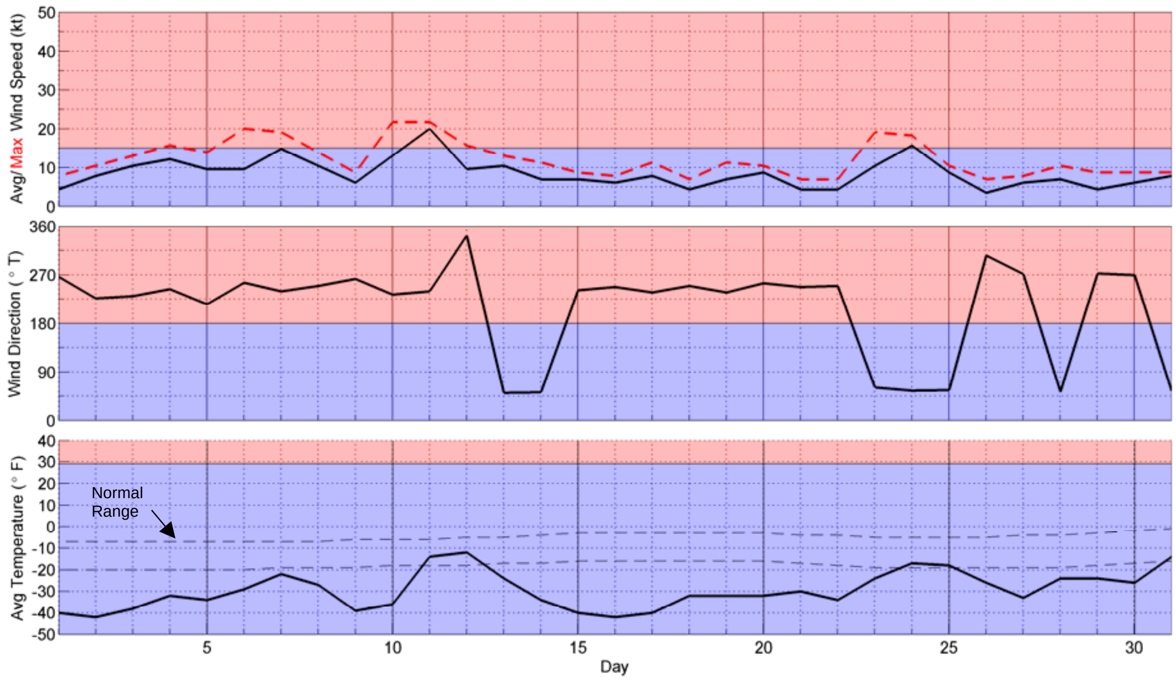


Figure 38. Time Series of Iridium Buoy Average Daily Speeds in February 2012

4.7.2. March 2012

Meteorological Conditions: Figure 39 presents the wind and temperature data recorded at Deadhorse Airport in March 2012. The below-normal air temperatures that began during the last week in February continued throughout the month of March. The winds tended to be light, with westerlies outnumbering easterlies by a ratio of more than three to one (24 days of westerly winds versus 7 of easterly winds).



Source: Weather Underground, 2012

Figure 39. Meteorological Conditions at Deadhorse Airport in March 2012

Two brief storm events occurred in March: a one-day westerly with speed of 20 kt (10 m/s) on the 11th, followed by a one-day easterly with a speed of 16 kt (8 m/s) on the 24th (Table 4).

Ice Thickness: The calculated thickness of undisturbed first-year ice increased by 24 cm, from 139 cm at the beginning of the month to 163 cm at the end.

Landfast Ice: Figure 40 presents the locations of the landfast ice edge derived from RADARSAT-2 images obtained on February 29th and March 14th (the last such image of the Beaufort Sea available for this study). During the two-week period between images, the landfast ice zone expanded modestly to the west of Stamukhi Shoal while shrinking dramatically between Prudhoe Bay and Barter Island. The large retreat of the landfast ice edge probably resulted from the westerly storm that occurred on the 11th, while the modest

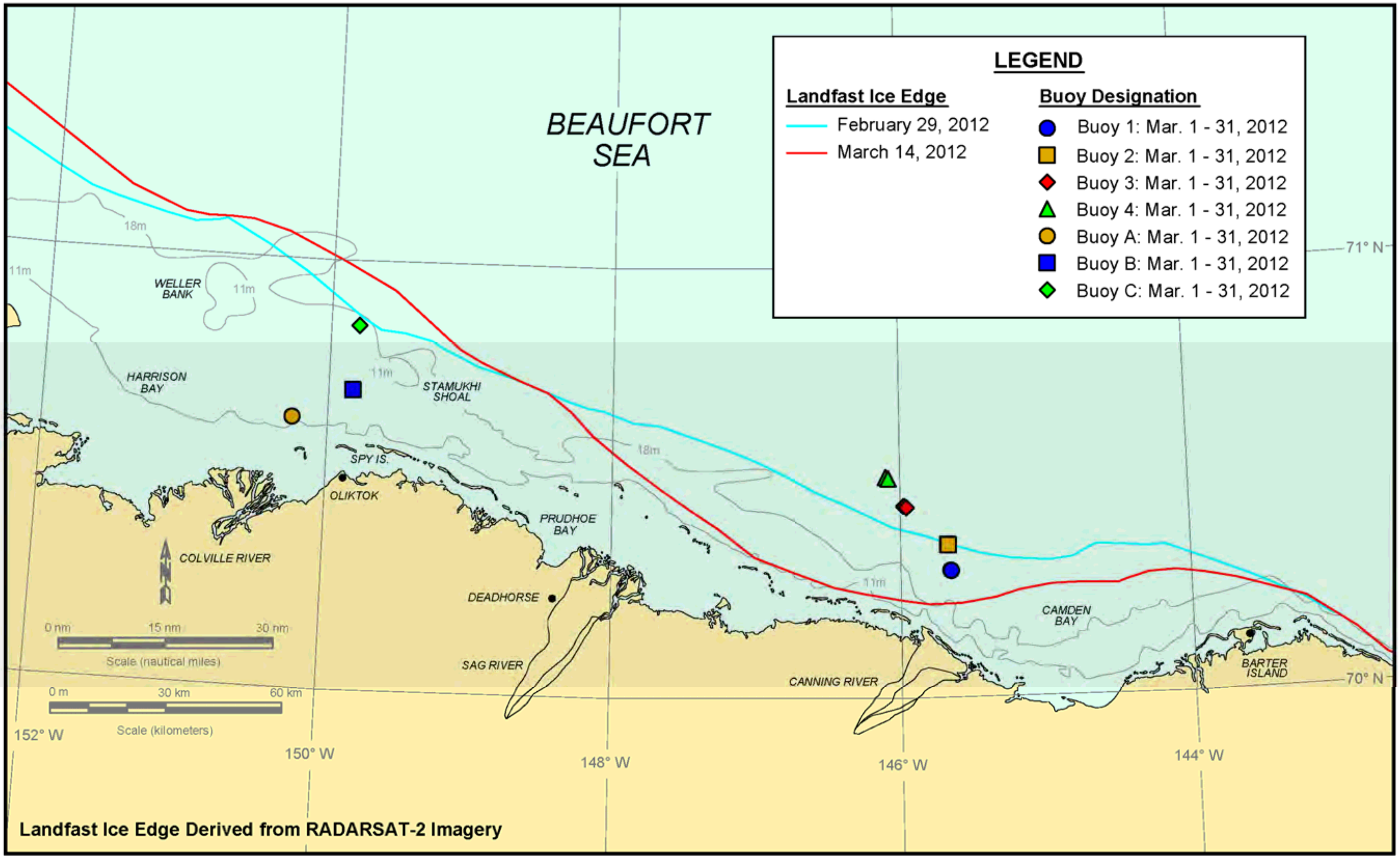


Figure 40. Beaufort Sea Landfast Ice Edge and Iridium Buoy Tracks in March 2012

advance may have resulted from the easterly winds that followed on the 13th and 14th (Figure 39).

Multi-Year Ice: The location and extent of the multi-year ice band on March 14th (Figure 41) closely resembled that on February 29th (Figure 35). Although no RADARSAT-2 images are available after March 14th, the CIS ice chart for March 26th depicts a similar situation: substantial separation between the Alaskan Beaufort Sea coast and the multi-year band except at Point Barrow (CIS, 2012).

Ice Movement: As indicated by the Iridium buoy tracks shown in Figure 40, minimal ice movement occurred in the nearshore region during the month of March. Buoys A, B, and C in eastern Harrison Bay remained stationary, while Buoys 1 through 4 in western Camden Bay moved to the southeast over distances that ranged from 0.1 nm (0.2 km) for Buoy 1 to 0.4 km (0.8 km) for Buoy 4. These small displacements probably resulted from the aforementioned westerly storm on the 11th (Table 4).

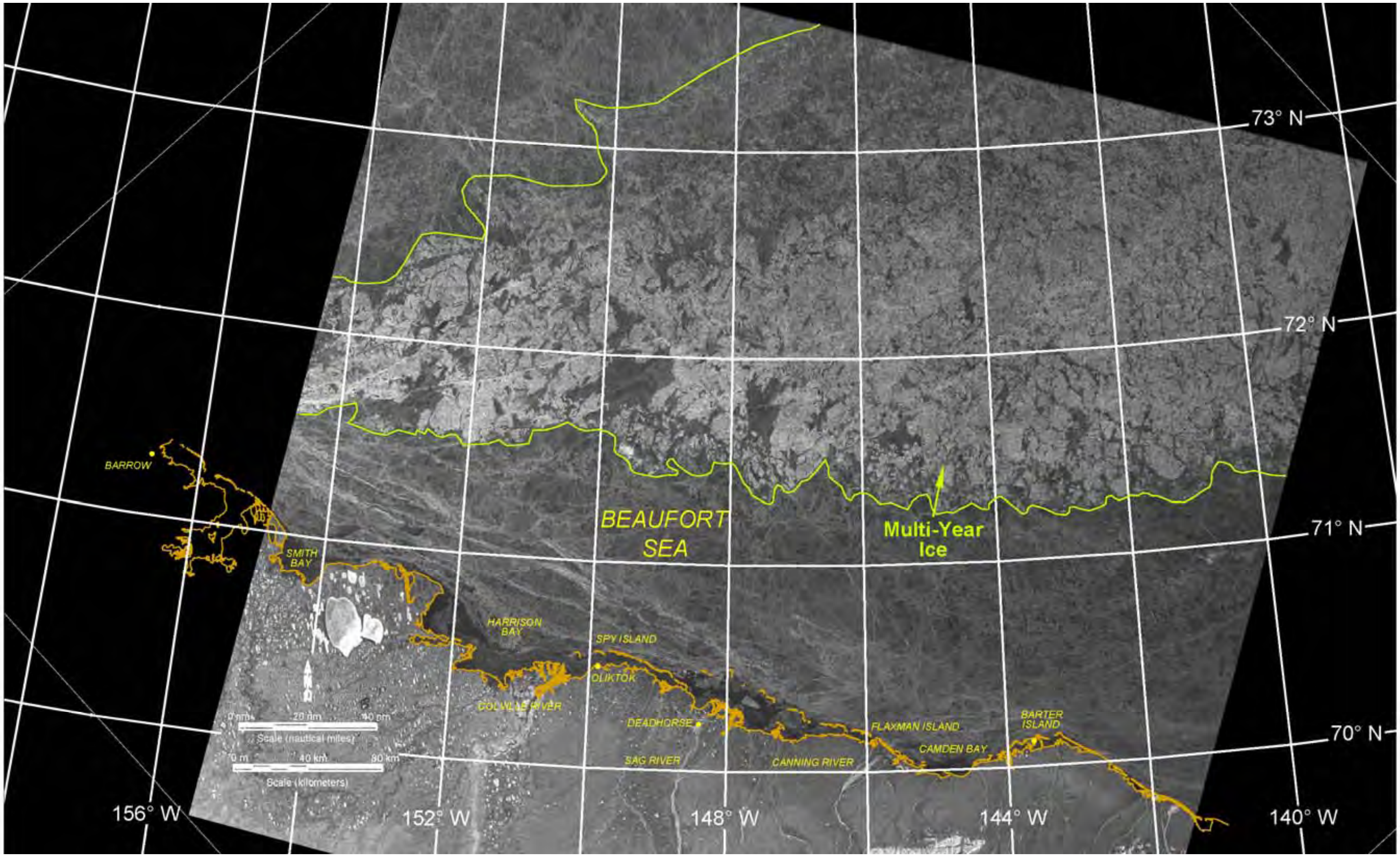


Figure 41. RADARSAT-2 Image of Beaufort Sea Acquired on March 14, 2012

5. CHUKCHI SEA

Section 5.1 presents a brief overview of the 2011-12 freeze-up season in the northeast Chukchi Sea. As in the case of Section 4.1, emphasis is placed on summary tables. A monthly analysis of the conditions that prevailed from October 2011 through March 2012 follows in Sections 5.2 through 5.7.

5.1 Overview

Air Temperatures: The air temperatures at Barrow Airport tended to range from normal to above-normal during October and the first three weeks in November. After a week-long cold snap in late November, normal temperatures returned at the beginning of December and persisted through the third week in January. Two weeks of colder-than-normal temperatures in late January and early February were followed by two weeks of warmer-than-normal temperatures in mid-month. The temperatures fell below normal again on February 24th, and remained so with only minor exceptions through the end of March.

Winds: Wind conditions during the 2011-12 freeze-up season are summarized in Table 9, which is based on the average daily speeds and directions recorded at Barrow Airport. In contrast to the Beaufort, where westerlies predominated, easterlies occurred 71% of the time in the Chukchi. The average monthly speeds tended to decrease as the season progressed, peaking at 13 kt (7 m/s) in October and diminishing to 8 kt (4 m/s) in March.

Table 9. Chukchi Sea Wind Characteristics, October 2011 – March 2012

Month	Days		Average Speed (kt)
	Easterly	Westerly	
October	28	3	13
November	16	14	10
December	27	4	11
January	14	17	9
February	23	6	9
March	22	9	8
Total Days	130	53	n/a
Frequency (%)	71	29	n/a

Note: Table 9 is based on the average daily wind speeds and directions recorded at Barrow Airport.

Storms: 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 10 for the six-month period from October 2011 through March 2012. Eight of the eleven events were easterlies, while only three were westerlies. October and November were the stormiest months, with ten and eight days of storm activity, respectively. Storm activity decreased thereafter, with five storm-days in December, two in each of January and February, and none in March.°

Table 10. Chukchi Sea Storm Characteristics, October 2011 – March 2012[1]

Month	Day	Duration (days)	Maximum Wind Speed (kt)[2]	
			Easterly	Westerly
October	12-16	5	26	
	22-26[3]	5	23	
November	Oct 30-Nov 2[4]	4		17
	9-12	4	26	
December	4-5	2	28	
	11-12	2	24	
	28	1	17	
January	8	1		17
	13	1		17
February	6	1	16	
	20	1	16	
March[5]				
Total Duration		**27**		
Total Number of Events			**8**	**3**

Notes:

1 Table 10 includes all storm events with a daily average sustained wind speed exceeding 15 kt at Barrow 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 24 but freshened to 22 kt on October 25.

4 Daily average wind speed decreased to 14 kt on October 31 and 15 kt on November 1 but freshened to 17 kt on November 2.

5 No storms occurred in March.

Ice Cover: Ice began to form in Kasegaluk Lagoon during the first week in October. By mid-month, the surface of the Lagoon was completely frozen while pack ice had begun to move south of the 75°N parallel and west of the 155°W meridian. Freeze-up progressed slowly over the next month, with complete ice coverage in the nearshore region occurring on November 20th. Complete coverage of the entire Chukchi Sea north of Cape Lisburne followed on November 30th.

Ice Thickness: The thickness of undeformed first-year ice at the end of each month was estimated using the relationship of Lebedev (Bilello, 1960) in concert with the accumulated freezing degree days (FDD) at Barrow shown in Table 1. The method of calculation is identical to that presented for the Beaufort Sea in Section 4.1. The results are provided in Table 11, which indicates that undisturbed first-year ice attained a thickness of approximately 167 cm at the end of May.

Table 11. Chukchi Sea Computed Ice Thicknesses, October 2011 – May 2012[1]

Date	FDD	Accumulated FDD	Ice Thickness[2] (cm)
31 October 2011	180	183	19
30 November 2011	876	1,059	53
31 December 2011	1,205	2,264	83
31 January 2012	1,550	3,814	112
29 February 2012	1,199	5,013	132
31 March 2012	1,575	6,588	154
30 April 2012	731	7,319	164
31 May 2012	237	7,556	167

Notes:

1 Table 11 is based on the average daily temperature data recorded at Barrow Airport.

2 Ice thickness is computed from accumulated FDD using method of Lebedev (Bilello, 1960).

Landfast Ice: As in the Beaufort, the extent of the landfast ice zone varied in response to the wind conditions. The correlation with direction was reversed, however, with westerly (onshore) winds producing expansion and easterly (offshore) winds producing contraction. At the end of November, the landfast ice zone consisted of a narrow strip between Icy Cape and Point Franklin, and a wider expanse in the embayment between Point Franklin and Barrow. Easterly storms produced a net loss in December, particularly in the aforementioned stretch between Point Franklin and Barrow. A predominance of westerly winds in January, coupled with two westerly storms, reversed the loss between Point Franklin and Barrow while causing landfast ice to accumulate on Blossom Shoals off Icy Cape. Nevertheless, the landfast ice zone remained extremely narrow in the vicinity of

Point Belcher and between Wainwright and the mouth of the Nokotlek River. In February, despite a high frequency of easterly winds and the occurrence of two brief easterly storms, the landfast ice zone remained unchanged in some areas and recorded modest gains in others. This outcome suggests that the modest strip of grounded ice had achieved a measure of stability during the prior month of westerly winds.

Ice Pile-Ups: Thirty one ice pile-ups occurred on the coast of the northeast Chukchi Sea during the 2011-12 freeze-up season. The highest concentrations were located on the spit that ends at Point Franklin, and on the barrier islands that lie to the east and south of Icy Cape. As shown in Table 12, the pile-up heights ranged from 3 to 18 m, the encroachment distances from 0 to 40 m (measured from the waterline), the alongshore lengths from 100 to 5,400 m, and the ice block thicknesses from 30 to 60 cm. All of the maximum dimensions were associated with a massive pile-up that overtopped the 15-m high bluff at Skull Cliff and spilled 3 m onto the tundra. The pile-ups probably resulted from two events: (1) a wind shift from northeasterly to north northwesterly that occurred on November 13th, and (2) a wind shift from southeasterly to westerly that occurred on January 7th.

Table 12. Ice Pile-Ups on Chukchi Sea Coast during 2011-12 Freeze-Up Season

No.	Region	Formation Date	Ice Block Thickness (cm)	Length[1] (m)	Height[2] (m)	Encroachment[3] (m)
1	Skull Cliff	1/7/2012	30-60	4,500	6	15
2	Skull Cliff	1/7/2012	30-60	5,400	18	40
3	Skull Cliff	11/13/2011	30	400	3	10
4	Skull Cliff	11/13/2011	30	2,400	3	10
5	Skull Cliff	11/13/2011	30	1,300	6	15
6	Skull Cliff	11/13/2011	30	1,200	4	30
7	Skull Cliff	11/13/2011	30	1,100	4	20
8	Pt. Franklin	11/13/2011	30	1,200	7	10
9	Pt. Franklin	11/13/2011	30	500	4	0
10	Pt. Franklin	11/13/2011	30	300	5	0
11	Pt. Franklin	11/13/2011	30	1,200	6	5

(continued)

Table 12. Ice Pile-Ups on Chukchi Sea Coast during 2011-12 Freeze-Up Season (continued)

No.	Region	Formation Date	Ice Block Thickness (cm)	Length[1] (m)	Height[2] (m)	Encroachment[3] (m)
12	Pt. Franklin	11/13/2011	30	300	6	10
13	Pt. Franklin	11/13/2011	30	2,300	10	10
14	Pt. Franklin	11/13/2011	30	800	5	0
15	Kuk R. Mouth	1/7/2012	30-60	300	3	5
16	E of Icy Cape[4]	11/13/2011	30	800	3	5
17	E of Icy Cape[4]	1/7/2012	30-60	1,200	5	10
18	E of Icy Cape[4]	11/13/2011	30	500	4	0
19	E of Icy Cape[4]	1/7/2012	30-60	1,300	5	5
20	E of Icy Cape[4]	11/13/2011	30	300	4	0
21	E of Icy Cape[4]	1/7/2012	30-60	1,200	8	20
22	E of Icy Cape[4]	11/13/2011	30	100	4	0
23	S of Icy Cape[5]	11/13/2011	30	400	4	8
24	S of Icy Cape[5]	1/7/2012	30-40	500	6	15
25	S of Icy Cape[5]	1/7/2012	30-40	100	3	5
26	S of Icy Cape[5]	1/7/2012	30-40	400	3	30
27	S of Icy Cape[5]	1/7/2012	30-40	300	8	5
28	S of Icy Cape[5]	1/7/2012	30-40	700	4	8
29	S of Icy Cape[5]	1/7/2012	30-40	3,000	5	30
30	S of Icy Cape[5]	1/7/2012	30-40	800	4	20
31	S of Icy Cape[5]	1/7/2012	30-40	400	4	5

Notes:

[1] "Length" indicates alongshore extent of pile-up.
[2] "Height" indicates maximum height of pile-up relative to MSL.
[3] "Encroachment" indicates distance ice advanced onto subaerial beach.
[4] Pile-up occurred on barrier islands east of Icy Cape.
[5] Pile-up occurred on barrier islands south of Icy Cape.

Multi-Year Ice: From Mid-November to mid-December, multi-year ice floes arriving from the Beaufort tended to remain above the 72°N parallel in the Chukchi. The situation changed dramatically in mid-December, when such floes began to enter the flaw lead off the northeast Chukchi coast and head to the southwest. This pattern of southwesterly drift, which persisted through March, introduced a substantial quantity of multi-year ice into a large area region that ultimately reached as far south as the 68°N parallel. The floe diameters ranged from less than 100 m to more than 20 km.

Ice Movement: Five of the eight multi-year ice floes that were tracked in the Beaufort Sea (Section 4.1) entered the Chukchi prior to the end of the study period. Their westerly drift continued despite a hiatus in January that resulted from westerly winds (Table 9). The primary difference from the Beaufort was a tendency for the floes to move southwest rather than west – an outcome that reflects the channeling effect of the coastal flaw lead as well as the reduced influence of the Beaufort Gyre to the south and west of Point Barrow. As shown in Table 13, the average floe speeds recorded during each month from November through February ranged from 0.3 to 7.8 nm/day (0.6 to 14.5 km/day). The average monthly value was 4.3 nm/day (8.0 km/day).

Table 13. Chukchi Sea Multi-Year Ice Floe Speeds, November 2011 - February 2012

Month	Monthly Speed (nm/day)[1]		
	Maximum	Minimum	Average[2]
November	7.8	7.8	7.8
December	7.9	5.2	6.2
January	0.9	0.3	0.6
February	2.9	2.2	2.5
Average			4.3

Notes:

1 Monthly speeds are derived from periods ranging from 12 to 27 days (depending on data availability).

2 Average monthly speeds are derived from 1 floe in November and 4 floes in each of December, January, and February.

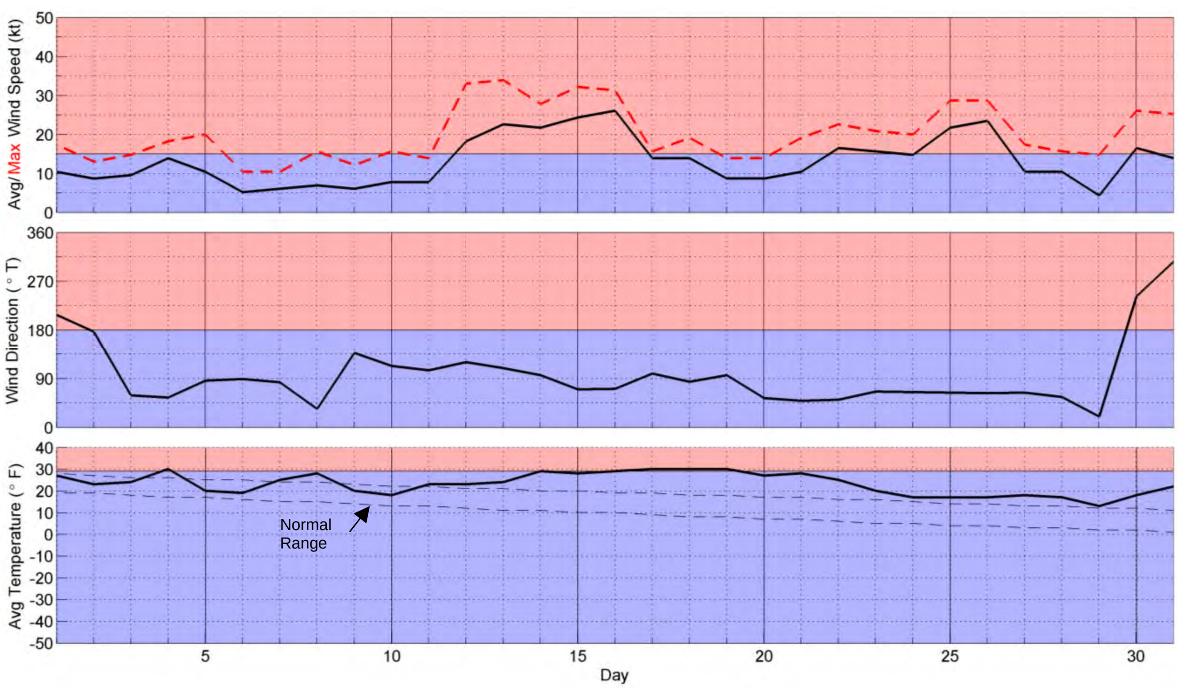
5.2 Late Summer 2011

At the beginning of August, open water prevailed along the entire Alaskan Chukchi Sea coast. Farther west, a tongue of ice centered on the 169°W meridian extended south to the 70°N parallel. In a pattern reminiscent of that which occurred in 2010, the ice edge retreated to the north and west throughout August and early September. By mid-September, the entire Chukchi was ice-free with the exception of two small patches located on or above the 73°N parallel.

5.3. Early Freeze-Up

5.3.1. October 2011

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 42. 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 8. 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).



Source: Weather Underground, 2012

Figure 42. Meteorological Conditions at Barrow Airport in October 2011

As in 2010, air temperatures ranged from normal to above normal in October 2011. With the exception of one day at the beginning and two days at the end, easterly winds prevailed throughout the month. Protracted easterly storms occurred on two occasions: a five-day event with a maximum wind speed of 26 kt (13 m/s) from the 12th through 16th, and a second five-day event with a maximum wind speed of 23 kt (12 m/s) from the 22nd through 26th. A westerly storm that began on the 30th will be covered in Section 5.3.2.

Ice Cover: Freeze-up in the Chukchi Sea began during the first week in October, when ice began to form in the protected waters of Kasegaluk Lagoon. By mid-month, the surface of the Lagoon was completely frozen while pack ice had begun to move south of the 75°N parallel and west of the 155°W meridian. The pack ice advanced slowly to the southwest during the remainder of the month, while a narrow strip of landfast ice developed along much of the coast between Wainwright and Cape Lisburne. At month-end, however, the majority of the Chukchi remained unfrozen (Figure 43).

Ice Thickness: The thickness of undisturbed first-year ice at the end of October was approximately 19 cm (Table 11).

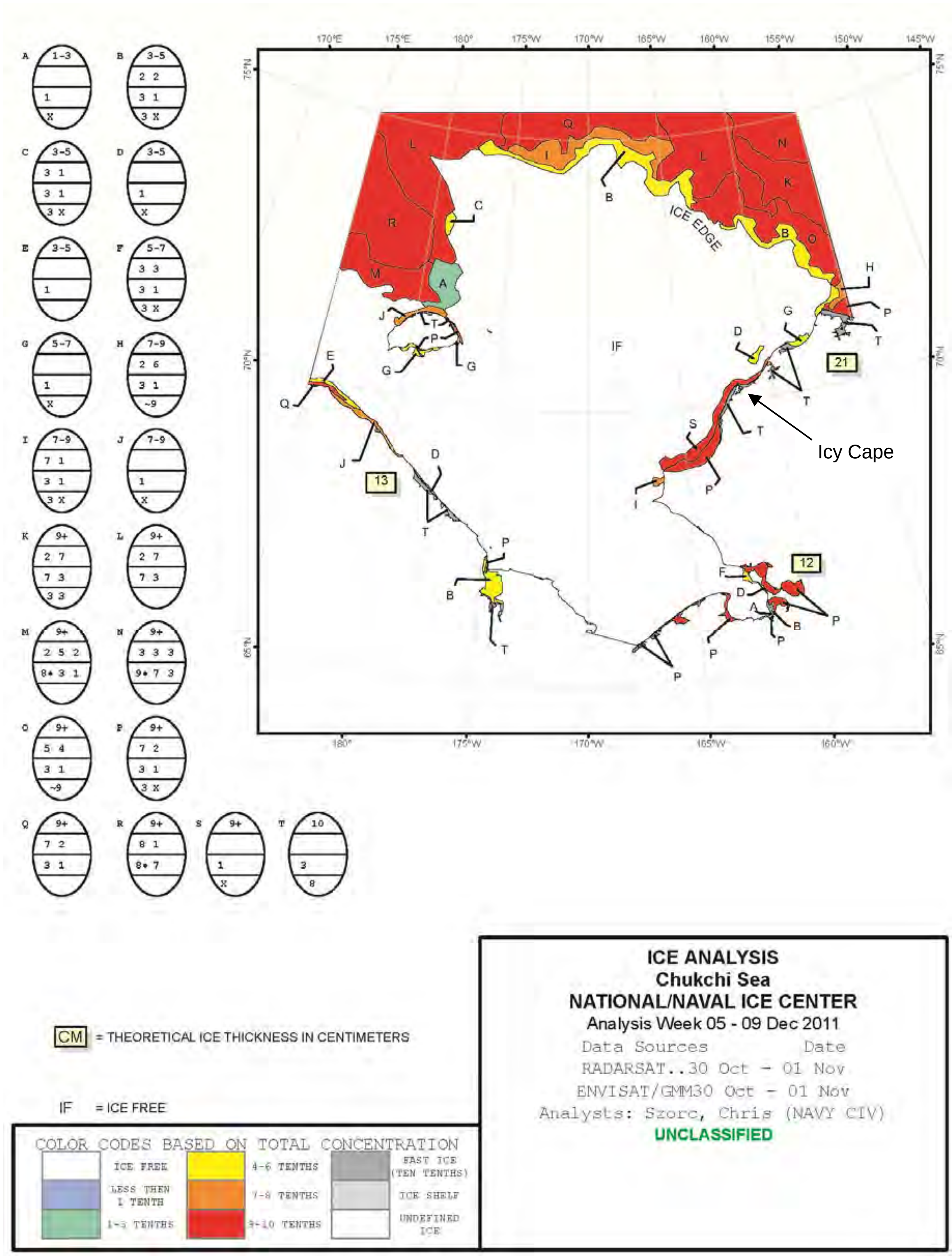
Multi-Year Ice: The ice charts and RADARSAT-2 images available for October indicate that no multi-year ice was present south of the 74°N parallel.

5.3.2. November 2011

Meteorological Conditions: The wind and temperature data acquired at Barrow Airport in November are shown in Figure 44. The average daily air temperatures varied between normal and above-normal during the first three weeks of the month before falling below normal at the end.

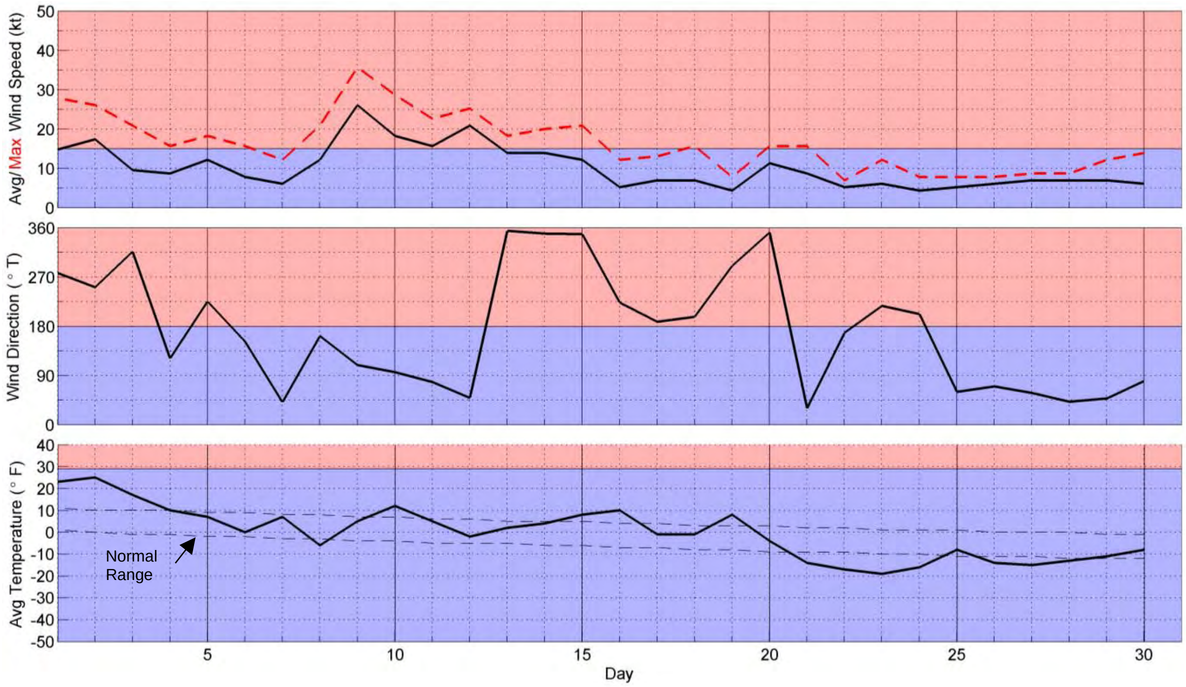
Easterly and westerly winds occurred with nearly equal frequency (Table 9). Storm events were limited to a four-day westerly from October 30th through November 2nd with a maximum wind speed of 17 kt (9 m/s), and a four-day easterly from November 9th through 12th with a maximum wind speed of 26 kt (13 m/s; Table 10).

Ice Cover: The measured pace at which freeze-up began in October persisted through the first three weeks in November, when the air temperatures remained relatively high. During this period, the southern edge of the pack ice moved south to the 72.5°N parallel while the loosely-consolidated band of ice along the coast expanded west to the vicinity of the 167°W meridian. Freeze-up in the nearshore region (defined for the present purpose as the region south of Point Barrow and east of the 163°W meridian, which passes through



After: National Ice Center, 2012

Figure 43. Chukchi Sea Ice Conditions on November 1, 2011



Source: Weather Underground, 2012

Figure 44. Meteorological Conditions at Barrow Airport in November 2011

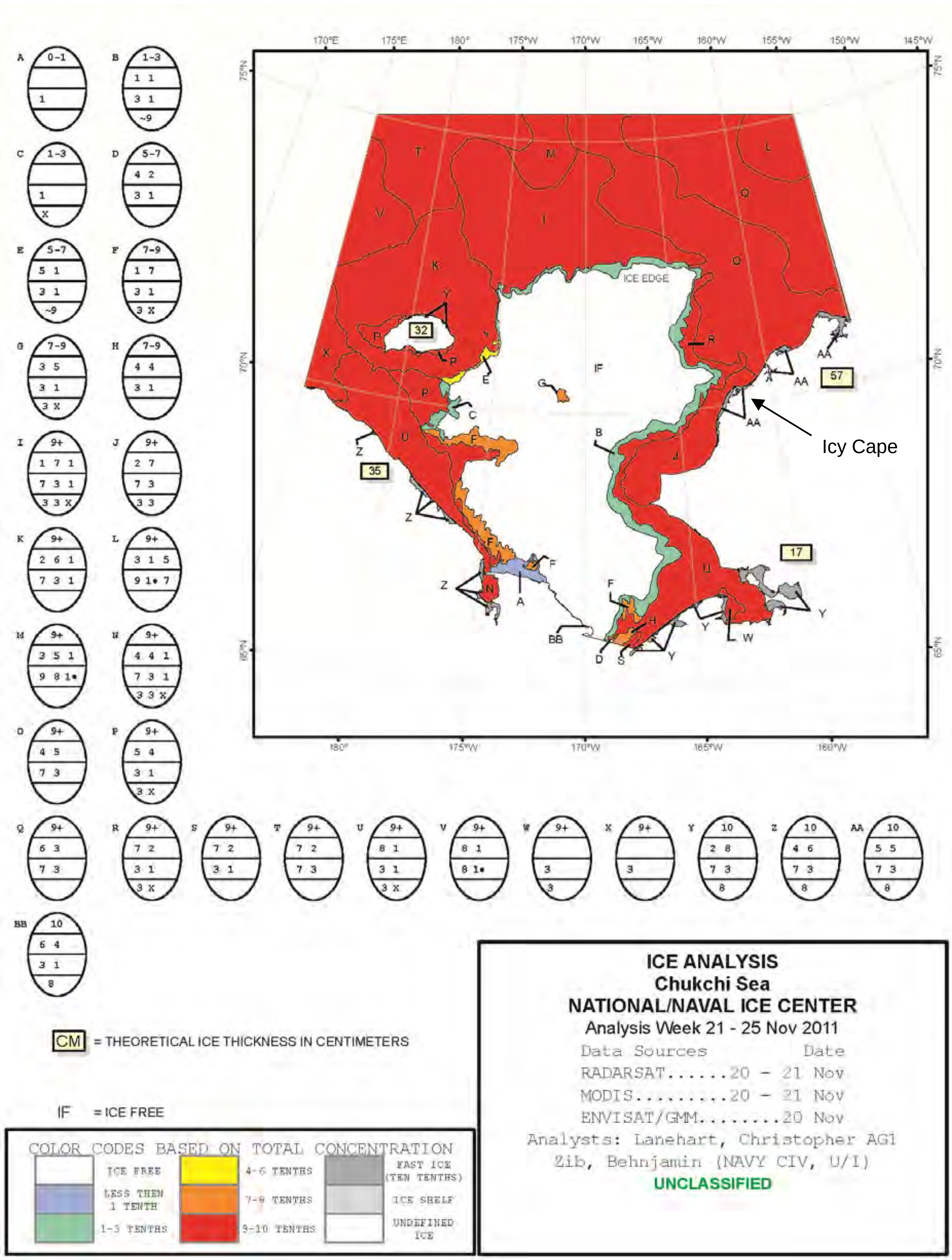
Point Lay) occurred on or about November 20th. (Figure 45). Six hundred and one FDD had accumulated at Barrow Airport prior to this date.

The pace of freeze-up quickened substantially during the last ten days of the month in response to air temperatures below 0°F (-18°C) coupled with a lack of strong winds (Figure 44). Complete freeze-up in the region north of Cape Lisburne occurred on or about November 30th (Figure 46), after 1,022 FDD had accumulated at Barrow Airport.

RADARSAT-2 images obtained at weekly intervals indicate that all four Shell prospects (Hanna Shoal, West, Crackerjack, and Burger) remained ice-free through November 9th. By the end of the month, all four were completely covered with ice. The progress of freeze-up in each prospect is summarized in Table 14

Ice Thickness: The calculated thickness of undisturbed first-year ice increased from 19 cm at the beginning of the month to 53 cm at the end (Table 11).

Landfast Ice: The first RADARSAT-2 image to display landfast ice was acquired on November 16th. As shown in Figure 47, the fast ice was confined to Peard Bay. By the 23rd,



After: National Ice Center, 2012

Figure 45. Chukchi Sea Ice Conditions on November 20, 2011

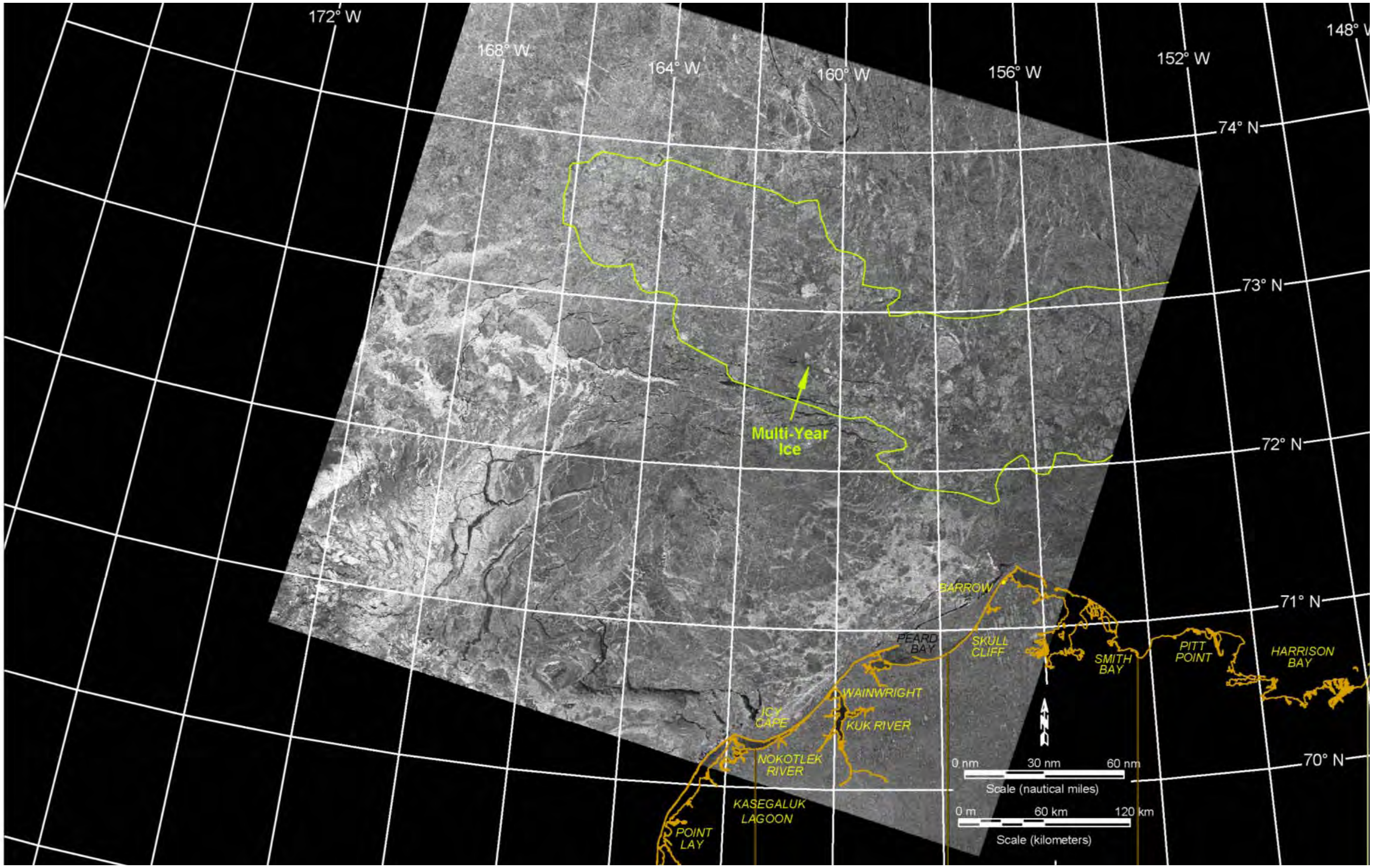


Figure 46. RADARSAT-2 Image of Chukchi Sea Acquired on November 30, 2011

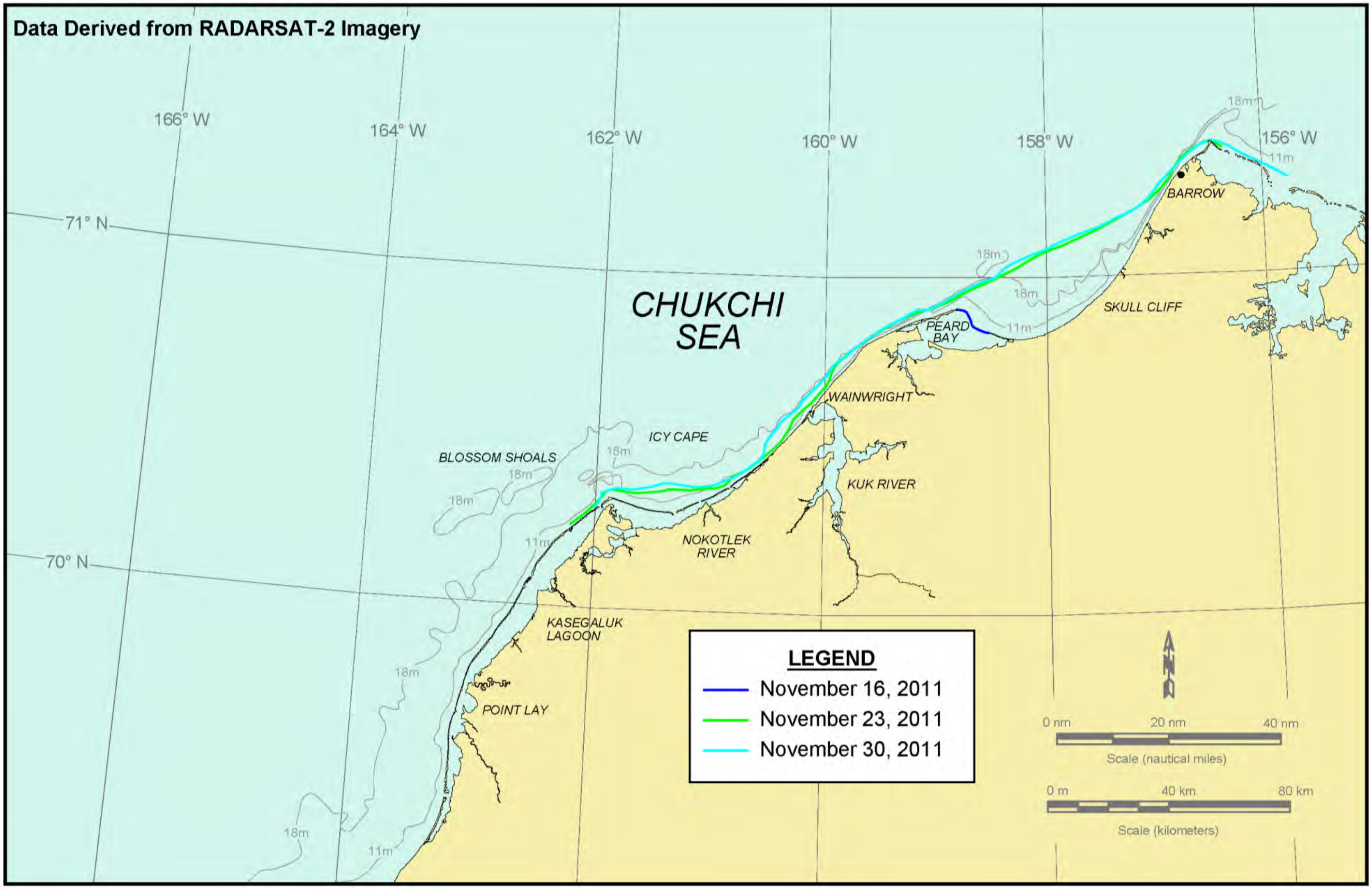


Figure 47. Chukchi Sea Landfast Ice Edge in November 2011

Table 14. Ice Cover in Shell's Chukchi Sea Prospects during Freeze-Up

Date	Ice Cover (%)			
	Hanna Shoal	West	Crackerjack	Burger
Nov 2	0	0	0	0
Nov 9	0	0	0	0
Nov 16	100	0	0	90
Nov 23	100	0	70	100
Nov 30	100	100	100	100

Note:[1] Ice cover is estimated from weekly RADARSAT-2 images.

an intermittent strip of landfast ice ranging from 0 to 4 nm (0 to 7 km) in width extended from Icy Cape to Point Franklin, and a much wider expanse covered the embayment between Point Franklin and Point Barrow. During the week that followed, the strip of ice in the vicinity of Wainwright widened by up to 2 nm (4 km) while the remainder of the landfast ice zone experienced only minor changes.

Ice Pile-Ups: During the aerial reconnaissance flights conducted on November 30th and February 11th (Section 3.5), seventeen ice pile-ups that appeared to have formed in November were observed on northwest-facing segments of the coast between Barrow and Point Lay (Table 12). The piles probably formed on November 13th, when strong northeasterly winds were followed by a moderate north northwesterly (Figure 44). Additional details are provided in Section 5.4.5.

Multi-Year Ice: By the third week in November, multi-year ice floes arriving from the Beaufort began moving south of the 72°N parallel as they entered the Chukchi. As shown in Figure 46, the southern boundary of the multi-year ice was located approximately 30 nm (56 km) off Point Barrow on November 30th.

Ice Movement: Floe A, which was tracked in the Beaufort Sea using RADARSAT-2 images obtained on November 11th and 18th (Figure 22), continued west into the Chukchi prior to the acquisition of another image on the 23rd. It then moved to the west northwest between the 23rd and 30th in a manner consistent with the circulation of the Beaufort Gyre (Figure 48). The average speed decreased from 8.9 nm/day (16.5 km/day) between 18th and 23rd to 7.1 nm/day (13.2 km/day) between the 23rd and 30th. The "monthly speed", computed on the basis of the net displacement between the 18th and 30th, was 7.8 nm/day (14.5 km/day; Table 13).

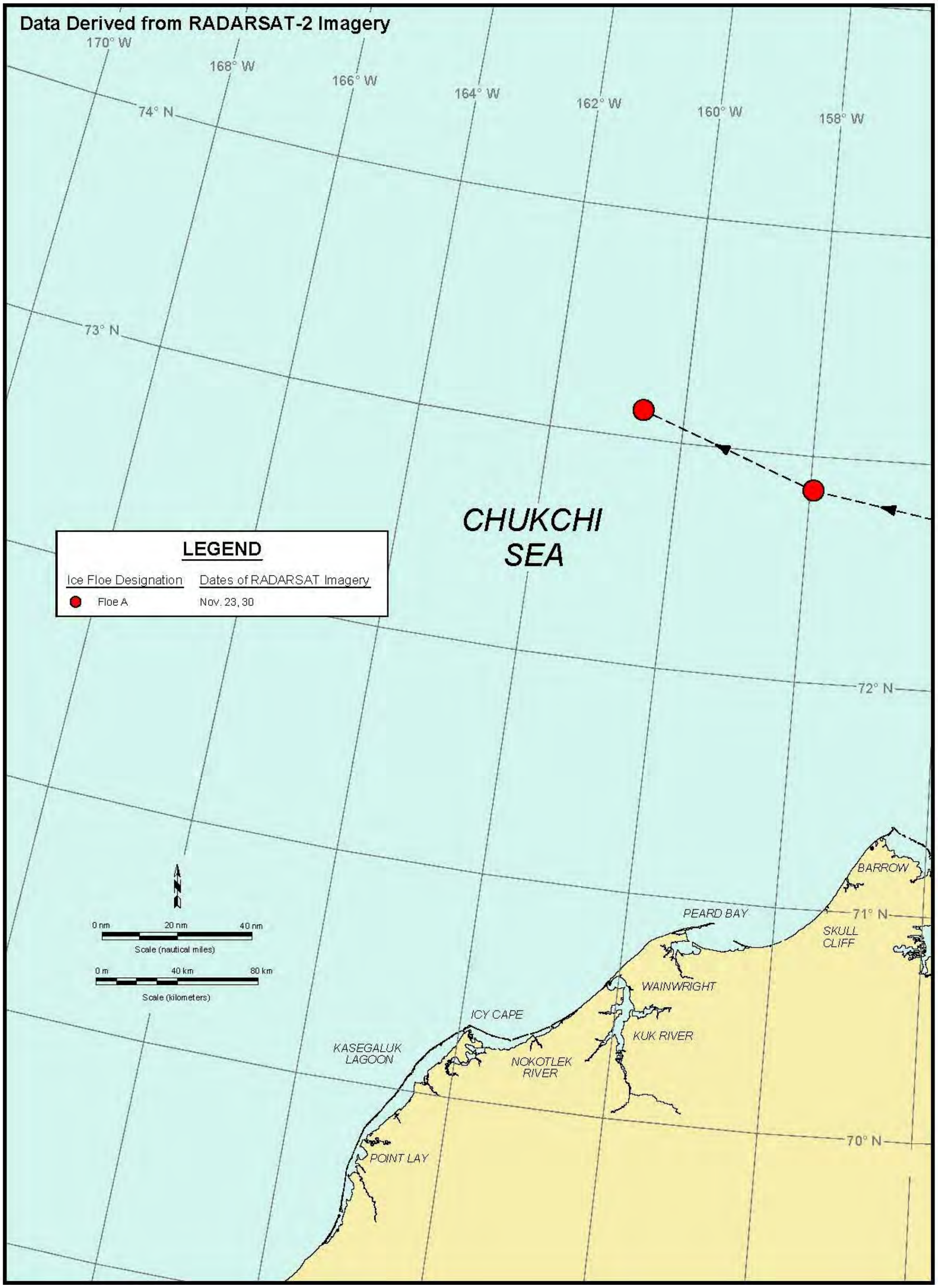


Figure 48. Chukchi Sea Multi-Year Ice Floe Displacements in November 2011

5.4 November Reconnaissance Flight

An aerial reconnaissance mission was undertaken on November 30th to observe the ice conditions that prevailed in the northwestern Chukchi Sea early in the freeze-up season (Section 3.5). Coincidentally, this was the date on which complete freeze-up occurred in the region north of Cape Lisburne (Section 5.3.2), and also the date on which a RADARSAT-2 image was acquired (Figure 46). The flight path, a counterclockwise loop that included the Burger Prospects, the Crackerjack Prospects, and the coast from Icy Cape to Point Franklin, is shown in Drawing CFC-863-01-002. As in the case of the Beaufort flight conducted on November 28th (Section 4.4), the acquisition of still and video images was hampered by limited daylight and intermittent clouds and fog.

5.4.1 Lagoon Ice

The nearshore ice in the protected waters of Kasegaluk Lagoon and Peard Bay was observed to be flat and undeformed. A representative view of the ice in the Lagoon off the mouth of the Nokotlek River is provided in Plate 29.

Plate 29. Flat, Undeformed Ice in Kasegaluk Lagoon off Nokotlek River Mouth (November 30, 2011)

5.4.2 Landfast Ice and Shear Zone

As suggested by the RADARSAT-2 image obtained on the day of the flight (Figure 46), the landfast ice observed along the coast between Icy Cape and Point Franklin consisted of a narrow strip that was completely absent in some areas. When landfast ice was present, it typically contained extensive rubble with heights to 8 m. The rubble probably formed on November 13th, when a wind shift from northeast to north northwest created the ice pile-ups described in Section 5.3.2. Plate 30, taken 8 nm (15 km) south of the Kuk River Mouth, illustrates several flat first-year floes surrounded by 6-m rubble and trapped behind an inactive, grounded shear line.

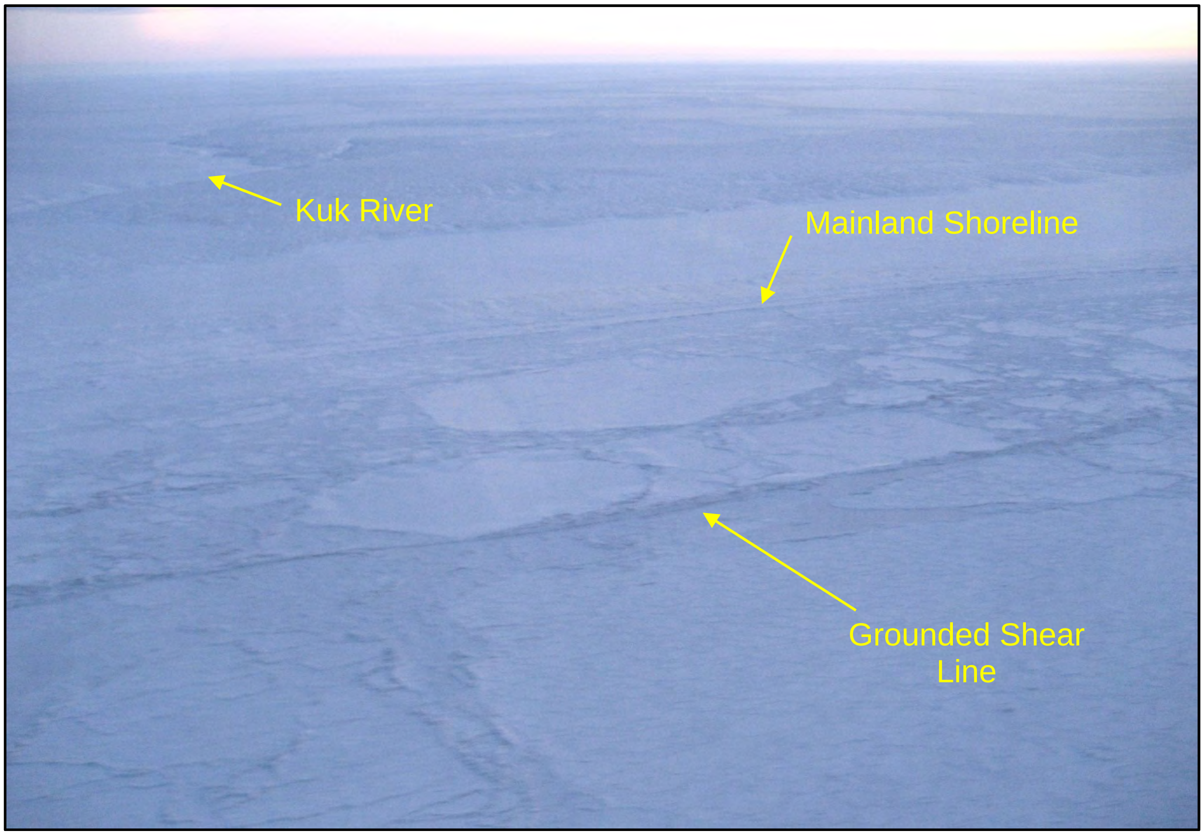


Plate 30. Landfast Ice with 6-m Rubble near Kuk River Mouth (November 30, 2011)

5.4.3 Offshore Ice

Seaward of the landfast ice zone, the nascent ice canopy was found to consist primarily of young ice (10-30 cm thick) and thin first-year ice (30-50 cm thick). Ice deformation was minimal, with sporadic ridges and rubble typically ranging from 1 to 3 m high. Plate 31 shows large sheets of thin first-year ice that were observed 80 nm (148 km) off Icy Cape, while Plate 32 shows a typical accumulation of 3-m rubble located 38 nm (70 km) off the same point of land.

Plate 31. Flat, Thin First-Year Ice with Refreezing Lead 80 nm off Icy Cape (November 30, 2011)

Plate 32. 3-m Rubble with Refreezing Lead 38 nm off Icy Cape (November 30, 2011)

5.4.4 Leads

Numerous leads, both open and refreezing, were observed during the reconnaissance flight. Among the most prominent was an open lead typically 1 to 2 nm (2 to 4 km) wide that marked the edge of the landfast ice zone from Barrow to the vicinity of Wainwright (Figure 46). Leads were omnipresent in the offshore area as well (Plates 31 and 32), reflecting the unconsolidated nature of the developing ice canopy.

5.4.5 Ice Pile-Ups

Twelve ice pile-ups were observed between Icy Cape and Point Franklin during the November 30th reconnaissance flight (Drawing CFC-863-01-002). All were located on beaches with exposure to the northwest, and all were composed of ice blocks estimated to be 30 cm thick. Five additional pile-ups with similar characteristics were noted at Skull Cliff during the reconnaissance flight conducted on February 6th. Because this region was excluded from the November flight due to darkness, it is likely that all seventeen pile-ups were created at the same time by an event that preceded the November flight.

As indicated in Section 5.3.2, the seventeen pile-ups probably formed on November 13th when the wind changed from a 21-kt (11-m/s) northeasterly to a 14-kt (7 m/s) north northwesterly. The heights of these features varied from 3 to 10 m above sea level, and the alongshore lengths from 100 to 2,400 m. Eleven of the pile-ups encroached onto the subaerial beach at distances ranging from 5 to 30 m past the waterline. The characteristics of each individual pile-up are provided in Table 12. Darkness precluded the acquisition of useful photographs.

5.4.6 Ice Conditions in Shell Prospects

Due to the time limitation imposed by the short window of daylight, Shell’s Hanna Shoal and West Prospects were excluded from the November reconnaissance flight. In the Burger Prospects, large plates of flat, thin first-year ice were separated by refreezing leads (Plate 33). Ice deformation was minimal, with scattered rubble typically 1 to 2 m high and no significant ridges.

Freeze-up was less advanced in the Crackerjack Prospects, where pans of flat, thin first-year ice were interspersed with numerous refreezing leads containing nilas (0 to 10 cm thick) and young ice (Plate 34). Rubble was limited to widely-scattered accumulations with heights to 1 m. As in the case of the Burger Prospects, ridges were conspicuously absent at the time of the flight.

Plate 33. Flat, Thin First Year Ice with Refreezing Leads in Burger Prospects (November 30, 2011)

Plate 34. Flat, Thin First-Year Ice, Young Ice, and Nilas in Crackerjack Prospects (November 30, 2011)

5.5 Late Freeze-Up

5.5.1 December 2011

Meteorological Conditions: The wind and temperature data recorded at Barrow Airport in December 2011 are provided in Figure 49. With the exception of the 8th, 9th, and 11th, which were unseasonably warm, and the 21st, which was unseasonably cold, air temperatures remained within the normal range for the entire month.

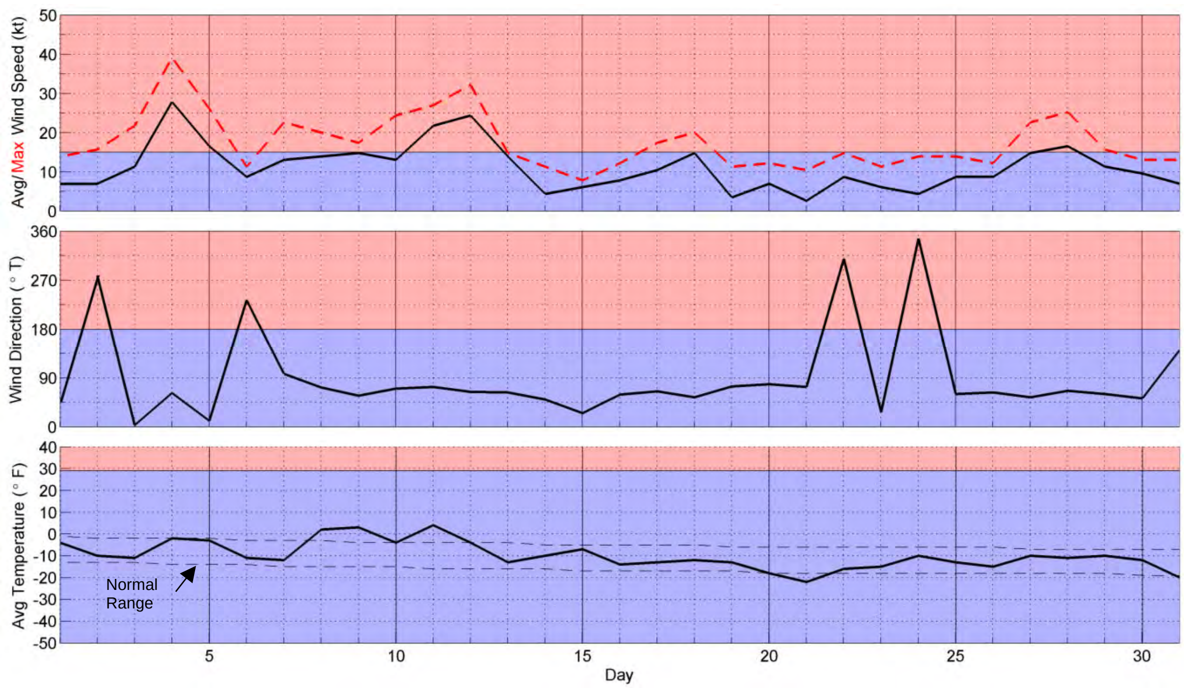


Figure 49. Meteorological Conditions at Barrow Airport in December 2011

Easterly winds predominated, occurring on 27 of the 31 days (Table 9). Easterly storm events took place on the 4th through 5th, 11th through 12th, and 28th, with maximum daily wind speeds of 28, 24, and 17 kt (14, 12, and 9 m/s), respectively (Table 10). No westerly storms were recorded.

Ice Cover: Despite the three easterly storms, the ice canopy remained intact throughout the month of December.

Ice Thickness: The calculated thickness of undisturbed first-year ice increased by 30 cm in December, from 53 to 83 cm.

Landfast Ice: The successive locations of the landfast ice edge in December were estimated from RADARSAT-2 images obtained on the 7th and 14th, and on January 4th. As shown in Figure 50, the zone of landfast ice remained narrow throughout the month. The easterly storm of December 4th and 5th caused a significant loss in the embayment between Point Franklin and Barrow, along with a modest loss in the already-narrow band between Point Belcher and the region south of Wainwright. A slight gain occurred to the east of Icy Cape, apparently due to westward-moving ice running aground on Blossom Shoals.

Between the 7th and 14th, a period that included the second easterly storm of the month (Figure 49), the landfast ice edge advanced up to 7 nm (13 km) in the semi-protected region to the east of Peard Bay, retreated up to 5 nm (10 km) to the east of Icy Cape, and remained extremely narrow elsewhere. Little change occurred from the 14th through January 4th despite the occurrence of a one-day easterly storm on the 28th.

On January 4th, the width of the landfast ice zone was only 0.5 nm (0.9 km) off Barrow, 0.4 nm (0.8 km) off Point Belcher, 1.0 nm (1.9 km) off Wainwright, 1.8 nm (3.3 km) off the mouth of the Nokotlek River, and 1.2 nm (2.2 km) off Icy Cape. These meager dimensions are consistent with the absence of westerly storms capable of pushing the ice against the coast with sufficient force to generate grounded rubble.

Leads: The RADARSAT-2 image obtained on December 7th shows numerous leads radiating offshore from the coastal region between Wainwright and Icy Cape. The leads typically ranged from 15 to 30 nm (28 to 56 km) in length and 0.2 to 0.5 nm (0.4 to 0.9 km) in width. A second cluster was centered in the vicinity of the West Prospects, between the 72°N and 73°N parallels. These features trended east-west, with lengths of 20 to 30 nm (37 to 56 km) and widths as large as 2 nm (3.7 km).

One week later, on December 14, shore-perpendicular leads once again emanated from the coastal region between Wainwright and Icy Cape (Figure 51). On this occasion, the lengths typically varied between 5 and 15 nm (9 and 28 km) and the widths between 0.2 and 1.0 nm (0.4 and 1.9 km). Farther west, north-south leads of varying lengths and widths on the order of 0.25 nm (0.5 km) were present in a large region that encompassed the Burger, Crackerjack, and West Prospects.

As noted in prior freeze-up reports (Coastal Frontiers and Vaudrey, 2010; 2011), a coastal flaw lead typically develops in the northeast Chukchi Sea during periods of strong easterly winds. Based on analysis of NIC ice charts (2012), CIS ice charts (2012), AVHRR imagery (National Weather Service, 2012) and the RADARSAT-2 images obtained on

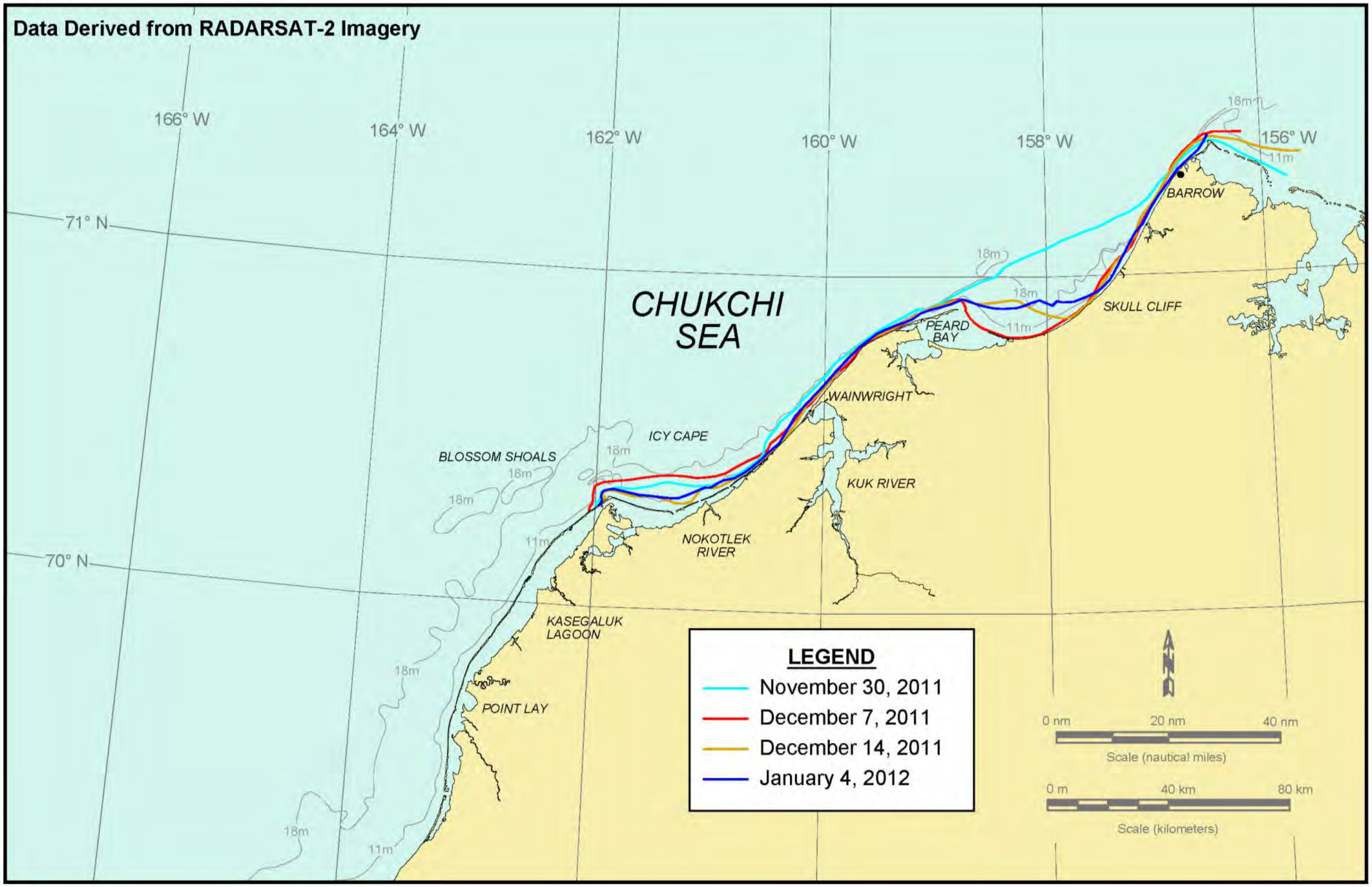


Figure 50. Chukchi Sea Landfast Ice Edge in December 2011

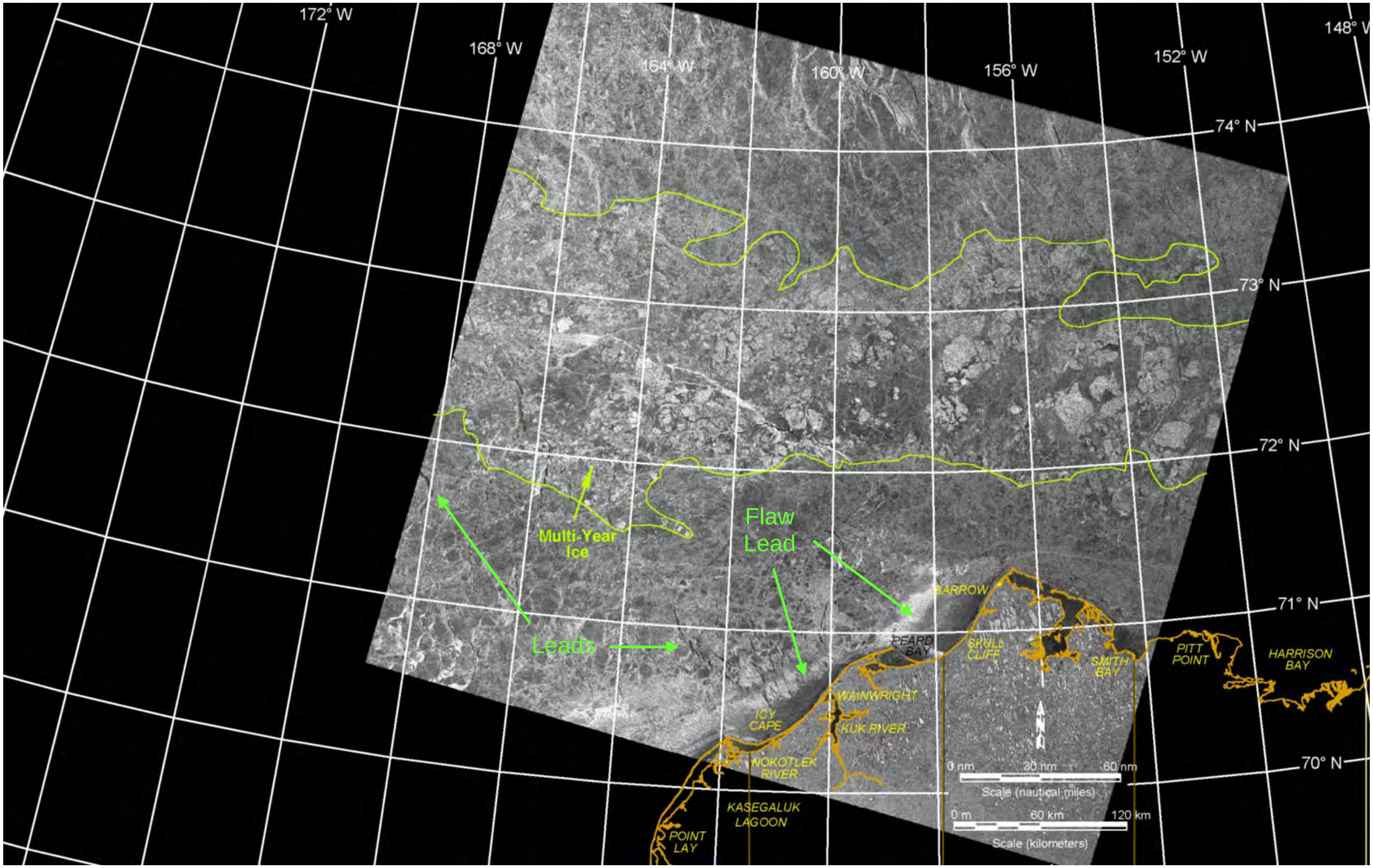


Figure 51. RADARSAT-2 Image of Chukchi Sea Acquired on December 14, 2011

December 7th and 14th, this feature was present more than half of the month of December – a finding that reflects the predominance of easterly winds (Table 9), the occurrence of three easterly storms (Table 10), and the complete absence of westerly storms capable of pushing the ice back onshore. Judging from the images available, the length of the flaw lead varied from 120 to 200 nm (222 to 371 km) while the maximum width varied from 25 to 60 nm (46 to 111 km). Figure 52 shows the flaw lead that developed in response to the easterly storm on December 4th and 5th, while Figure 51 shows the flaw lead that developed in response to the easterly storm on the 11th and 12th.

Multi-Year Ice: Multi-year ice continued to stream west from the Beaufort into the northern Chukchi during the first half of December. The RADARSAT-2 images from December 7th and 14th indicate that while most of this ice remained above the 72°N parallel, a tongue reached as far south as 71.5°N (Figure 51).

The situation changed dramatically during the third week, when the coastal flaw lead opened not only to the southwest of Point Barrow, but also up to 75 nm (139 km) to the northeast. As illustrated in Figure 53, multi-year floes arriving from the Beaufort began to enter the flaw lead and head to the southwest. This pattern, which persisted for the rest of December, introduced a substantial quantity of multi-year ice into a large region that extended roughly from 70°N to 73°N and from the coast to 168°W.

Ice Movement: Movement rates for the multi-year ice floes entering the Chukchi from the Beaufort were investigated using Floe A, (which reached the Chukchi in November (Section 5.3.2), and Floes B, C, and H (which arrived in January). The successive positions of these floes (Figure 54) were derived from RADARSAT-2 images acquired on November 30th (Floe A only) December 7th (Floe A only), December 14th (all four floes), and January 4th (Floes B, C, and H).

Floe A, which passed out of the study area prior to January 4th, moved to the southwest during the first week of December (a period that included winds from the north northeast) and to the northwest during the second (a period dominated by winds from the east northeast). The other three floes, which were tracked during the second half of the month, all experienced similar displacements to the west southwest that appear to reflect the influence of the coastal flaw lead (Figure 53).

The speeds computed between successive floe positions varied between 5.2 and 8.3 nm/day (9.6 and 15.4 km/day). Monthly speeds computed on the basis of the net displacements between the first and last recorded positions during the month averaged 6.2 nm/day (11.5 km/day; Table 13), with a range of 5.2 to 7.9 nm/day (9.6 to 14.6 km/day).

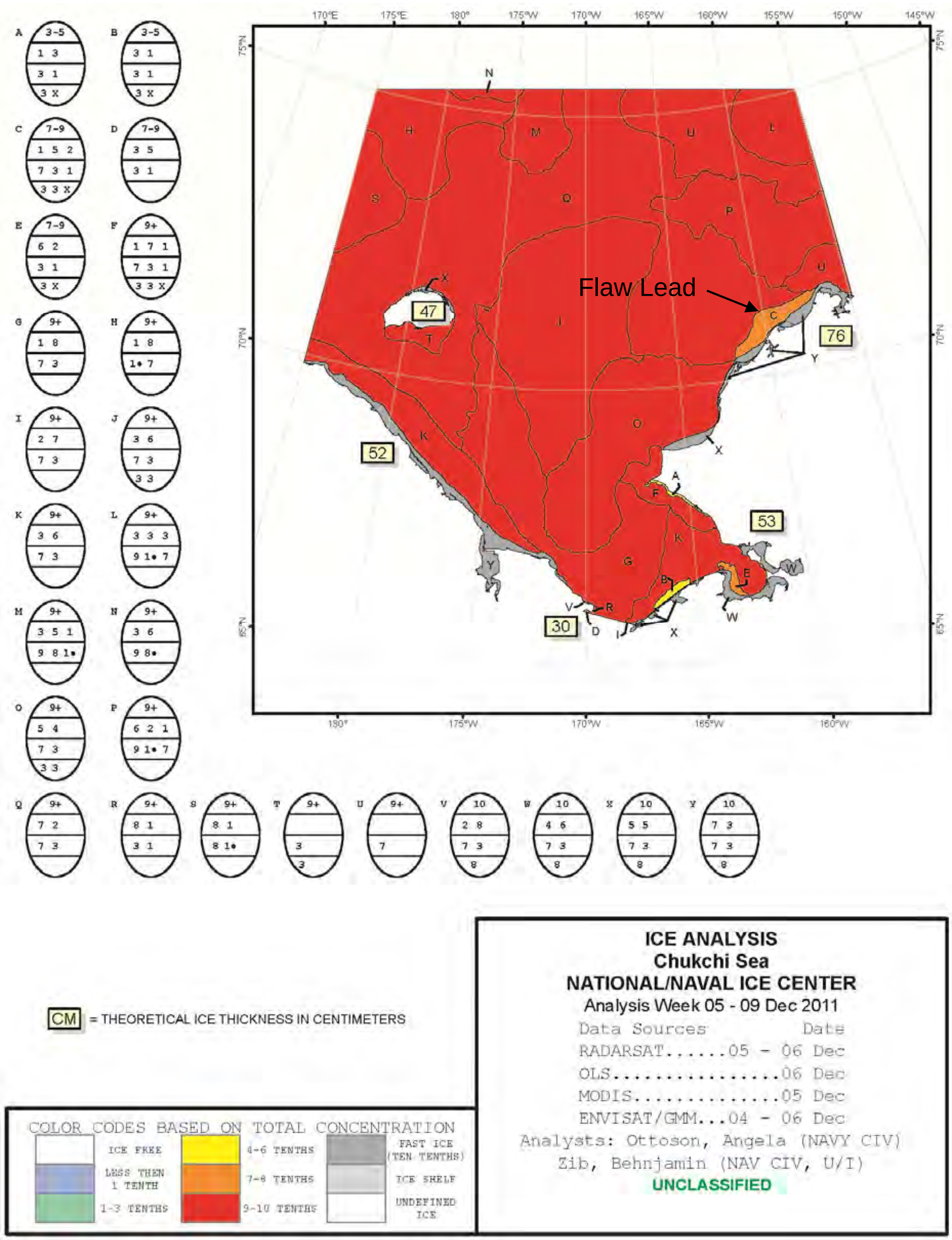
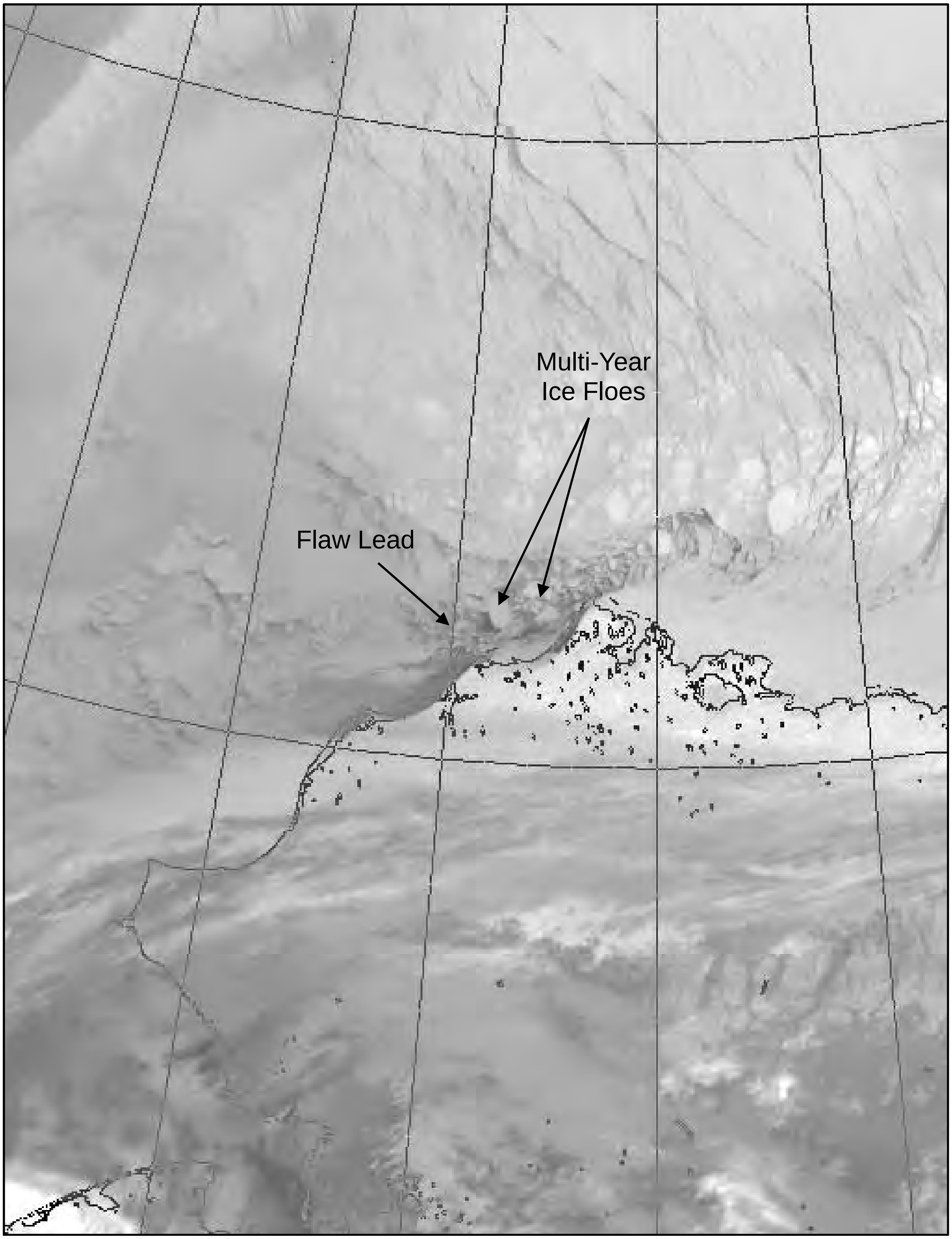


Figure 52. NIC Ice Chart for December 5, 2011, Showing Coastal Flaw Lead



Source: National Weather Service, 2011

Figure 53. AVHRR Image Acquired on December 20, 2011, Showing Multi-Year Ice Floes Entering Coastal Flaw Lead

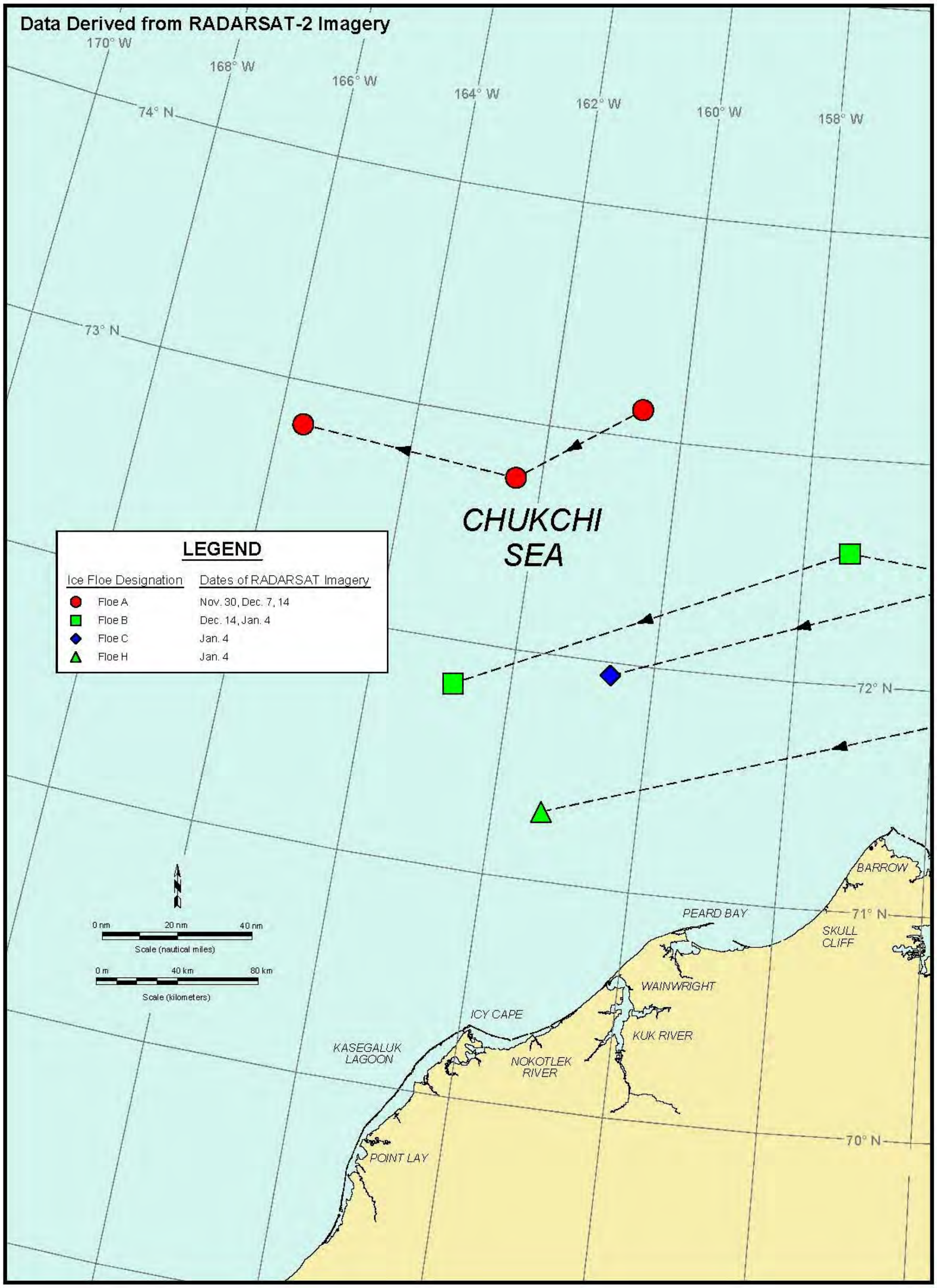
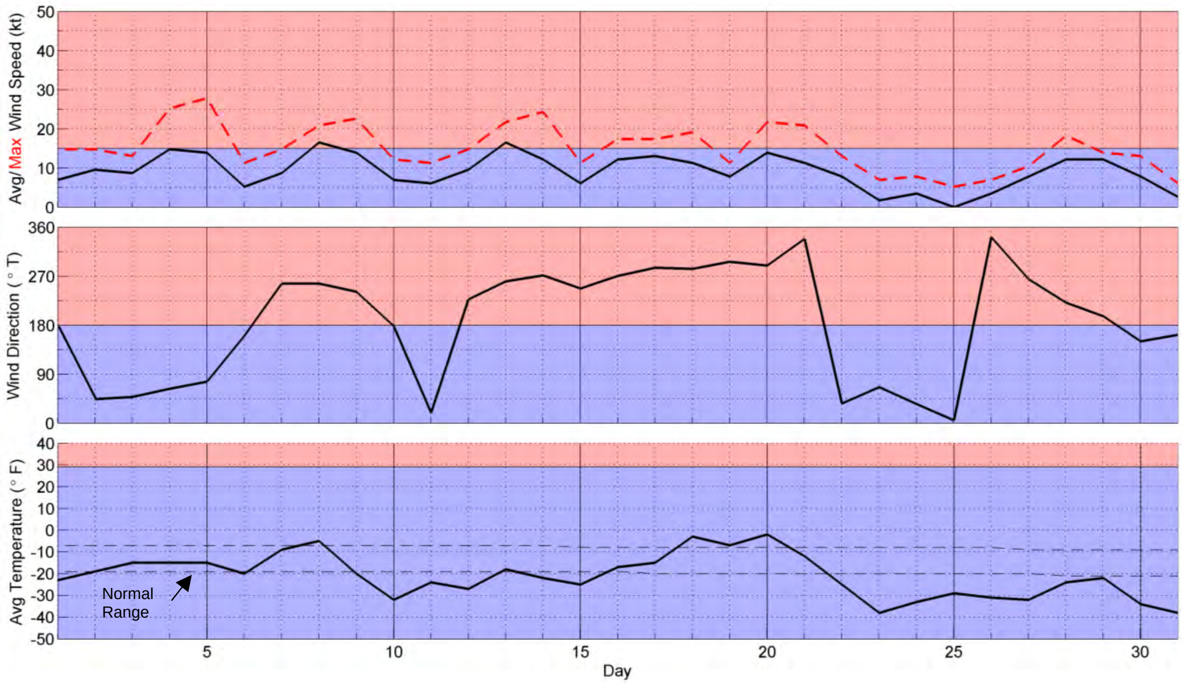


Figure 54. Chukchi Sea Multi-Year Ice Floe Displacements in December 2011

5.5.2. January 2012

Meteorological Conditions: Figure 55 presents the wind and temperature data recorded at Barrow Airport in January 2012. Air temperatures fluctuated within or close to the normal range during the first three weeks before falling below normal from the 22nd through the end of the month.



Source: Weather Underground, 2012

Figure 55. Meteorological Conditions at Barrow Airport in January 2012

Easterly winds prevailed on 14 days, while westerlies prevailed on 17 (including included a 10-day stretch in mid-month). Storm activity consisted of two one-day westerly events, each with a daily average wind speed of 17 kt (9 m/s). The first occurred on January 8th, while the second occurred on the 13th.

Ice Thickness: The calculated ice thickness increased from 83 cm at the beginning of the month to 112 cm at the end.

Landfast Ice: Figure 56 illustrates the locations of the landfast ice edge derived from RADARSAT-2 images obtained on January 4th, 17th, 28th, and 31st. The absence of easterly storms, coupled with the relatively high frequency of westerly (onshore) winds and the occurrence of two brief westerly storms, produced gradual widening of the landfast ice zone in most of the study area over the course of the month. The greatest gains occurred in the vicinity of Icy Cape, where the landfast ice edge once again advanced to Blossom Shoals,

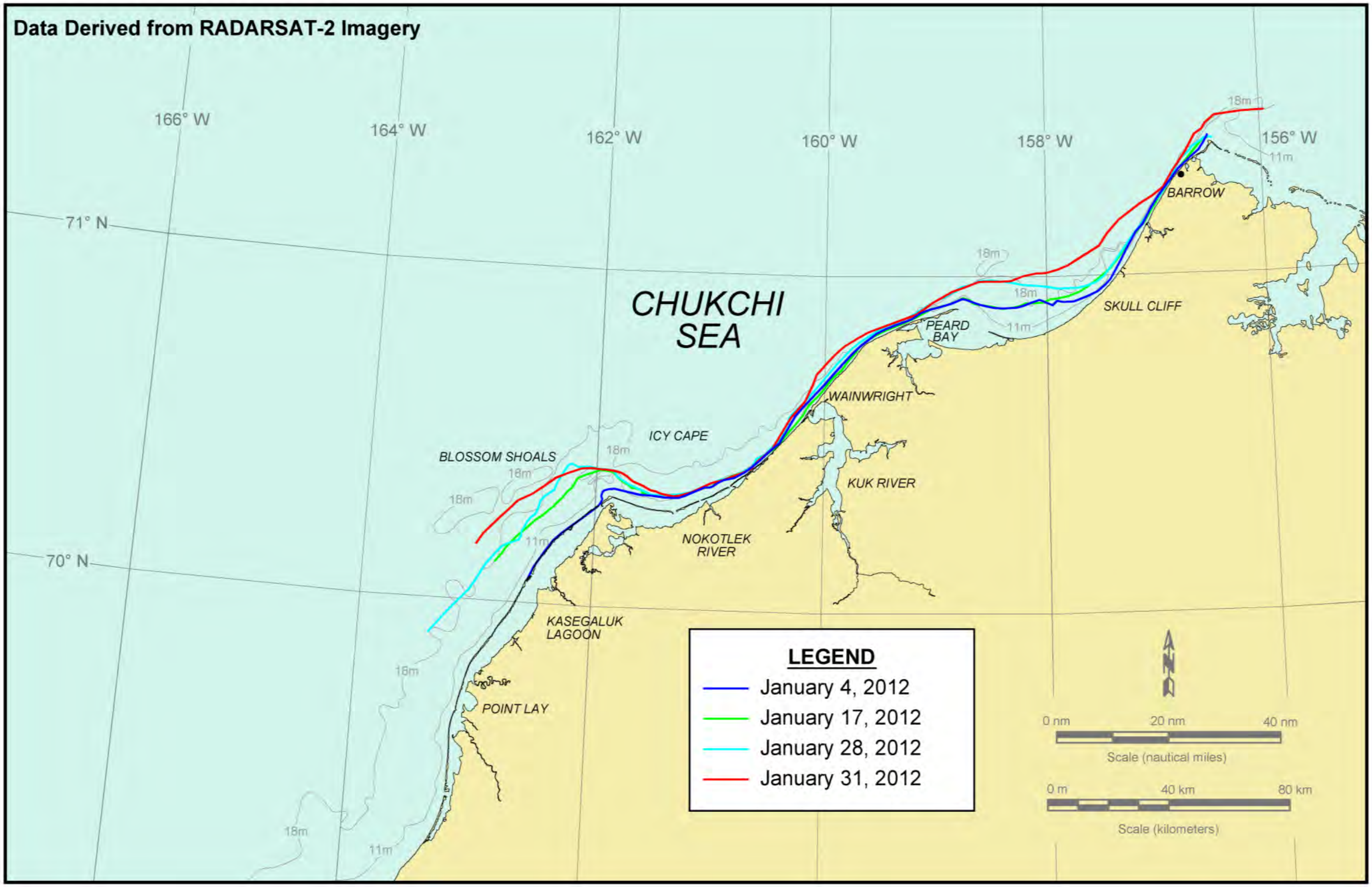


Figure 56. Chukchi Sea Landfast Ice Edge in January 2012

and in the embayment between Point Franklin and Barrow. Between the mouths of the Nokotlek and Kuk Rivers, the strip of landfast ice remained extremely narrow.

Leads: The coastal flaw lead that existed at the end of December (Figure 53) persisted through January 6th due to sustained easterly winds with average daily speeds ranging from 5 to 15 kt (3 to 8 m/s; Figure 55). During this period, the feature attained a maximum length of 150 nm (278 km) and maximum width of 50 nm (93 km). The westerly winds that ensued caused the lead to close from the 7th through the 21st, but it re-opened from the 22nd through 26th when easterly flow resumed. Although the lead stretched approximately 180 nm from northeast of Point Barrow to the vicinity of Point Lay at this time, it remained narrow with a maximum width of approximately 30 nm (56 km). After closing again on the 27th in response to westerly winds, it began to open on the 30th and remained open into early February (Figure 57).

With the exception of the coastal flaw lead, significant leads were absent from the RADARSAT-2 images of the Chukchi acquired over the course of the month.

Multi-Year Ice: The multi-year ice that invaded the region to the south and west of Barrow in late December experienced minimal movement in January, an outcome that may be explained by the absence of easterly storms and relatively high frequency of westerly winds. On January 31st, the ice was concentrated in a band that grew from approximately 40 nm (74 km) wide off Point Barrow to 70 nm (130 km) off Icy Cape, and that lay within 5 nm (9 km) of the coast at Point Belcher (Figure 57).

Ice Movement: Ice movement rates were computed from the locations of Floes B, C, D, and H as noted in RADARSAT-2 images obtained on January 4th, 17th, 28th, and 31st (Figure 58). All four floes remained nearly stationary over the course of the month, with net displacements ranging from 9 to 23 nm (17 to 43 km).

The speeds between successive positions ranged from 0.4 to 4.7 nm/day (0.7 to 8.7 km/day). The monthly speeds, computed on the basis of the floe positions on January 4th and 31st, varied between 0.3 and 0.9 nm/day (0.6 and 1.7 km/day). The average was a paltry 0.6 nm/day (1.1 km/day).

5.6. February Reconnaissance Flights

Fixed-wing aerial reconnaissance missions were undertaken in the Chukchi Sea on February 6th and 7th. Chukchi Sea Flight No. 1 (Flight “C1” on Drawing CFC-863-02-003) was used to observe the coastal and nearshore ice conditions between Barrow and Point

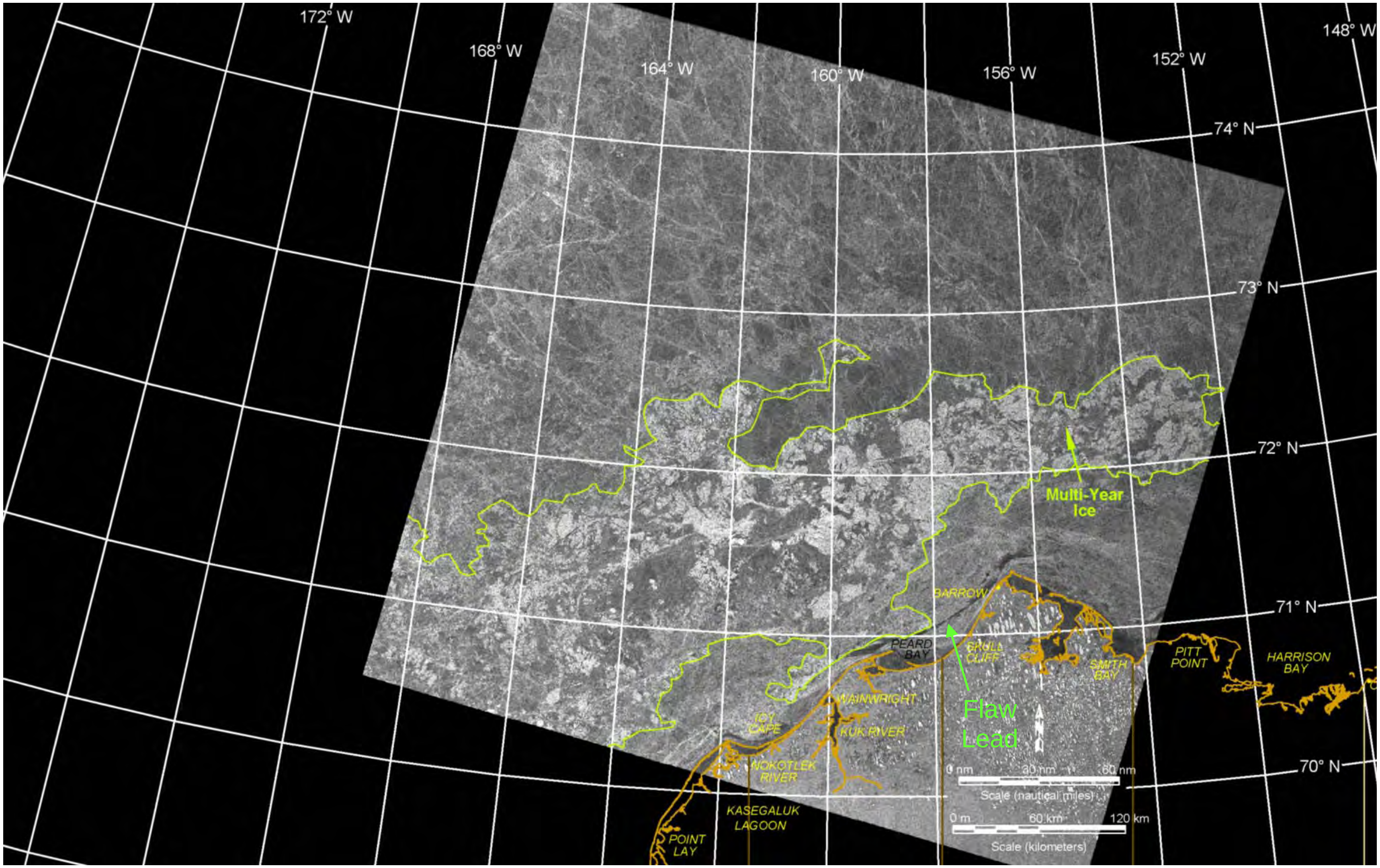


Figure 57. RADARSAT-2 Image of Chukchi Sea Acquired on January 31, 2012

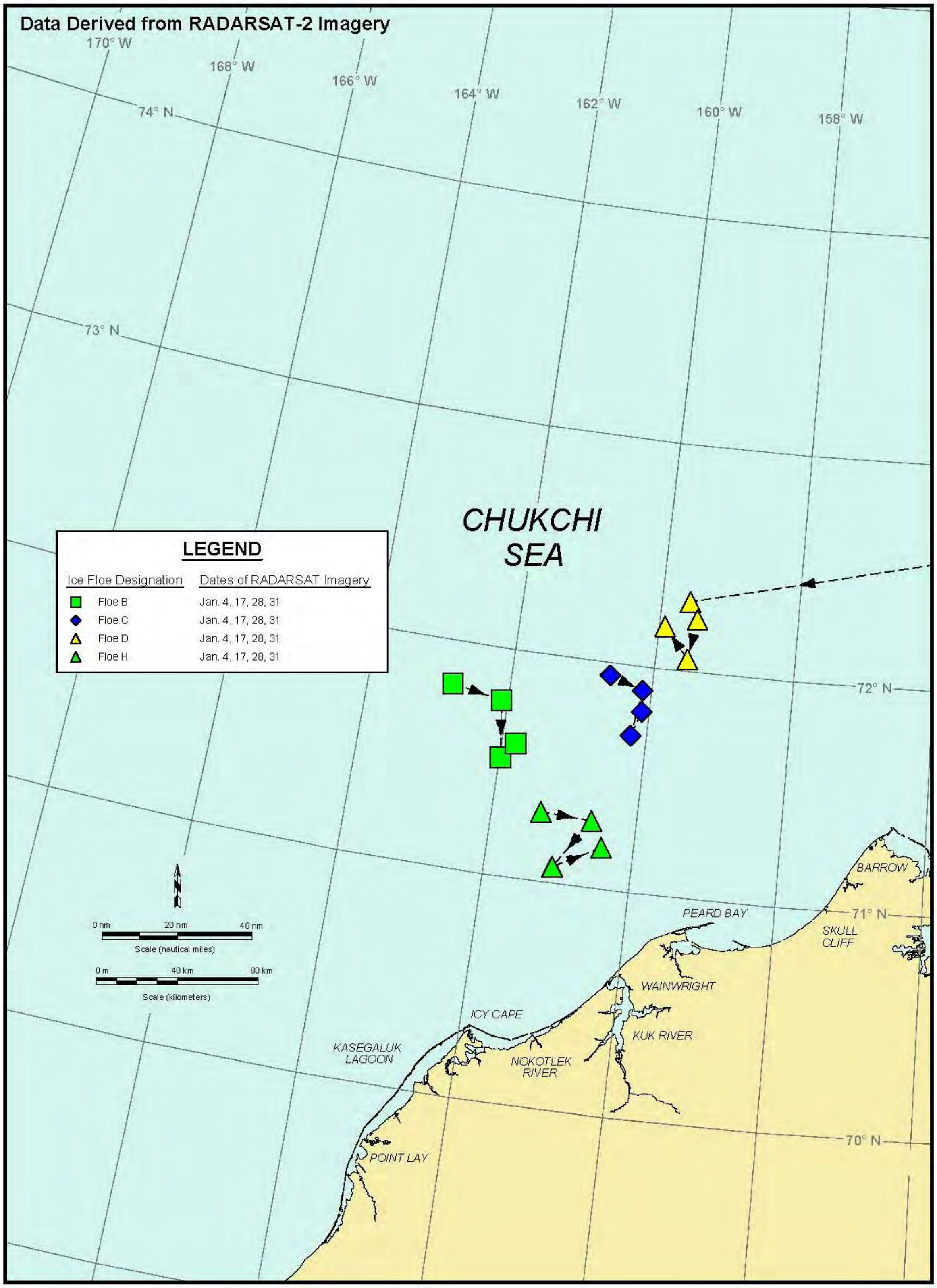


Figure 58. Chukchi Sea Multi-Year Ice Floe Displacements in January 2012

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 (46 km) to the southwest of Hanna Shoal itself.)

5.6.1. Lagoon Ice

As in November, the ice in the protected waters of Kasegaluk Lagoon and Peard Bay was found to be flat and undeformed. The ice in the Lagoon off the mouth of the Nokotlek River is shown in Plate 35.

Plate 35. Flat, Undeformed Ice in Kasegaluk Lagoon off Nokotlek River Mouth (February 6, 2012)

5.6.2. Landfast Ice

The landfast ice zone on February 6th was reminiscent of that observed on November 30th in that it consisted of a narrow strip with rubble heights to 8 m. It differed, however, in that the strip was continuous rather than intermittent over the entire length of the study area, and contained more ridges (with heights to 7 m). The width was found to be 0.9 nm (1.7 km) off Barrow, a miniscule 0.1 nm (200 m) off Point Belcher, and 6.0 nm

(11.3 km) off Point Lay. Plate 36 shows the extremely narrow strip off Point Belcher that was anchored by 4-m high grounded rubble.

Although both active and inactive shear lines were observed in the landfast ice zone, they tended to be widely spaced and poor-developed. The most prominent shear lines were located in the vicinity of Barrow (Plate 37).

5.6.3. Offshore Ice

As in the case of similar reconnaissance flights conducted in February 2010 and February 2011 (Coastal Frontiers and Vaudrey, 2010; 2011), a distinct change in the nature of the offshore ice canopy was noted approximately 40 to 50 nm (74 to 93 km) off the coast. Inshore of that location, the ice evidenced significant deformation with ridge and rubble heights to 8 m. Farther offshore, the ice tended to be relatively flat. Ridges and rubble fields were more widely spaced, with heights typically less than or equal to 3 m. The contrast is illustrated in Plates 38 and 39. The former, taken approximately 33 nm (61 km) off Point Belcher, shows an extensive accumulation of first-year ridges and rubble with heights to 7 m. The latter, taken 49 nm (91 km) off Point Belcher, displays larger pans of first-year ice with widely-scattered, 3-m rubble.

The change in the nature of the ice canopy reflects the influence of the coastal flaw lead. As discussed in the 2010-11 Freeze-Up Study report (Coastal Frontiers and Vaudrey, 2011), the presence of the lead causes the nearshore ice to lose confinement when the wind shifts from east to west. The rapid movement that follows can produce extensive ridging and rafting as floating pans of ice collide with, or rotate about, one another. At distances greater than about 50 nm (93 km) off the coast, where the influence of the coastal flaw lead tends to diminish, the differential motion between ice pans and the resulting deformations at their edges are greatly reduced.

5.6.4. Leads

Easterly winds prevailed from February 2nd through 7th, peaking at 16 kt (8 m/s) on the 6th (Table 10). As a result, the coastal flaw lead was clearly evident when the reconnaissance flights were conducted on the 6th and 7th. At Barrow, a continuous expanse of open water and nilas was observed with an estimated width of 15 nm (28 km; Plate 40). At Point Lay, numerous smaller leads in various stages of refreezing were interspersed with swaths of first-year ice over a combined width approaching 40 nm (74 km; Plate 41).

Farther offshore, numerous smaller leads punctuated the entire 200-nm (371-km) stretch between the flaw lead off Barrow and the West Prospects (Drawing CFC-863-02-

Plate 36. Narrow Strip of Landfast Ice Anchored by 4-m Grounded Rubble off Point Belcher (February 6, 2012)

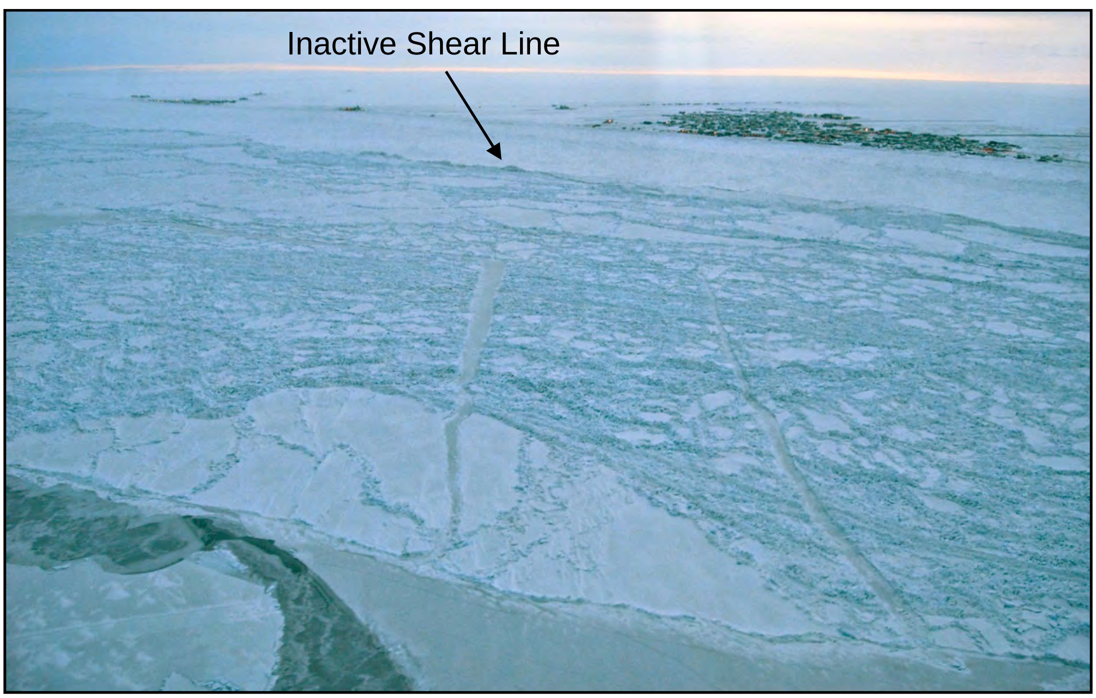


Plate 37. Inactive Shear Line and 8-m Rubble off Barrow (February 6, 2012)

Plate 38. First-Year Ridges and Rubble with Heights to 7 m Located 33 nm off Point Belcher (February 7, 2012)

Plate 39. First-Year Ice with Widely-Scattered, 3-m Rubble Located 49 nm off Point Belcher (February 7, 2012)

Plate 40. Coastal Flaw Lead off Barrow (February 7, 2012)

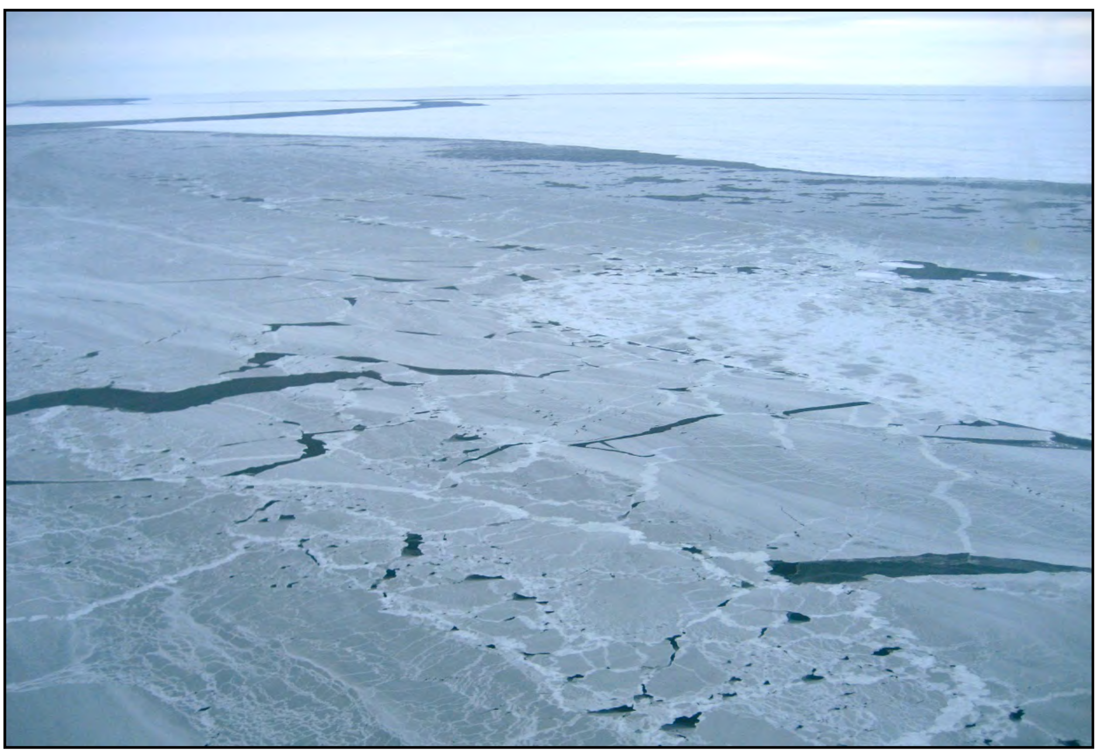


Plate 41. Coastal Flaw Lead off Point Lay (February 6, 2012)

003). The lengths varied from less than 1 nm (2 km) to more than 5 nm (9 km), while the widths typically were less than 0.5 nm (0.9 km). A representative example observed between the Crackerjack and Burger Prospects is provided in Plate 42.

Plate 42. Lead between Crackerjack and Burger Prospects (February 7, 2012)

5.6.5. Ice Pile-Ups

Twenty seven ice pile-ups were observed on the Chukchi Sea coast during the February 6th reconnaissance flight (Drawing CFC-863-02-003). Eight of these had been mapped previously during the November 30th flight, while five with similar characteristics were discovered at Skull Cliff in an area not covered in November. As discussed in Section 5.4.5, all thirteen pile-ups along with four others that were observed in November but not in February probably formed when the wind shifted from northeast to north northwest on November 13th.

Of the remaining fourteen pile-ups observed during the February flight, two were located at Skull Cliff, one at the Kuk River Mouth, three to the east of Icy Cape, and eight between Icy Cape and Point Lay. The six pile-ups between Skull Cliff and Icy Cape were composed of ice blocks estimated to range from 30 to 60 cm thick, while those between Icy Cape and Point Lay were composed of blocks that were 30 to 40 cm thick. All fourteen pile-ups probably formed when the wind shifted from southeasterly to westerly on January 7th and accelerated to 17 kt (9 m/s) on the 8th.

The locations of these pile-ups are indicated in Drawing CFC-863-02-003, while their characteristics are summarized in Table 12. The heights varied from 3 to 18 m above sea level while the alongshore lengths ranged from 100 to 5,400 m. All fourteen pile-ups encroached onto the subaerial beach at distances ranging from 5 to 40 m past the waterline.

The largest pile-up, with a height of 18 m, length of 5,400 m, and encroachment distance of 40 m, was located at Skull Cliff. As shown in Plate 43, the 30- to 60-cm thick ice blocks overtopped a 15-m high bluff and spilled 3 m onto the tundra. A smaller but nevertheless substantial pile-up that occurred on Icy Cape is depicted in Plate 44. This feature was estimated to be 8 m high and 1,200 m long with an encroachment distance of 20 m. An extensive rubble pile was located offshore of the pile-up, attesting to the dynamic nature of ice movements that occur around this exposed point of land.

5.6.6. Multi-Year Ice

With the exception of the landfast ice zone and coastal flaw lead, multi-year ice was present throughout the study area when the reconnaissance flights were undertaken on February 6th and 7th. The floe diameters ranged from less than 100 m to more than 20 km, while the concentrations varied from less than 10% to as high as 90%. Although the highest concentrations were located on the northernmost portion of the offshore flight path, in the general vicinity of Hanna Shoal and the Hanna Shoal Prospects (Drawing CFC-863-02-003), large-diameter floes were observed as far south as 71°N.

Plate 45 displays a large multi-year floe with an estimated maximum horizontal dimension of 2 km that was located 70 nm (130 km) northwest of Point Barrow, while Plate 46 shows a small fragment embedded in first-year ice 40 nm (74 km) off Icy Cape. As illustrated in Plate 47, some of the floes appeared to have been fractured in the recent past. Others contained substantial ridges with estimated heights to 5 m (Plate 48).

5.6.7. Ice Conditions in Shell Prospects

All four of Shell’s Chukchi Sea prospects – Hanna Shoal, West, Crackerjack and Burger – were covered during the reconnaissance flight conducted on February 7th, but the West Prospects were completely obscured by fog. Multi-year ice predominated in the Hanna Shoal Prospects, with concentrations estimated at 75% in the northern portion

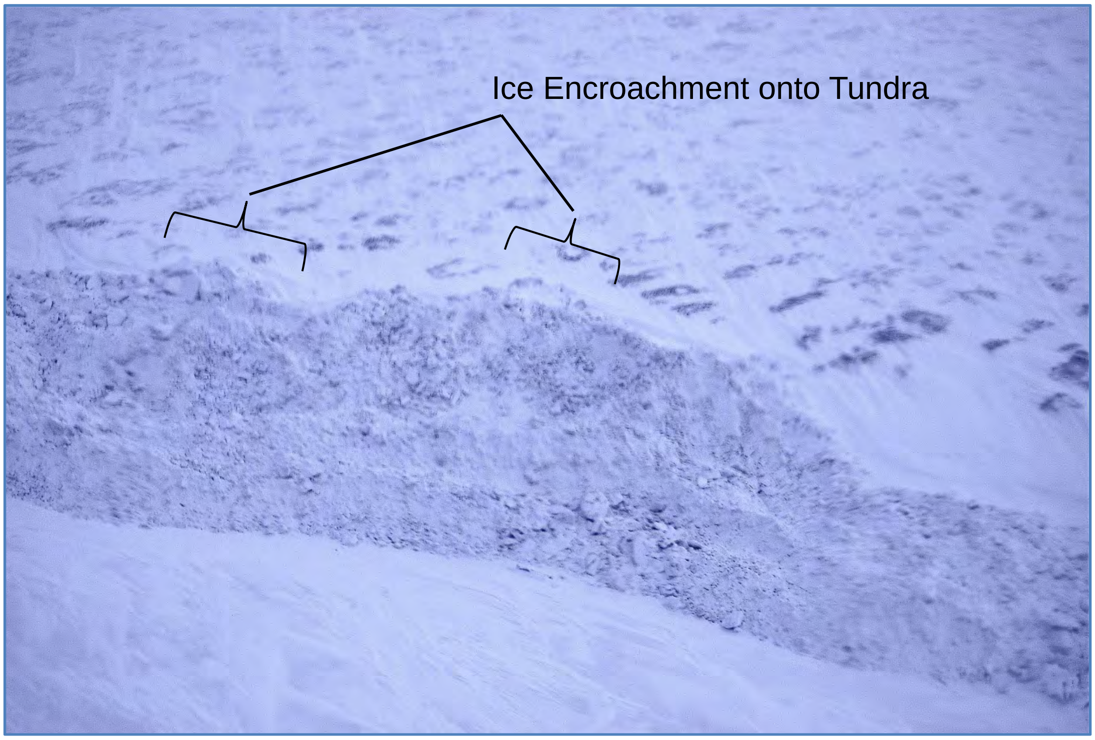


Plate 43. 18-m High Ice Pile-Up at Skull Cliff (February 6, 2012)

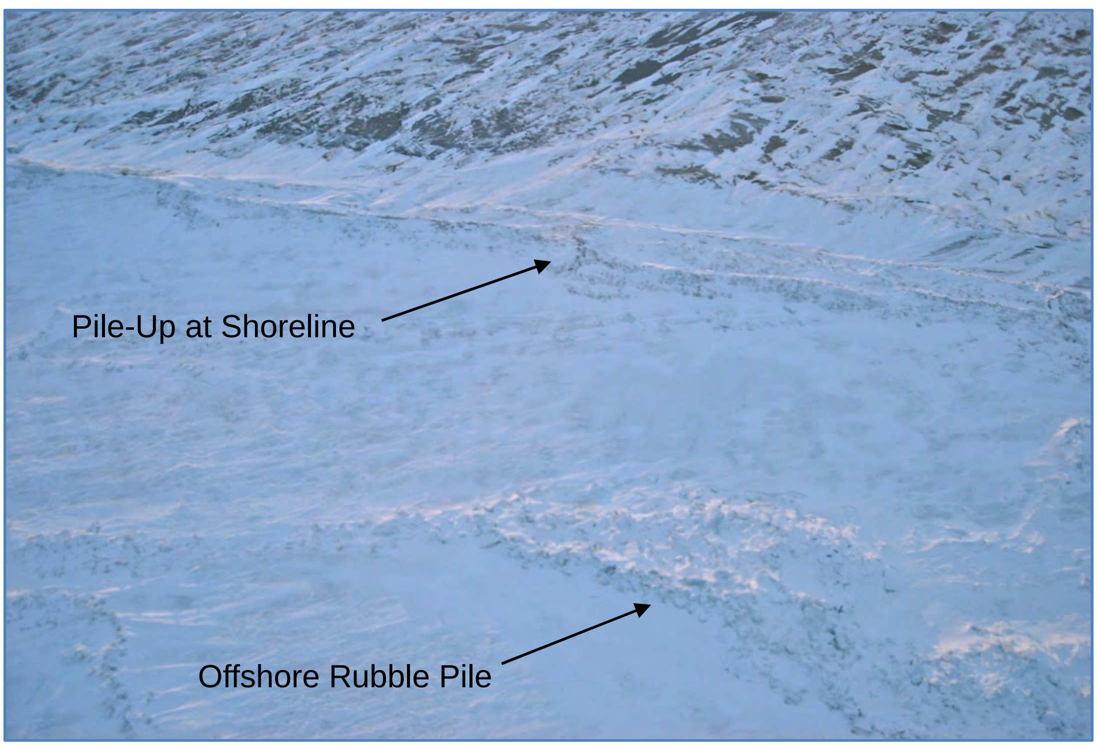


Plate 44. 12-m High Ice Pile-Up with Offshore Rubble Pile at Icy Cape (February 6, 2012)

Plate 45. Large Multi-Year Ice Floe 70 nm Northwest of Point Barrow (February 7, 2012)

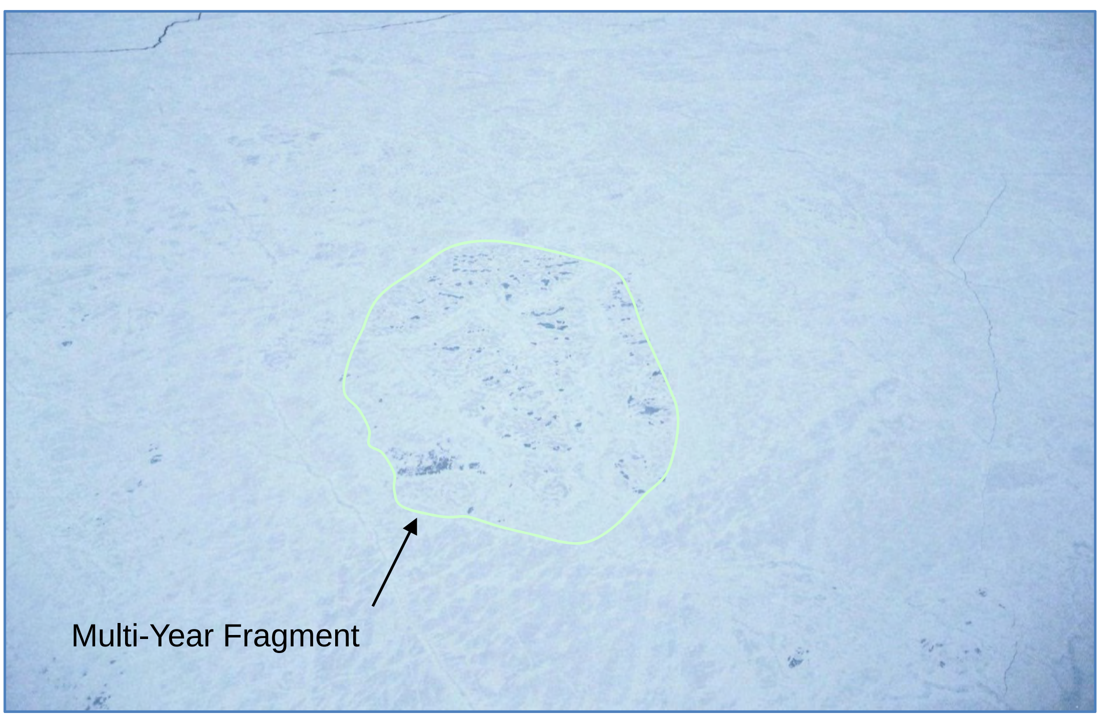


Plate 46. Small Multi-Year Fragment Embedded in First-Year Ice 40 nm off Icy Cape (February 6, 2012)

Plate 47. Fractured Multi-Year Floe in Burger Prospects (February 7, 2012)

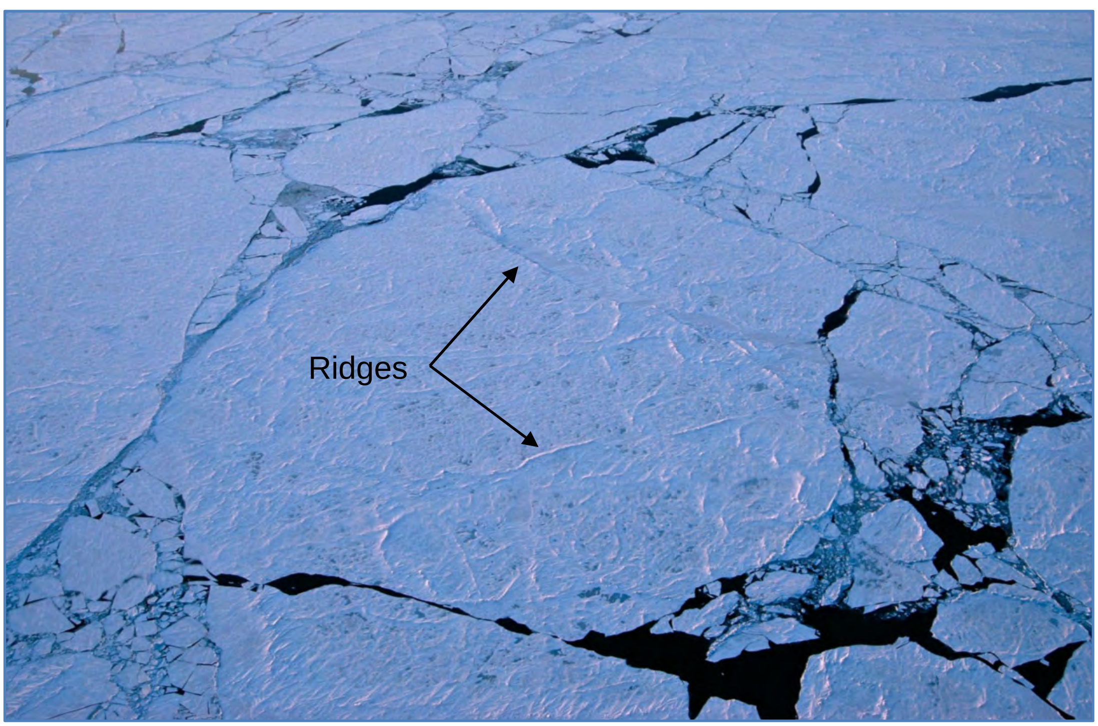


Plate 48. Multi-Year Floe with Embedded Ridges near Hanna Shoal (February 7, 2012)

and 90% in the central portion. Many of the floes were large, with typical diameters of 1 to 5 km (Plate 49).

In the Crackerjack Prospects, large, irregularly-shaped pans of first-year ice with diameters to 5 km predominated (Plate 50). Deformation was observed to be minimal, in that ridges and rubble piles were widely scattered with heights limited to 2 m. Multi-year floes and fragments with diameters less than 0.5 km were present in the northern and central portions of the Prospects, at concentrations ranging from 10 to 40%.

The ice conditions in the Burger Prospects resembled those in Crackerjack, with a predominance of large, first-year pans evidencing minimal deformation. The ice was less well-consolidated, however, with more cracks and small leads (Plate 51). Multi-year floes and fragments were observed (Plate 47) at concentrations ranging from 5 to 20%.

5.6.8. 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, 162°W (Drawing CFC-863-02-003). The shallowest water depth on the shoal is about 12 m, while the surrounding depths exceed 30 m.

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 52) 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 sea level. The long axis was oriented northeast-southwest, and the shallowest water depth was located at the southwest tip.

When the reconnaissance flight was conducted on February 7th, 2012, Katie's Floeberg was estimated to be 10 km (5.4 nm) long and 5.0 km (2.7 nm) wide, with the major axis oriented north northeast – south southwest (Plate 53). These dimensions are substantially larger than those observed a year earlier: 2.8 km long and 1.9 km wide (1.5 nm by 1.0 nm; Coastal Frontiers and Vaudrey, 2011). The highest rubble, with a maximum estimated height of 10 m above sea level, was located on the east side. This rubble is shown in Plate 54 along with one of the numerous multi-year ice floes that had become embedded in the feature.

Plate 49. Large Multi-Year Floes in Hanna Shoal Prospects (February 7, 2012)

Plate 50. Large Pans of First-Year Ice in Crackerjack Prospects (February 7, 2012)

Plate 51. First-Year Ice Pans with Cracks and Small Leads in Burger Prospects (February 7, 2012)

Plate 52. Katie's Floeberg in April 1980

Plate 53. Katie's Floeberg on February 7, 2012 (looking south)

Plate 54. 10 m High Rubble and Embedded Multi-Year Floe on East Side of Katie's Floeberg (February 7, 2011)

5.6.9. Grounded Ice Features

As illustrated in Plates 55, 56, and 57, an extraordinary ice feature was discovered off Point Belcher while conducting the coastal reconnaissance flight on February 6th. Located approximately 3 nm (6 km) from shore in a charted water depth of 32 m (National Ocean Service, 2003), the feature was estimated to be 80 m long, 40 m wide and up to 20 m above sea level. Based on the first-year ice rubble accumulating on its northeast side and the wake forming on its southwest side, the feature was hard aground. A second grounded ice feature was identified 12 nm (22 km) southwest of Icy Cape, approximately 0.8 nm (1.5 km) seaward of the barrier islands (Plate 58). Although much smaller than that off Point Belcher, it appeared to be similar in terms of composition. The locations of both ice features are shown in Figure 59 and Drawing CFC-863-02-003.

A high-resolution RADARSAT-2 image of the Point Belcher region was acquired on February 17th for the express purpose of studying the larger ice feature. Two conclusions resulted from the analysis that followed: (1) despite the 2-m nominal resolution of the image, the feature would not have been identified if its location had not been known in advance, and (2) the feature’s plan-view dimensions were similar to those estimated during the reconnaissance flight: 92 m long by 44 m wide.

Although the nature of the grounded ice features cannot be identified with certainty, possible explanations include: (1) fragments of a massive multi-year ridge, and (2) fragments of an ice island. Ice islands are tabular features that have calved off ice shelves on the north coast of Ellesmere Island (Jeffries and Sackinger, 1989). With the warmer temperatures in the Arctic, these ice shelves are disintegrating rapidly. Based on the exceptional thickness of the Point Belcher ice feature, along with the fact that a similar feature measuring 200 m by 70 m was identified 12 nm (22 km) east of Point Barrow in July 2012 (Restino, 2012), the most likely source appears to be an ice island.

The fate of the Point Belcher ice feature after its discovery in February, along with the nature of the gouge it created in the sea bottom, currently are under investigation through a separate Joint Industry Project entitled “Bathymetric Survey at the Site of a Grounded Ice Feature in the Chukchi Sea” (Coastal Frontiers, in progress).

5.7 Midwinter

5.7.1. February 2012

Meteorological Conditions: Wind and temperature data recorded at Barrow Airport in February 2012 are presented in Figure 60. The below-normal air temperatures that

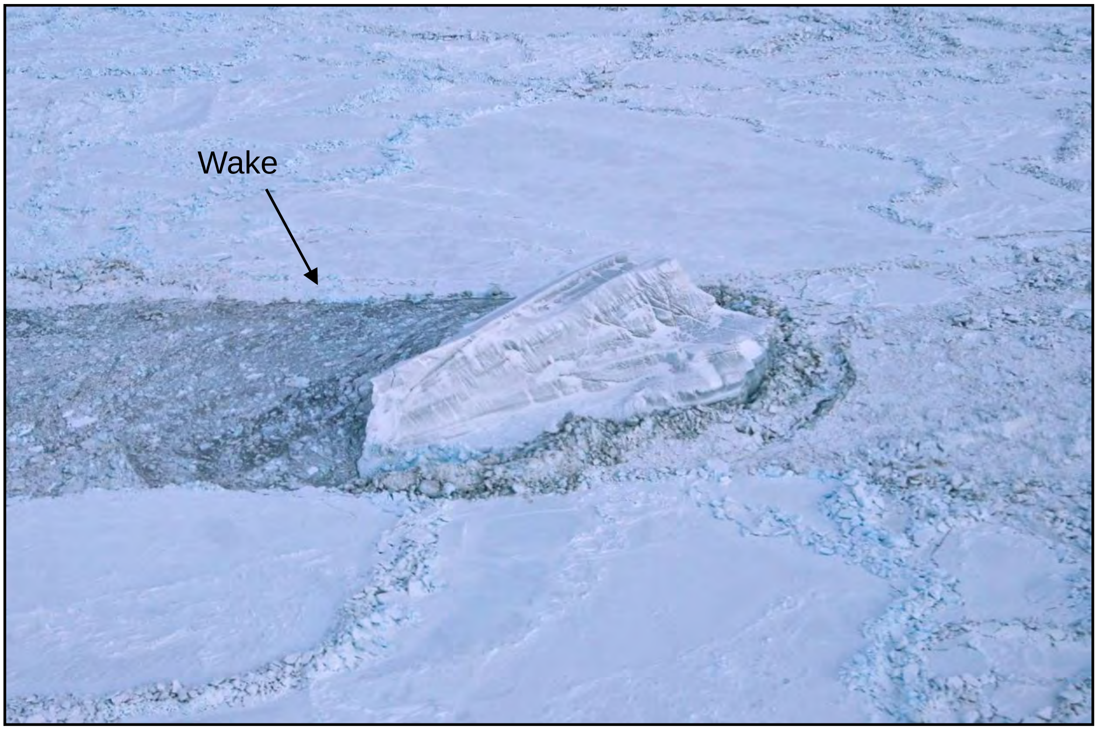


Plate 55. Grounded Ice Feature off Point Belcher (February 6, 2012)

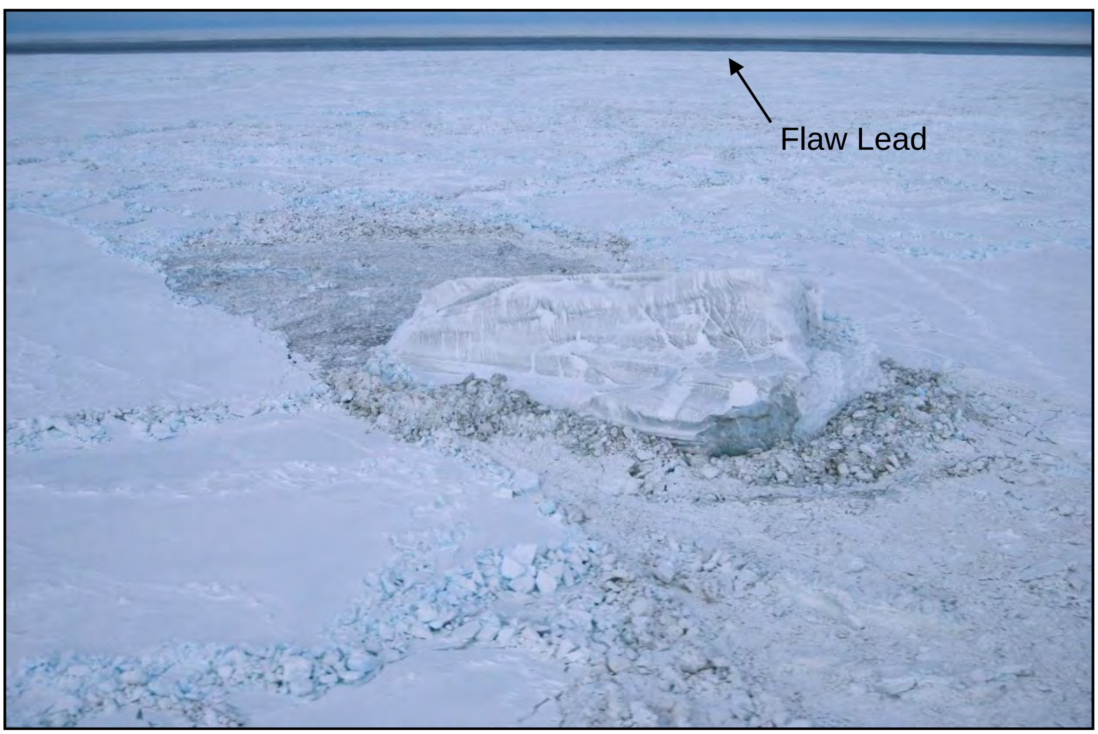


Plate 56. Grounded Ice Feature and Coastal Flaw Lead off Point Belcher (February 6, 2012)

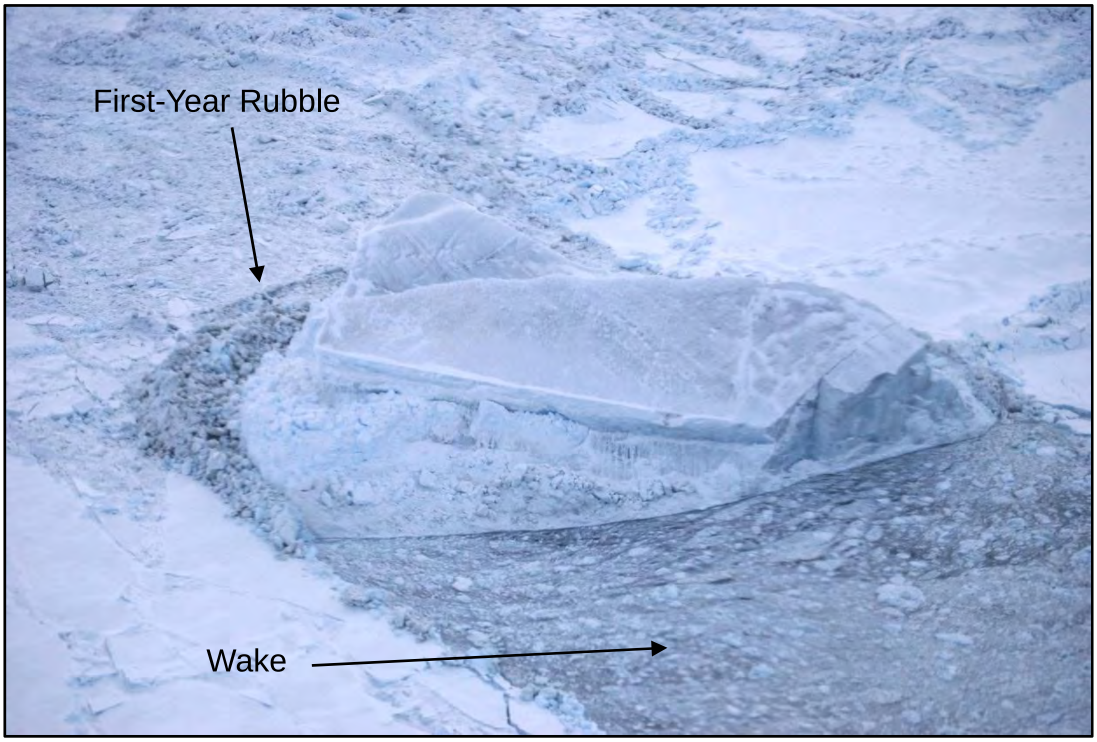


Plate 57. First-Year Rubble and Wake Generated by Grounded Ice Feature off Point Belcher (February 6, 2012)

Plate 58. Grounded Ice Feature 12 nm Southwest of Icy Cape (February 6, 2012)

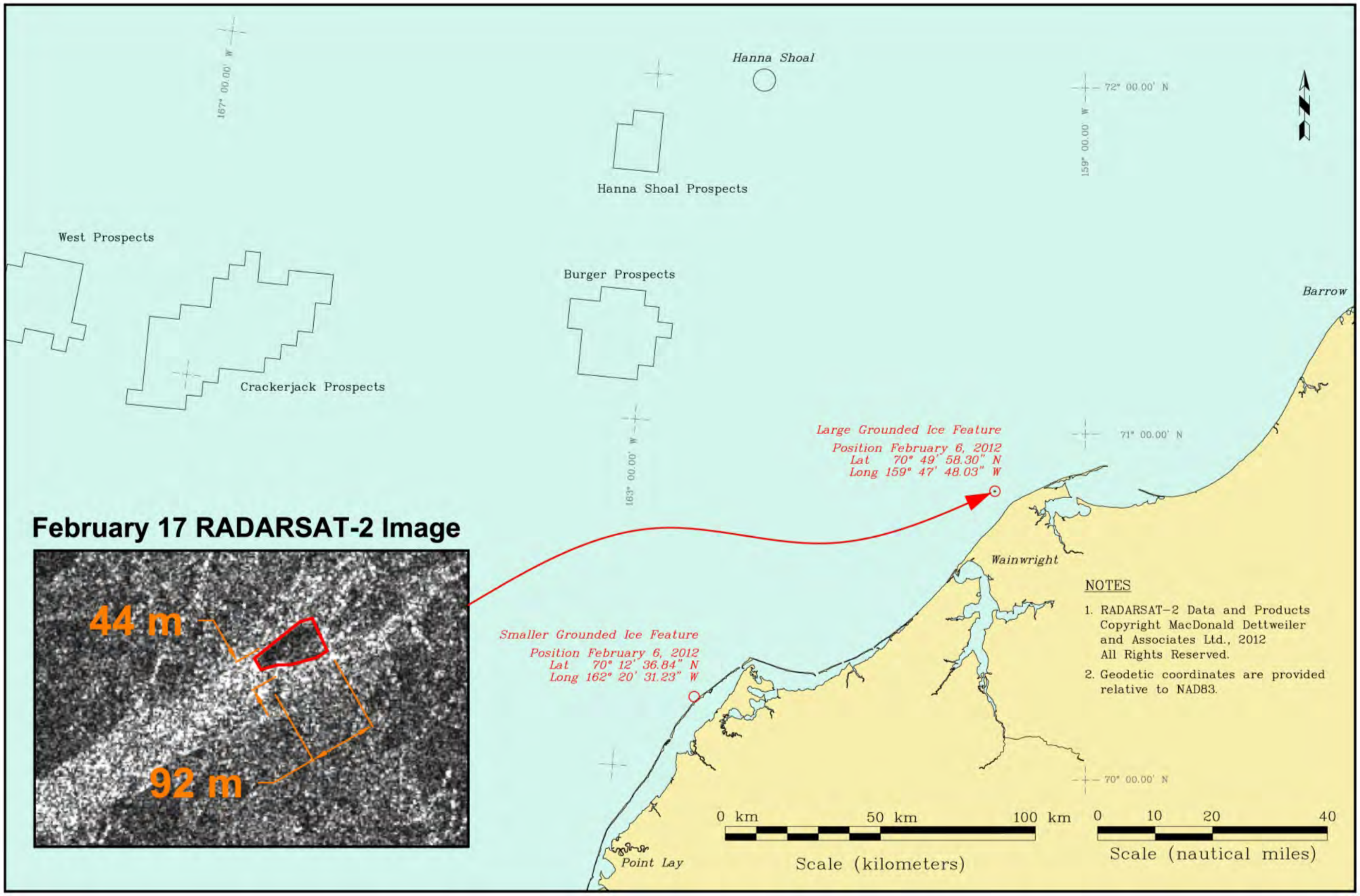
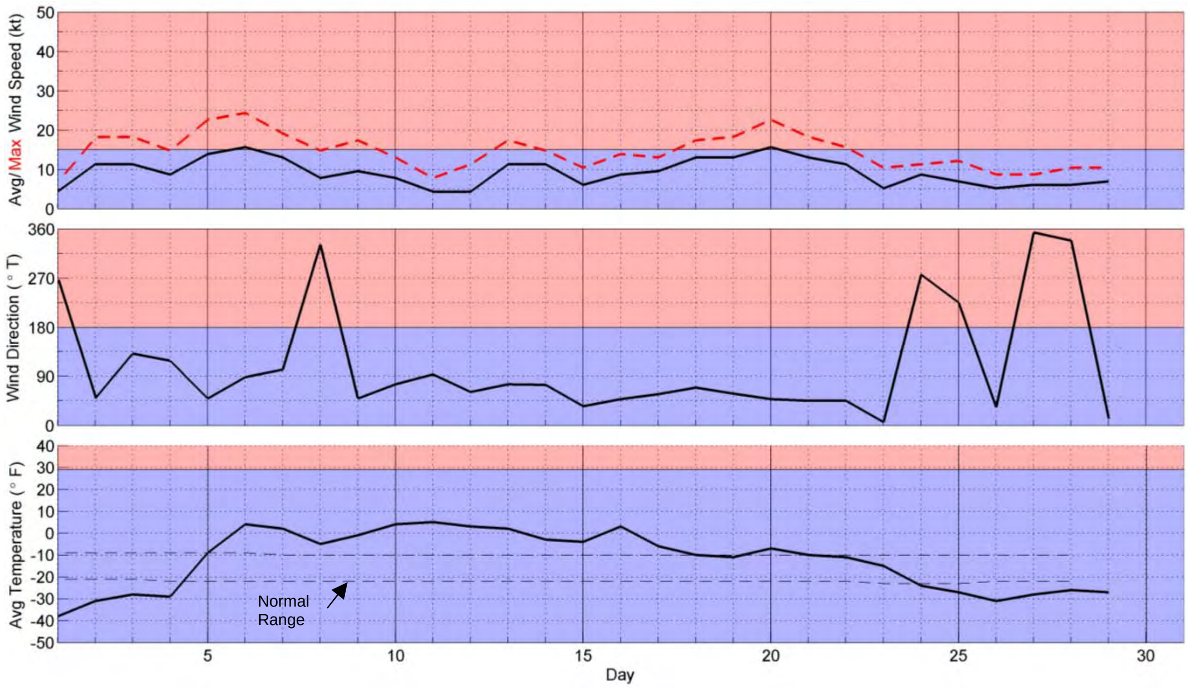


Figure 59. Locations of Grounded Ice Features off Chukchi Sea Coast



Source: Weather Underground, 2012

Figure 60. Meteorological Conditions at Barrow Airport in February 2012

prevailed in late January continued during the first four days of February, followed by above-normal temperatures through the 20th. Cooler temperatures returned at the end of the month, with below-normal readings commencing on the 24th and continuing into March.

Easterly winds predominated in February, occurring on 23 of the 29 days. The only two storms were one-day easterlies: a 16-kt (8 m/s) event on the 6th and another 16 kt (8 m/s) event on the 20th.

<u>Ice Thickness</u>: The calculated ice thickness was 132 cm at the end of the month, representing 20 cm more than at the beginning.

<u>Landfast Ice</u>: Figure 61 presents the locations of the landfast ice edge derived from RADARSAT-2 images obtained on January 31st, February 10th, and February 27th. During the period between the first two images, which included the easterly storm of February 6th, the most significant change was a retreat of up to 6 nm (11 km) to the south of Icy Cape. An advance of up to 4 nm (7 km) to the 18-m contour occurred between the Nokotlek River Mouth and Wainwright, along with an advance of up to 3 nm (6 km) off Skull Cliff. The occurrence of modest gains in these areas, along with the stability of the ice edge in others, suggests that the ice had become sufficiently well-grounded in January to resist displacement during the easterly storm on February 6th.

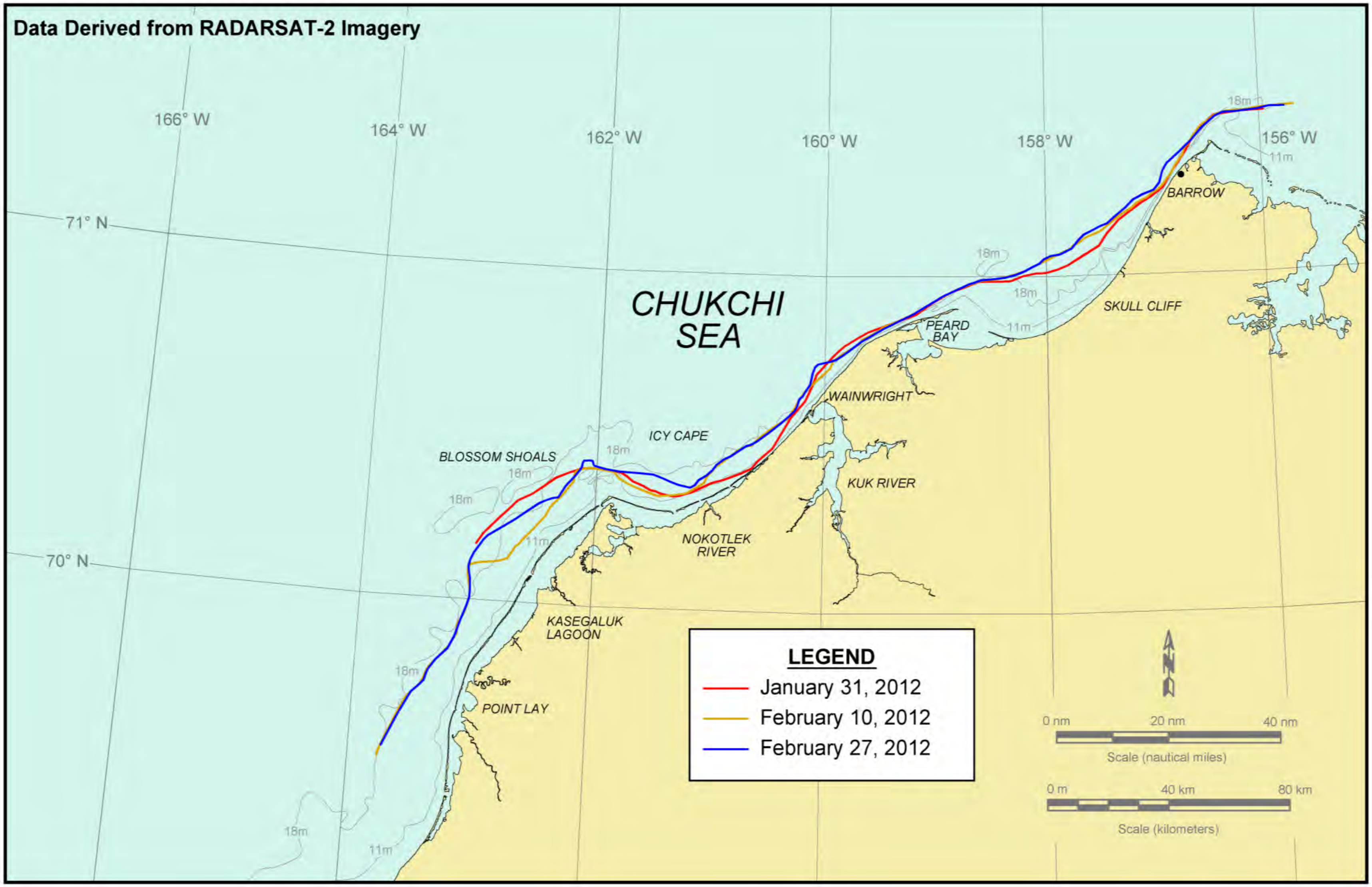


Figure 61. Chukchi Sea Landfast Ice Edge in February 2012

The period between February 10th and 27th was dominated by easterly winds, including the easterly storm on the 20th (Table 10), but also included several days of light to moderate westerlies at the end (Figure 60). The landfast ice edge remained stationary on the 18-m contour in the vicinity of Point Lay, advanced up to 5 nm (9 km) to the south of Icy Cape and 3 nm (6 km) to the east, and remained essentially stationary from the Nokotlek River Mouth to Point Barrow.

Leads: Based on an analysis of AVHRR imagery, the coastal flaw lead that opened on January 30th did not close until February 8th – a finding supported by the observations made during the reconnaissance flights on the 6th and 7th (Section 5.6.4). The maximum length and width during this 10-day stretch were estimated to be 200 and 25 nm (371 and 46 km), respectively. The lead narrowed or closed in response to westerly winds on the 8th (Figure 60), but re-opened on the 10th (Figure 62) and, based on a CIS ice chart (2012), remained open at least until the 13th. The length was about 50 nm (93 km) while the width was 10 nm (19 km). Another brief opening occurred from the 19th through 22nd, apparently caused by the easterly winds that peaked on the 20th. Although 200 nm (371 km) long, the lead remained narrow (about 10 nm or 19 km) during this period.

With the exception of the coastal flaw lead evident in the RADARSAT-2 image obtained on February 10th (Figure 62), significant leads and polynyas were absent from that image and the one obtained subsequently on the 27th.

Multi-Year Ice: As shown in Figure 62, multi-year ice occupied a broad swath in the northeast Chukchi Sea when the RADARSAT-2 image was obtained on February 10th. The swath was approximately 40 nm (74 km) wide off Point Barrow, and 75 nm (139 km) wide off Icy Cape. The next image, acquired on the 27th, indicates that the ice drifted to the southwest while expanding to a width of 50 nm (93 km) off Point Barrow and 80 nm (148 km) off Icy Cape.

According to ice charts prepared by the NIC (2012), the multi-year ice extended as far south as 68°N at month-end.

Ice Movement: After remaining nearly stationary in January, Floes B, C, D, and H moved to the west or west northwest between January 31st and February 10th before heading southwest between the 10th and 27th (Figure 63). The speeds between successive positions remained modest, varying from 2.1 to 3.5 nm/day (3.9 to 6.5 km/day). The monthly speeds ranged from 2.2 to 2.9 nm/day (4.1 to 5.4 km/day) while averaging 2.5 nm/day (4.6 km/day; Table 13).

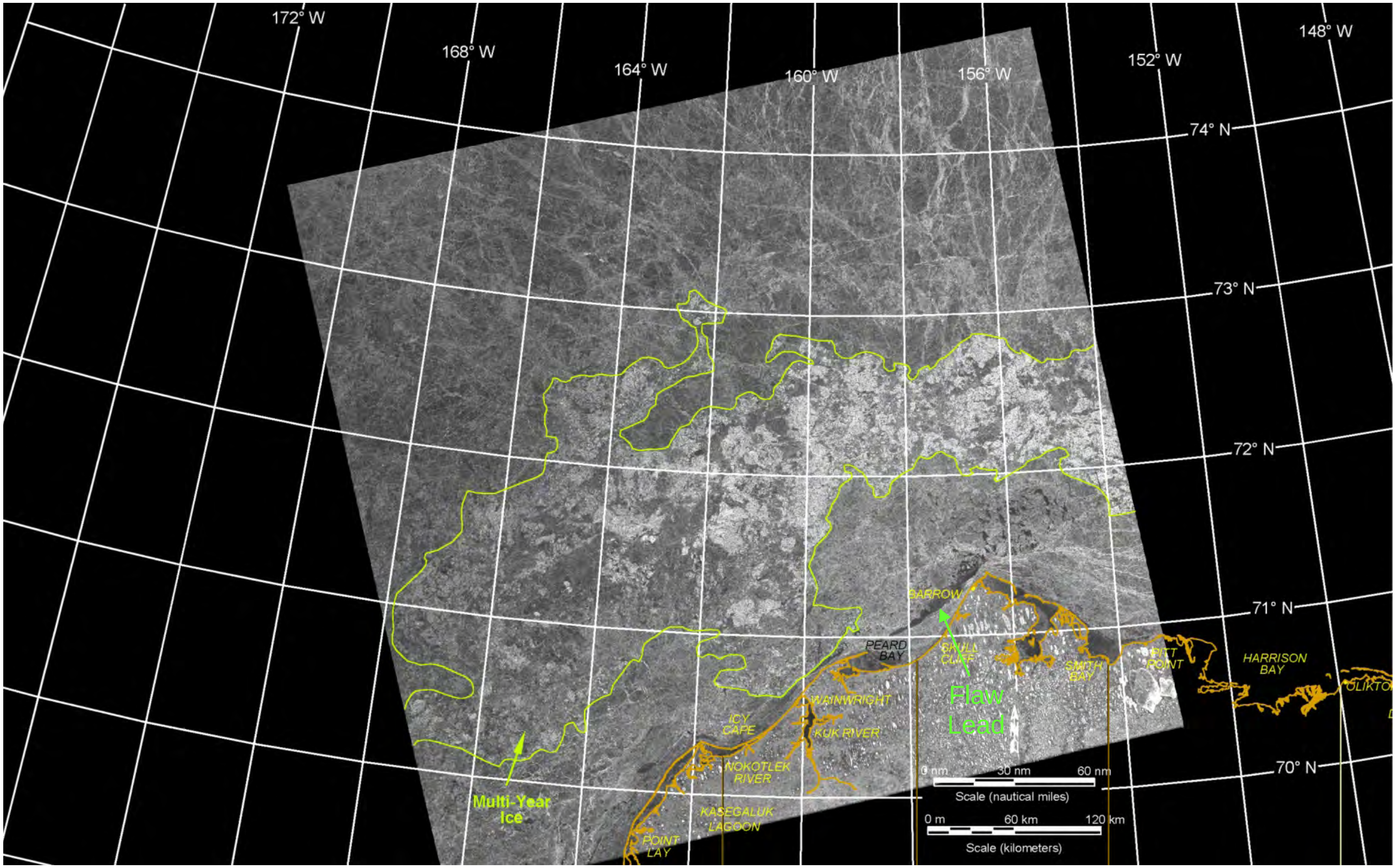


Figure 62. RADARSAT-2 Image of Chukchi Sea Acquired on February 10, 2012

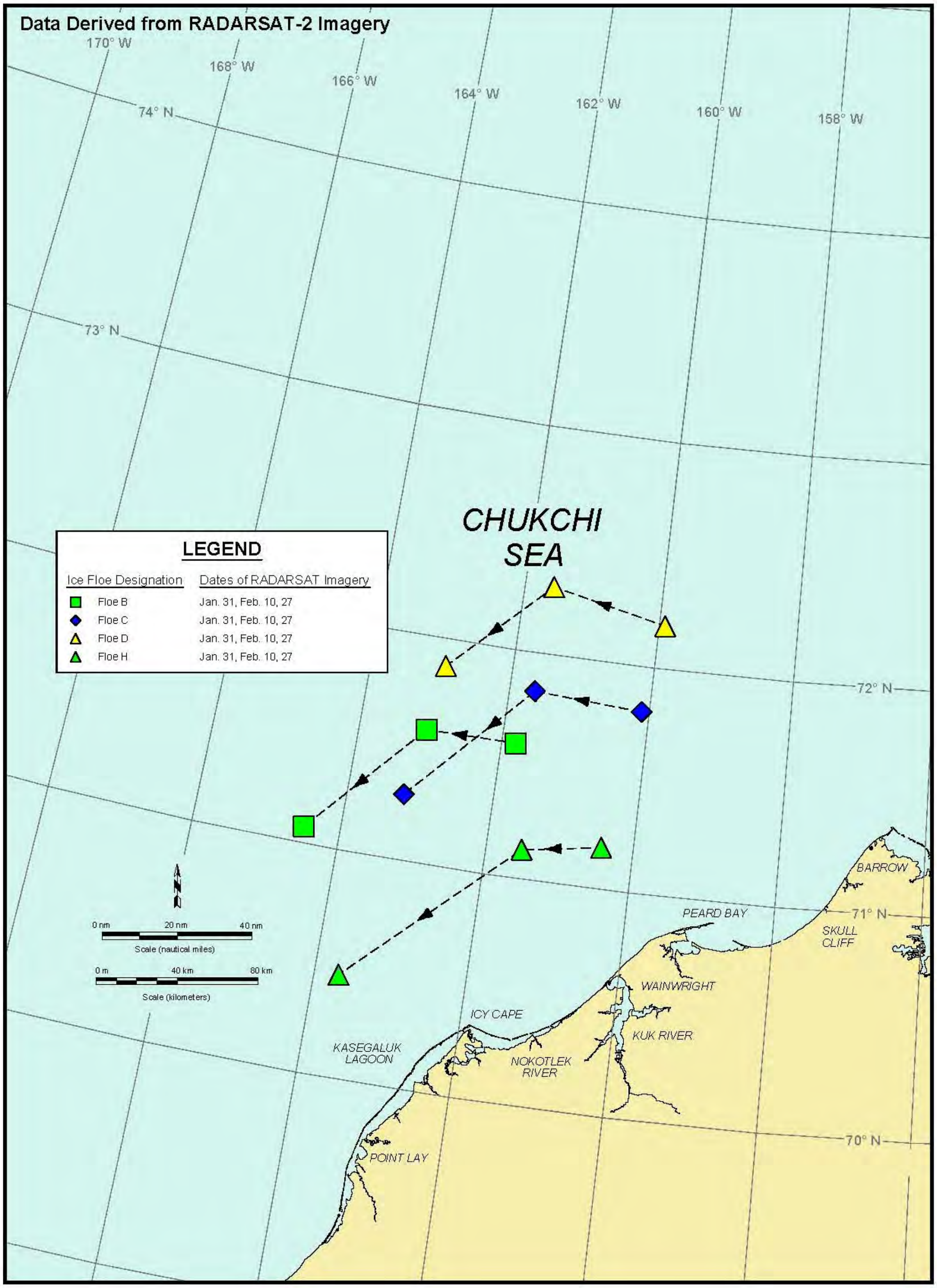
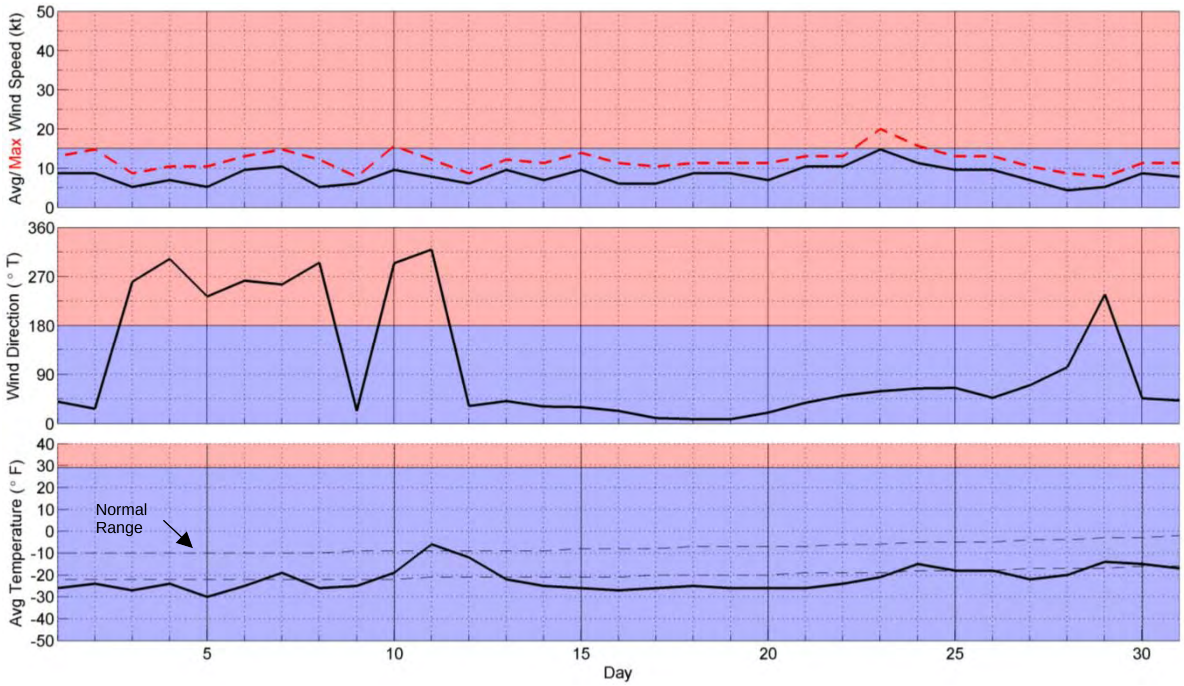


Figure 63. Chukchi Sea Multi-Year Ice Floe Displacements in February 2012

5.7.2. March 2012

Meteorological Conditions: Figure 64 presents the wind and temperature data recorded at Barrow Airport in March. Notwithstanding several brief exceptions, the cold snap that began in late February persisted for the entire month.

Easterly winds outnumbered westerlies by a substantial margin (22 days vs. 9 days), with the westerlies concentrated at the beginning of the month. No storms were recorded, and the average monthly wind speed of 8 kt (4 m/s) was lower than that in any other month during the study period.



Source: Weather Underground, 2012

Figure 64. Meteorological Conditions at Barrow Airport in March 2012

Ice Thickness: The calculated thickness of undisturbed first-year ice at the end of March was 154 cm, an increase of 22 cm over the course of the month. The calculation is based on an accumulation of 6,588 FDD since the beginning of the freeze-up season. By comparison, the calculated thickness for the Beaufort was 6% greater, at 163 cm (Section 4.7.2), based on 7,290 FDD.

Because the landfast ice was displaced from nearly all of the northeast Chukchi coast on one or more occasions during freeze-up, it is likely that the first-year ice in the landfast ice zone attained the calculated thickness only in protected areas that included Kasegaluk Lagoon, Peard Bay, and the region immediately east of Icy Cape.

Multi-Year Ice: A RADARSAT-2 image acquired on March 15th (Figure 65) suggests that the band of multi-year ice in the northeast Chukchi Sea changed little between the end of February and the middle of March. Its width was approximately 45 nm (83 km) off Point Barrow and 70 nm (130 km) off Icy Cape.

Leads: AVHRR images indicate that the coastal flaw lead remained closed during the first part of March. The ice canopy changed dramatically, however, when the westerly winds that predominated through the 11th were followed by light to moderate northerlies in mid-month (Figure 64). As shown in Figure 66, a large expanse of ice located to the south of Katie's Floeberg broke loose and began to move to the south southwest. Evidence of this displacement appears in the RADARSAT-2 image acquired on March 15th in the form of shore-normal leads off Point Lay, a long, sinuous lead in the band of multi-year ice, and a long, narrow lead to the north of Point Barrow (Figure 65).

The ice canopy changed again during the third week in March, when the wind veered to the northeast. A massive lead trending northeast-southwest opened from Ledyard Bay to about 300 nm (556 km) northeast of Point Barrow (Figure 67), a distance of more than 500 nm (927 km). The portion off the Chukchi coast (the coastal flaw lead) attained a maximum width of approximately 30 nm (56 km). Based on AVHRR imagery, the lead opened between March 20th and 23rd, and remained open at least through the 28th. As in December 2011, it appears that the extension of the coastal flaw lead to the northeast of Point Barrow facilitated the entry of multi-year ice floes into the region south and west of Barrow (Figure 67).

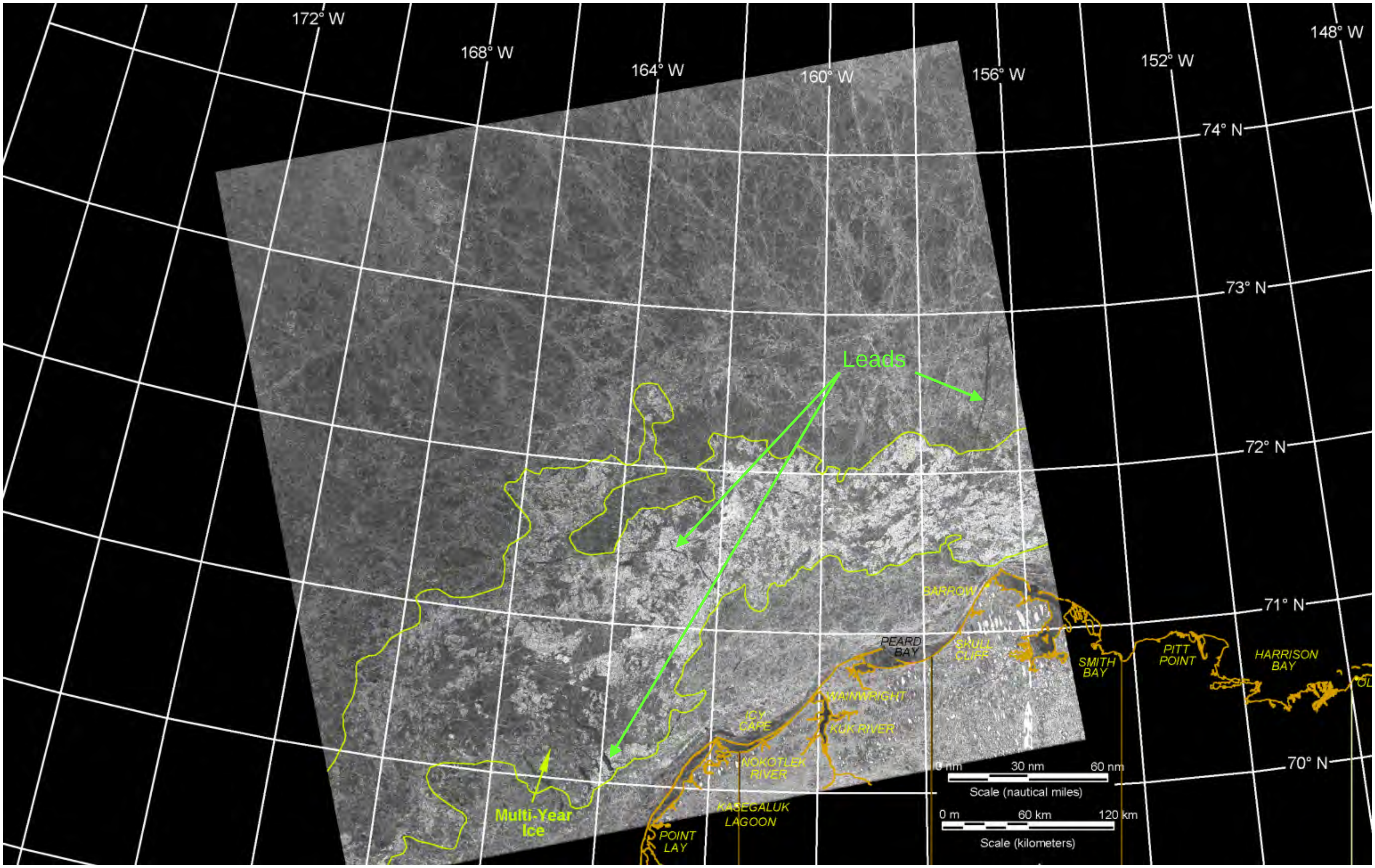
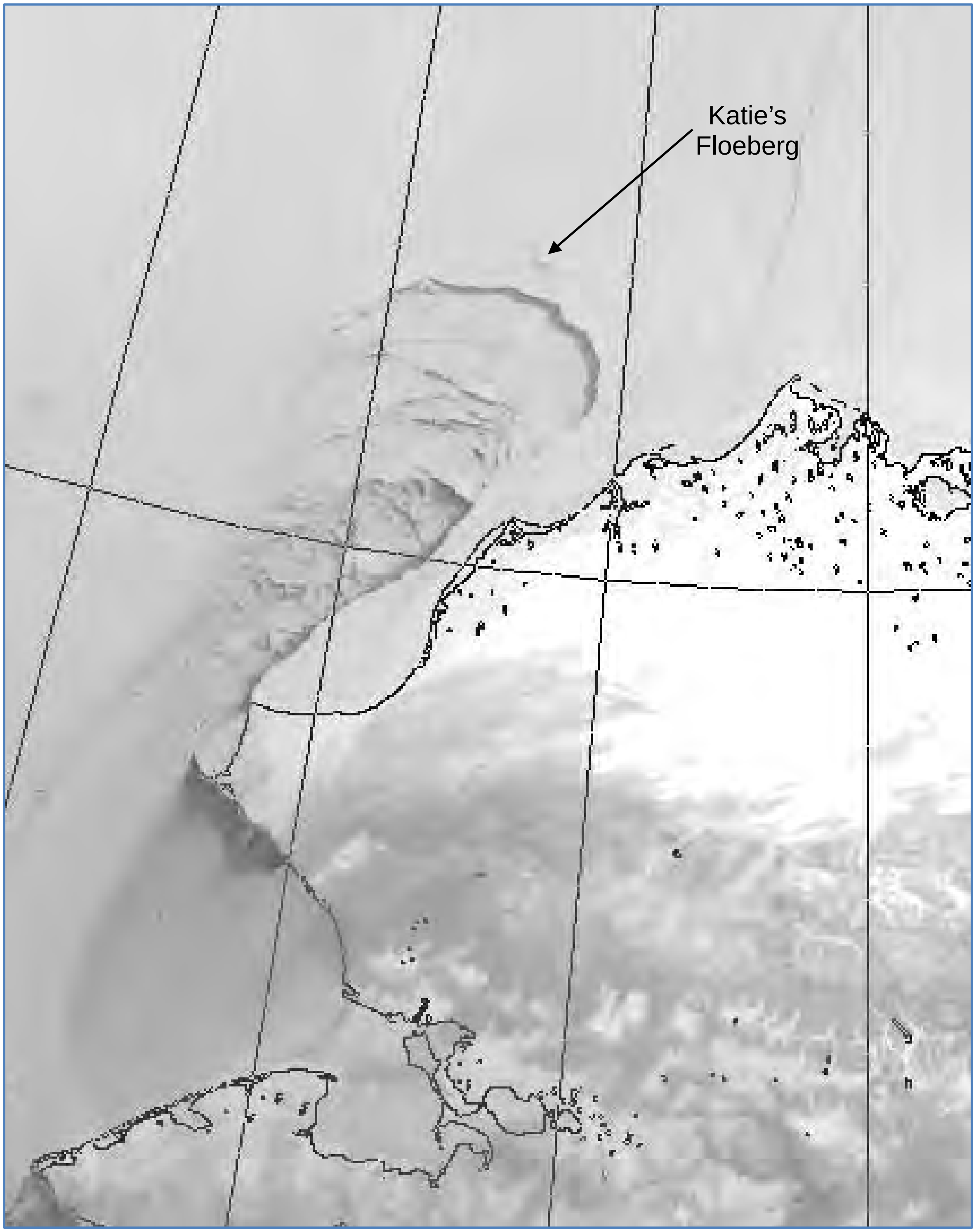
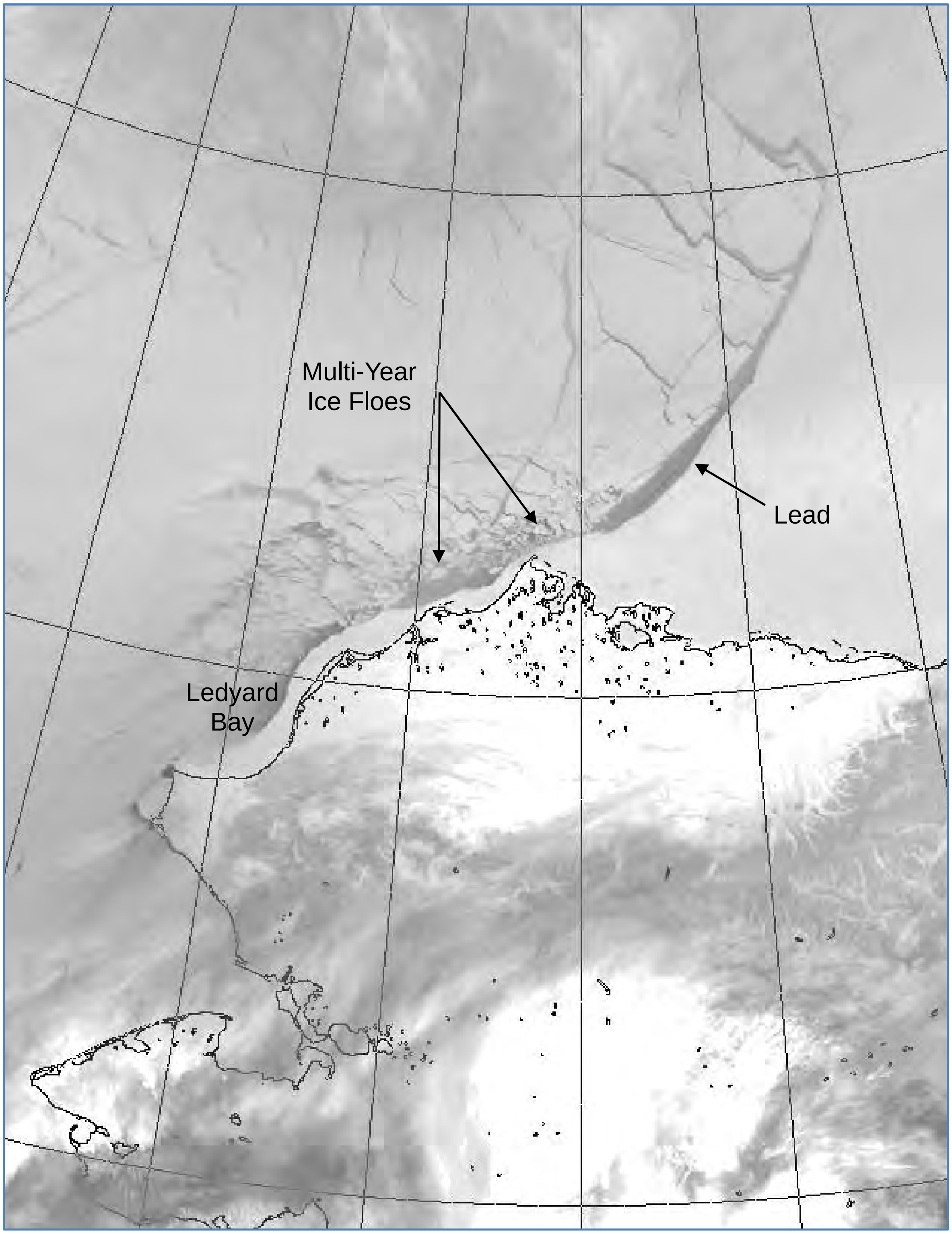


Figure 65. RADARSAT-2 Image of Chukchi Sea Acquired on March 15, 2012



Source: National Weather Service, 2012

Figure 66. AVHRR Image Acquired on March 16, 2012, Showing Ice Moving South Southwest



Source: National Weather Service, 2012

Figure 66. AVHRR Image Acquired on March 28, 2012, Showing Massive Lead Extending from Ledyard Bay to 300 nm Northeast of Point Barrow

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

The primary objectives of this section are to characterize present-day freeze-up processes using the data acquired during the past three years (2009-10, 2010-11, and 2011-12), and to compare them with those documented 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: 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 three years and the 1980s, potential long-term trends in ice behavior are identified. It should be recognized that the past three 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 15 presents the FDD accumulated at Barrow on a monthly basis for each winter season from 1970-71 through 2011-12. The values were 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 22-year period from 1990-91 through 2011-12. The column on the right side displays the rank of each winter over the entire 42-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. 42) to the coldest (most FDD at the end of May).

Table 15: Accumulated Freezing-Degree Days (<29°F) at Barrow, 1970-71 through 2011-12

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	42-yr Rank
1970-71	129	1013	2009	3224	4727	6270	7734	8738	9098	41
1971-72	7	466	1351	2603	4004	5402	6912	7914	8252	37
1972-73	30	275	1103	2092	3410	4591	6135	7086	7393	21
1973-74	9	307	958	2024	3255	4859	6381	7488	7826	32
1974-75	18	725	1823	3546	5263	6453	7579	8584	8891	40
1975-76	155	893	2102	3677	5162	6667	8043	8976	9342	42
1976-77	12	486	1281	2689	3836	5107	6694	7756	8066	35
1977-78	0	272	1309	2444	3529	4738	5963	6785	7176	14
1978-79	17	696	1404	2734	3710	5082	6496	7393	7684	26
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	38
1983-84	153	835	1666	2546	3919	5717	7128	8316	8700	39
1984-85	0	366	1479	2799	3925	5218	6517	7585	7780	29
1985-86	60	635	1424	2537	3901	4959	6407	7508	7784	30
1986-87	13	404	1262	2359	3661	5033	6295	7306	7579	25
1987-88	51	240	1272	2447	3672	4931	6224	7052	7337	18
1988-89	49	886	2164	3351	4994	5546	6637	7327	7687	27
1989-90	0	363	1611	2805	4417	5878	7131	7776	7903	34
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**	**42-yr Rank**
1990-91	25	400	1477	2863	4177	5499	6947	7718	7748	28
1991-92	27	384	1494	2883	4358	5788	6972	7818	8076	36
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	33
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	31
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
2011-12	3	183	1059	2264	3814	5013	6588	7319	7556	24
Average	**23**	**324**	**1125**	**2276**	**3585**	**4784**	**6070**	**6840**	**7071**	
Std. Dev.	**37**	**206**	**313**	**423**	**453**	**518**	**537**	**554**	**538**	

Whereas 2009-10 and 2010-11 were among the warmest winters in the past 42 years, ranking sixth and third, respectively, 2011-12 was decidedly colder. As the coldest winter since 1999-2000, it ranked near the middle of the 42-year period under consideration (24^{th}).

The accumulated freezing-degree days at the end of each winter season are plotted against time in Figure 68. A long-term trend toward warmer conditions is readily apparent, with freezing-degree days decreasing at an average rate of 42/yr since 1970-71. Spikes of a magnitude comparable to that which occurred in 2011-12 are evident on several prior occasions, indicating that the colder temperatures during the past winter probably represent normal variability rather than a reversal of the trend toward declining FDDs.

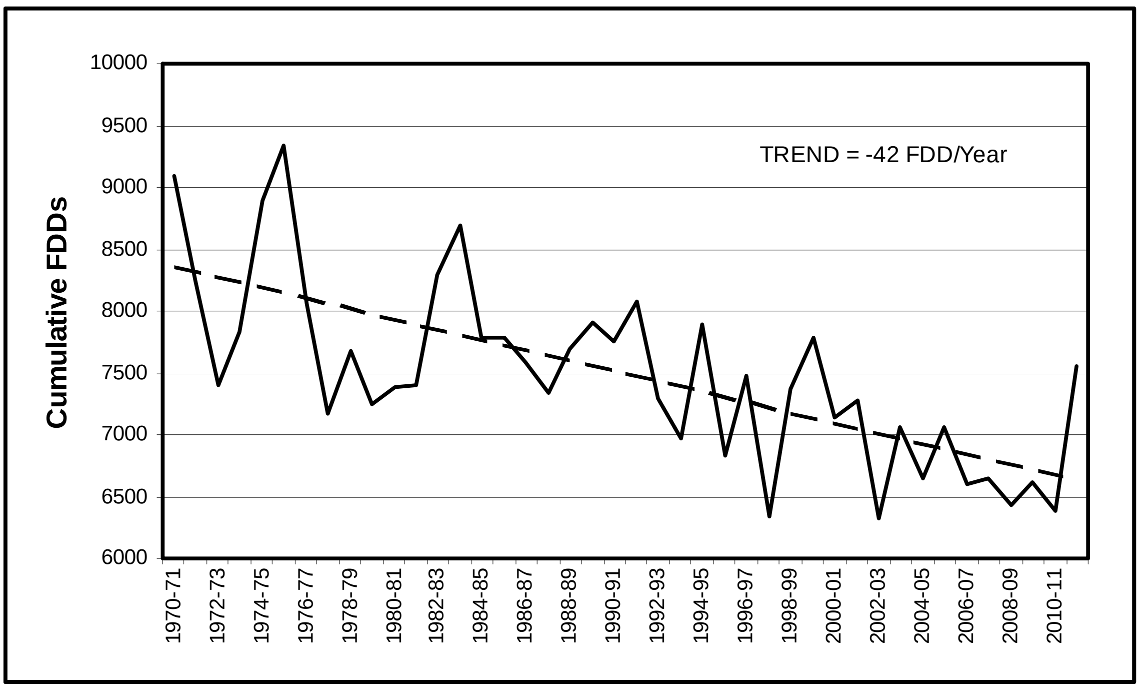


Figure 68. Annual Cumulative Freezing-Degree Days (<29°F) at Barrow, 1970-71 through 2011-12

Melling and Riedel (2005) found a similar warming 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. Based on the data presented in Table 15, the average annual accumulated freezing-degree days declined by 4% from the 1970s to the 1980s, 5% from the 1980s to the 1990s, and 8% from the 1990s to the past twelve years (2000-01 through 2011-12). The total decline from 1970s to the most recent 12-year period was nearly 16%.

Additional evidence of the long-term increase in winter air temperatures can be seen in Figure 69, which displays the difference between each monthly value in 2009-10, 2010-11, and 2011-12, and the corresponding long-term average at Barrow for the 29-year period from 1971-72 through 1999-2000. The recent value exceeded the long-term average in seven of nine months in 2009-10 and eight of nine months in 2010-11. Even in 2011-12, which was substantially colder, the recent value exceeded the long-term average in seven months. With the exception of January and March, the monthly temperatures in 2011-12 bore a strong resemblance to those recorded during the prior two winters.

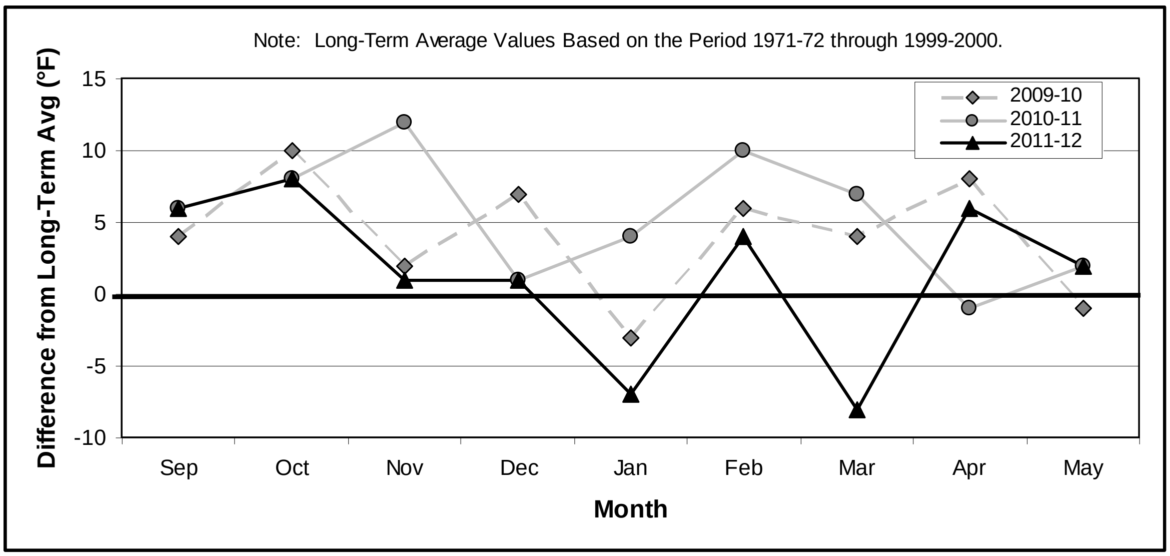


Figure 69. Differences between Recent Monthly Air Temperatures and Long-Term Average Values at Barrow

<u>Trend</u>: Since the 1970s, progressively warmer winter seasons have caused the number of freezing-degree days at Barrow to decline at an average rate of 42 per year. Nevertheless, as demonstrated in 2011-12, a substantial deviation from this trend can occur in any given year.

6.2. Winds

The wind directions that prevailed at Deadhorse and Barrow Airports during the each of the past three freeze-up seasons (October 1st through March 31st) are summarized in Tables 16 and 17. Westerlies occurred slightly more often than easterlies at Deadhorse, with the frequency ranging from a low of 50% in 2010-11 to a high of 60% in 2011-12. The average frequency of westerly winds over the past three winters was 54%. Easterlies predominated at Barrow, with frequencies from 65% in 2010-11 to 71% in 2011-12. The average value was 68%.

Table 16. Beaufort Sea Wind Directions, 2009-10 through 2011-12

Month	2009-10 Days		2010-11 Days		2011-12 Days	
	Easterly	Westerly	Easterly	Westerly	Easterly	Westerly
October	20	11	25	6	23	8
November	19	11	15	15	7	23
December	15	16	13	18	15	16
January	7	24	16	15	3	28
February	16	12	8	20	19	10
March	11	20	14	17	7	24
Total Days	**88**	**94**	**91**	**91**	**74**	**109**
Frequency	**48%**	**52%**	**50%**	**50%**	**40%**	**60%**

Note: Table 16 is based on the average daily wind directions recorded at Deadhorse Airport.

Table 17. Chukchi Sea Wind Directions, 2009-10 through 2011-12

Month	2009-10 Days		2010-11 Days		2011-12 Days	
	Easterly	Westerly	Easterly	Westerly	Easterly	Westerly
October	23	8	29	2	28	3
November	21	9	18	12	16	14
December	22	9	22	9	27	4
January	13	18	21	10	14	17
February	22	6	10	18	23	6
March	24	7	18	13	22	9
Total Days	**125**	**57**	**118**	**64**	**130**	**53**
Frequency	**69%**	**31%**	**65%**	**35%**	**71%**	**29%**

Note: Table 17 is based on the average daily wind directions recorded at Barrow Airport.

The storms that occurred at Deadhorse and Barrow Airports during each of the past three freeze-up seasons are summarized in Tables 18 and 19. Both the number of discrete storm events and the total number of days with storm conditions ("storm-days") are shown. As in the case of Sections 4 and 5, a storm is defined as an event during which the daily average sustained wind speed exceeds 15 kt (8 m/s).

Table 18. Beaufort Sea Storms, 2009-10 through 2011-12[1]

Freeze-Up[2]	Storm Events			Storm-Days		
	Easterly	Westerly	Total	Easterly	Westerly	Total
2009-10	10	5	15	24	13	37
2010-11	8	11	19	19	22	41
2011-12	8	6	14	16	18	34
Average	**9**	**7**	**16**	**20**	**18**	**38**

Notes:
[1] Table 18 includes all storm events with a daily average sustained wind speed exceeding 15 kt at Deadhorse Airport.
[2] The period of record extends from October 1st through March 31st.

Table 19. Chukchi Sea Storms, 2009-10 through 2011-12[1]

Freeze-Up[2]	Storm Events			Storm-Days		
	Easterly	Westerly	Total	Easterly	Westerly	Total
2009-10	14	3	17	37	4	41
2010-11	10	8	18	27	13	40
2011-12	8	3	11	21	6	27
Average	**11**	**5**	**16**	**28**	**8**	**36**

Notes:
[1] Table 19 includes all storm events with a daily average sustained wind speed exceeding 15 kt at Barrow Airport.
[2] The period of record extends from October 1st through March 31st.

In the Beaufort (Table 18), easterly storm events and storm days tended to outnumber their westerly counterparts by narrow margins, with an average of nine easterly events producing 20 storm-days per year versus seven westerly events producing 18 storm-days per year. Also noteworthy is the comparative calm that prevailed in 2011-12, when both the total number of storms (14) and the total number of storm days (34) were lower than those in each of the two prior years.

In the Chukchi (Table 19), the easterly dominance in wind direction was reflected in the storm population as well. The annual averages consisted of 11 easterly storm events producing 28 storm-days, and five westerly storm events producing eight storm-days. As in the case of the Beaufort, 2011-12 was marked by reduced storminess, with combined totals of only 11 storm events and 27 storm days.

Unfortunately, data from the 1980's suitable for direct comparison with those in Tables 18 and 19 are not available. However, an indication of storm conditions in that era 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 mid-winter storm frequency in the early 1980s with that which occurred in 2009-10, 2010-11 and 2011-12.

Whereas Dickins and Vaudrey computed an average of 8.5 storm events per mid-winter season for the years from 1981 through 1986, a similar analysis of the recent wind data produced an average of nine storm events per season (10 storms in 2010, 10 storms in 2011 and 7 storms in 2012). This outcome suggests a minimal increase in storm frequency, although the near-term average was reduced from ten per season to nine by the small number of storms in 2011-12. Additional data will be required to determine whether the storm frequency has increased only marginally since the early 1980s, or the recent average was unduly depressed by the comparative paucity of storms in 2011-12.

A cyclical trend in storm frequency is evident in the data compiled 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 (Figure 70). The storm count during freeze-up increased from the mid-1950s until mid-1960s, declined from the mid-1960s until mid-1970s, rose again from the mid-1970s until early 1990s, and remained nearly static thereafter. The criteria used to identify storm events are not specified, but the data nevertheless indicate that the rise in storm frequency that began in the mid-1970s was sustained through the mid-2000s. Although other wind characteristics such as direction, intensity, and duration also influence ice dynamics, the rise in the number of storm events during freeze-up since the mid-1970s suggests a possible increase in wind-driven ice movement.

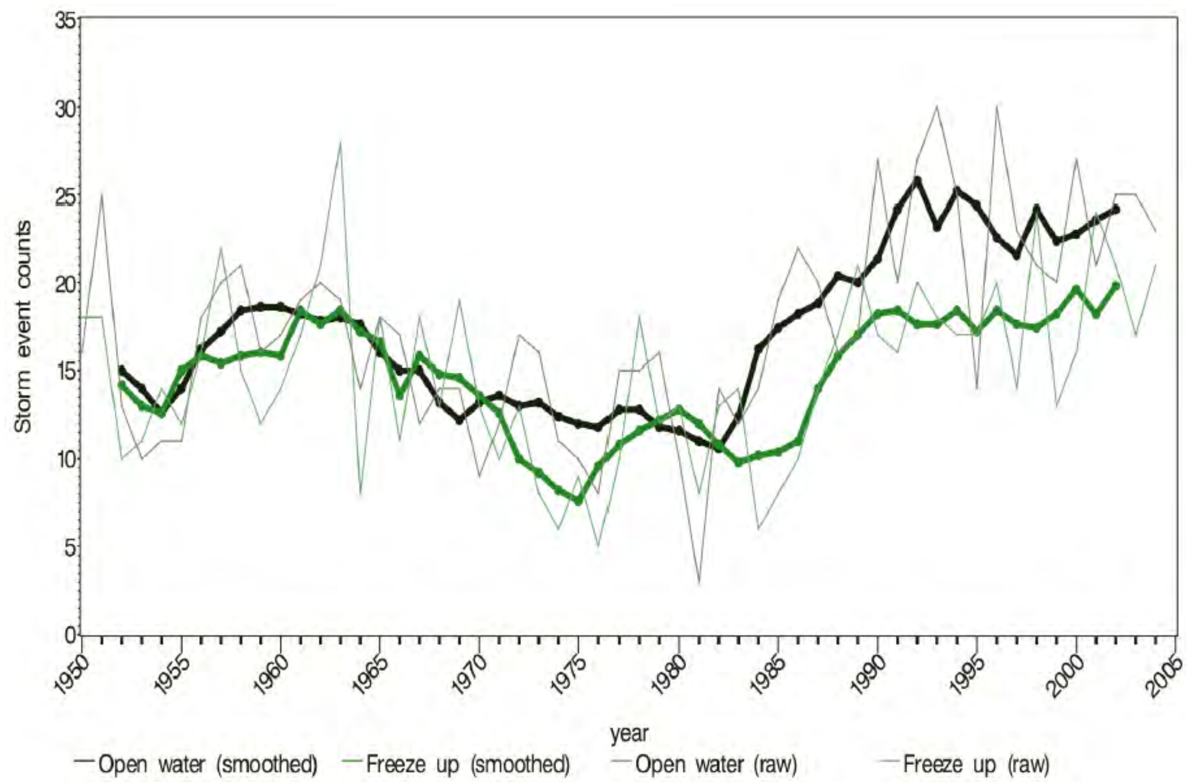


Figure 70. Yearly Storm Count at Barrow during the Open-Water and Freeze-Up Seasons, 1950-2004 (Walsh and Eicken, 2007)

Trends: Since the mid-1970s, the frequency of storm events during freeze-up has increased by more than 50%. The frequency of storm events in mid-winter (January through April) also may have increased, but additional data will be required to quantify the extent of the change.

6.3. Timing of Freeze-Up

Since 2002, the monthly average air temperature at Barrow has exceeded the long-term average for the period from 1971 through 1999 by 4°F (2°C) in September and 9°F (5°C) in October. This pattern was repeated in 2011-12, when the difference amounted to 6°F (3°C) in September and 8°F (4°C) in October.

The warmer air temperatures in late summer and early autumn appear to have contributed to, and in turn been intensified by, a decline in the extent of the pack ice (Section 4.2) and an increase in the temperature of the sea surface. The end result of this feedback loop (warmer air temperatures → reduced ice cover → warmer sea surface 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.

The chronology of freeze-up in the Alaskan Beaufort Sea during the past three years is presented in Table 20. The date of freeze-up in the nearshore region ranged from October 11th to October 26th. The average, October 20th, is identical to the average that prevailed during the five-year period from 2002 through 2006 (Vaudrey, 2007) but 16 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). The accumulated freezing-degree days (FDD) at the time of nearshore freeze-up varied between 80 and 106, with a mean value of 96.

Complete freeze-up in the Alaskan Beaufort Sea occurred between November 1st and 9th. The average was November 4th. The number of FDD at complete freeze-up varied widely, from 412 in 2009 to 201 in 2011, suggesting that factors including the sea surface temperature and wind conditions exert powerful influences on the freeze-up process.

Table 20. Chronology of Freeze-Up in the Alaskan Beaufort Sea, 2009 through 2011

Event	2009		2010		2011		Average	
	Date	FDD	Date	FDD	Date	FDD	Date	FDD
First Ice[1]	Sep 28	15	Oct 4	19	Oct 12	14	**Oct 5**	**16**
Nearshore Freeze-Up[2]	Oct 22	106	Oct 11	80	Oct 26	102	**Oct 20**	**96**
Complete Freeze-Up[3]	Nov 9	412	Nov 2	305	Nov 1	201	**Nov 4**	**306**

Notes:

1 "First Ice" refers to the date on which ice began to form in protected waters.

2 "Nearshore Freeze-Up" refers to the date on which ice covered the region typically occupied by landfast ice.

3 "Complete Freeze-Up" refers to the date on which ice covered the entire Alaskan Beaufort Sea.

Freeze-up dates in the Chukchi Sea during the past three years are presented in Table 21. Nearshore freeze-up occurred between November 4th and 20th, with an average of November 13th. This date is 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 has increased from approximately 30 days in the late 1970s to 125 days at present. The accumulated FDD at the time of nearshore freeze-up averaged 467 during the past three years but varied widely, from 265 to 601.

Table 21. Chronology of Freeze-Up in the Chukchi Sea, 2009 through 2011

Event	2009		2010		2011		Average	
	Date	FDD	Date	FDD	Date	FDD	Date	FDD
First Ice[1]	Oct 9	17	Oct 7	16	Oct 6	24	**Oct 7**	**19**
Nearshore Freeze-Up[2]	Nov 16	535	Nov 4	265	Nov 20	601	**Nov 13**	**467**
Complete Freeze-Up[3]	Nov 29	949	Dec 7	959	Nov 30	1022	**Dec 2**	**977**

Notes:

[1] "First Ice" refers to the date on which ice began to form in protected waters.

[2] "Nearshore Freeze-Up" refers to the date on which ice covered the region south of Point Barrow and east of the 163°W meridian.

[3] "Complete Freeze-Up" refers to the date on which ice covered the entire Chukchi Sea north of Cape Lisburne.

Complete freeze-up in the Chukchi Sea north of Cape Lisburne took place between November 29th and December 7th. The average date was December 2nd, corresponding to an average of 977 FDD.

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 second week in November in the northeastern Chukchi.

6.4. First-Year Ice Growth

As discussed in Section 4.1, the growth of undeformed first-year ice can be estimated on the basis of freezing-degree days (FDD) using the relationship of Lebedev (Bilello, 1960). Table 22 presents the computed ice thickness on a monthly basis for each winter season from 1970-71 through 2011-12. The results were obtained using the FDD data for Barrow compiled in Table 15, 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. 42) to the highest thickness.

In keeping with the relatively warm temperatures that prevailed in 2009-10 and 2010-11, the computed ice thicknesses for these years were among the lowest on record: 154 cm in 2009-10 (tied for 5th lowest) and 151 cm in 2011-12 (tied for the minimum ever recorded). The substantially colder air temperatures in 2011-12 produced a computed thickness of 167 cm that tied for 24th among the 42 values shown in Table 22. Notwithstanding this substantial increase, the average thickness over the past three

Table 22. Computed Ice Thickness (cm) at Barrow, 1970-71 through 2011-12

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	42-yr Rank
1970-71	16	52	77	102	127	150	169	182	186	41
1971-72	3	33	61	90	115	137	158	171	176	37
1972-73	7	24	55	79	105	125	148	161	165	19
1973-74	3	26	50	78	102	129	151	166	170	29
1974-75	5	43	73	108	135	152	167	180	183	40
1975-76	18	48	79	110	134	155	173	184	189	42
1976-77	4	34	60	92	113	133	156	169	173	35
1977-78	0	24	60	87	107	127	145	157	162	14
1978-79	5	42	63	93	110	133	153	165	169	26
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	37
1983-84	17	47	69	89	114	142	161	176	181	39
1984-85	0	29	65	94	114	135	153	167	170	29
1985-86	10	40	63	89	114	131	152	166	170	29
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	26
1989-90	0	29	68	94	122	144	161	170	171	33
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**	**42-yr Rank**
1990-91	6	30	65	95	118	139	159	169	169	26
1991-92	6	30	65	95	121	143	159	170	173	35
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	33
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	29
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
2011-12	2	19	53	83	112	132	154	164	167	24
Average	**4**	**26**	**55**	**83**	**108**	**128**	**147**	**157**	**160**	
Std. Dev.	**5**	**9**	**9**	**9**	**8**	**8**	**7**	**7**	**7**	

years, 157 cm, is 14 cm less than that computed for the six-year period from 1980-81 through 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 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 first-year 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 six-month freeze-up season (October 1st through March 31st) has increased dramatically, from 34 cm in the 1980s to 64 cm in the 1990s and 102 cm from 2000-01 through 2011-12 (Figure 71). Over the past three freeze-up seasons, the average has risen to 128 cm – a nearly four-fold increase since the 1980s.

In addition to reducing the 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 8% (14 cm) since the early to mid-1980s. However, a significant increase in 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 greater impacts on ice behavior than reduced ice thickness.

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.

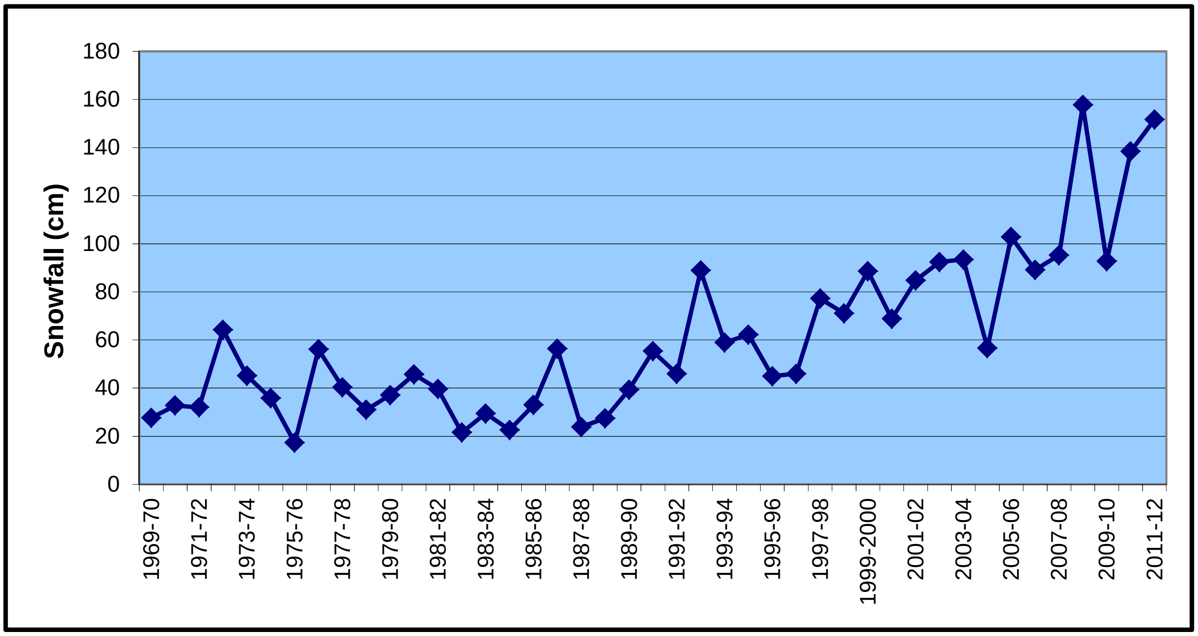


Figure 71. Annual Snowfall at Barrow during Freeze-Up (October 1 - March 31), 1969-70 through 2011-12

Beaufort Sea: Winds constitute the dominant driving force for ice movement in the Alaskan Beaufort Sea. Easterlies tend to produce westerly ice motion with an onshore component, 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 up to 25 nm (46 km) offshore. The most prominent are Weller Bank, which lies in northeastern Harrison Bay, and Stamukhi Shoal, which lies between Harrison and Prudhoe Bays. The large grounded rubble piles that typically form on these shoals lead to 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 and 2011-12 freeze-up seasons, warm air temperatures and a lack of sustained easterly winds in the fall produced a narrow landfast ice zone that persisted into early December. By late December, however, easterly storm activity had created a landfast ice zone anchored by a grounded shear zone to the west of Prudhoe Bay that was reminiscent of the conditions 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 either of the two bracketing years.

To the east of Prudhoe Bay, the contrast between the 1980s and the past three years 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 recent years, however, the ice tended to remain poorly-grounded and mobile into mid-winter except in close proximity to the islands.

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 0.1 and 5 nm (0.2 and 9.3 km) off the coast, and the ice often experiences severe deformation except in a narrow ice foot adjacent to the shoreline. The width of the landfast ice zone can increase in the region between Icy Cape and Point Lay, where the slope of the nearshore sea bottom is more gradual, and in the semi-protected embayments to the east of Point Franklin and Icy Cape.

The tendency toward a narrow, ephemeral landfast ice zone was maintained in each of the past three freeze-up seasons. The situation was particularly acute in 2010-11, when a stable strip of well-grounded landfast ice failed to materialize throughout freeze-up and mid-winter. Although a continuous strip did develop in 2011-12, quasi-stability was not achieved until well into January.

Seaward of the landfast ice zone, the ice is driven offshore during periods of easterly winds. The resulting coastal flaw lead separates the landfast ice from the highly mobile pack ice, 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.

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. These tendencies were observed in recent years as well: the lead attained a width of 40 to 50 nm (74 to 93 km) and remained open for a 25-day period from mid-February to early March of 2010, a width of 60 nm (111 km) in January of 2011, and maximum widths of 60, 50, 25, and 30 nm (111, 93, 46, and 56 km) in December, January, February, and March of 2011-12. Also noteworthy in 2011-12 were the significant amount of time that the lead remained open, including more than half of the months of December and February, and several periods when its length equaled or exceeded 200 nm (371 km).

Trend: The locations and shapes of the landfast ice zones and the associated leads and polynyas are similar to those in previous decades, but the landfast ice develops more slowly while the lead widths and polynya sizes tend to be larger. An additional difference in the Beaufort Sea is the absence of a stable, grounded shear zone to the east of Prudhoe Bay during freeze-up and early winter.

The data acquired during late freeze-up and mid-winter in 2009-10, 2010-11, and 2011-12 suggest that the coastal flaw lead in the Chukchi Sea tends to attain greater widths and persist longer than in the 1980s. A feedback loop may have developed under which warmer air temperatures and heavier snowfall produce weaker ice that is more susceptible to wind stress, the flaw lead opens at lower wind speeds, and the new ice that forms between wind events is thinner and more prone to displacement.

6.6. Multi-Year Ice

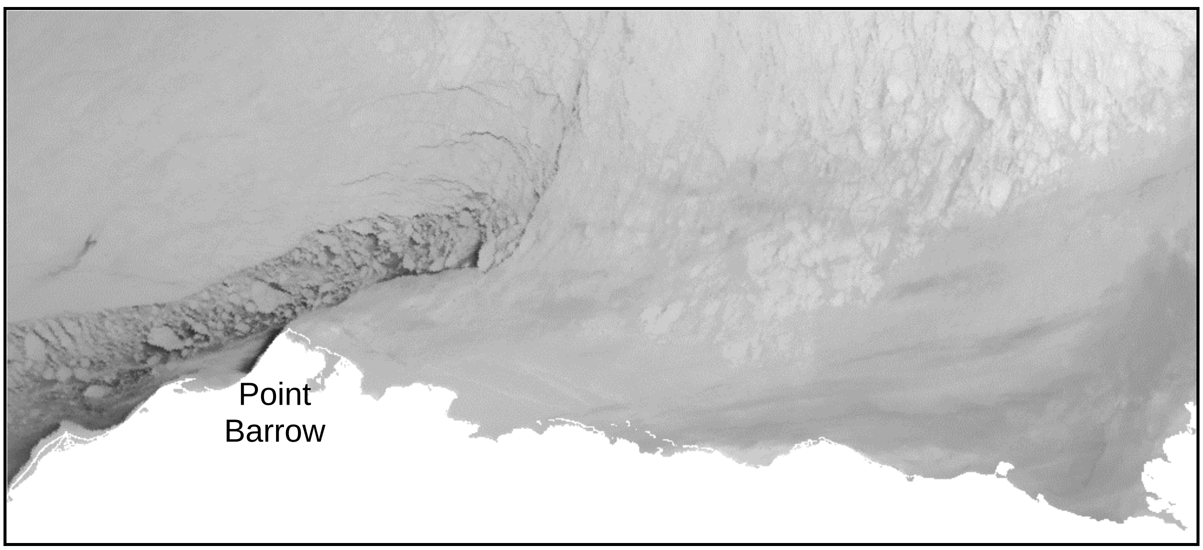
Two types of "multi-year" or "old" ice can occur in the Beaufort and Chukchi Seas: (1) true multi-year floes from the perennial polar pack in the Arctic Ocean ("pack floes"), and (2) second-year ice formed in the nearshore zone and spared from melting and/or transport offshore during the ensuing summer 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 in the 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: When the initial round of freeze-up studies was conducted in the 1980s, 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: 1980-81, 1983-84, and 1985-86 (Vaudrey, 1981-86). Grounded multi-year fragments with diameters as large as 120 m were observed during the other three seasons (1981-82, 1982-83, and 1984-85).

In the nine years that preceded the resumption of freeze-up studies in 2009-10, large multi-year floes invaded the nearshore region on only one occasion: 2001-02, when a low concentration approached the coast in the western Beaufort and northern Chukchi during the initial stages of freeze-up. The next invasion occurred in 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 Chukchi (Coastal Frontiers and Vaudrey, 2010). Although grounded fragments of old ice were observed on many of the barrier islands in 2010-11 (Coastal Frontiers and Vaudrey, 2011), large multi-year floes were absent from southern portion of the Alaskan Beaufort Sea in both that year and 2011-12. Hence, during the past 12 years, such floes have entered the nearshore region on only two occasions.

Chukchi Sea: Multi-year ice was present in the 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 characterized by concentrations up to 70% and southerly limits between 70.5° and 71°N.

Since 2000-01, large multi-year floes have invaded the region to the south and west of Point Barrow on six occasions: 2000-01, 2001-02, 2003-2004, 2005-2006, 2009-10, and 2011-12. The invasion in 2000-01 resembled that during the past winter, in that the coastal flaw lead stretched well past Point Barrow and channeled multi-year ice floes into the Chukchi (Figure 72).



After Eicken, *et al*., 2006

Figure 72. AVHRR Image Acquired on March 12, 2001, Showing Multi-Year Ice Floes Entering Coastal Flaw Lead

In 2009-10, floes with diameters approaching five kilometers were present at concentrations as high as 70% (Coastal Frontiers and Vaudrey, 2010). With the exception of small fragments embedded in a limited number of first-year floes, multi-year ice was absent from the Chukchi in 2010-11 (Coastal Frontiers and Vaudrey, 2011). Large multi-floes returned in 2011-12, however, when the coastal flaw lead extended sufficiently far north of Point Barrow to entrain the ice arriving from the offshore portion of the Beaufort (Section 5.5.1). Floes with diameters from 100 m to more than 20 km attained concentrations as high as 90%, and moved as far south as 68°N. In summary, large multi-year floes have entered the region to the south and west of Barrow in six of the past 12 years including two of the past three.

Trend: The probability of large multi-year ice floes invading the nearshore portion of the Alaskan Beaufort Sea in any given year is substantially 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 4.2), 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 in the nearshore region of the Beaufort. Furthermore, fragments of old ice analogous to those observed in 2010-11 can be present even if large multi-year floes remain well offshore.

The probability of multi-year ice entering the Chukchi Sea to the south and west of Barrow also appears to have decreased since the 1980s, but the validity of this conclusion is challenged by the invasions that occurred in two of the past three freeze-up seasons. If northward extensions of the coastal flaw lead beyond Point Barrow become commonplace, as occurred in 2011-12, a rebound in the frequency of multi-year ice incursions into the Chukchi is likely to ensue. Factors that could facilitate this outcome include the increased dimensions and persistence of the coastal flaw lead (Section 6.5), and the thinner, weaker nature of the first-year ice canopy that could promote lead expansion (Section 6.4).

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 (ratio of floe speed to wind speed) 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).

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; Coastal Frontiers and Vaudrey, 2010). In the Chukchi, where the westward set of the Beaufort Gyre tends to diminish to the 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 9 nm/day (2 to 17 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 (Coastal Frontiers and Vaudrey, 2011). All of the floes in the Chukchi remained well north of Point Barrow, and hence were not sheltered from the Beaufort Gyre. The monthly drift rates in the Beaufort averaged 4.8 nm/day (8.9 km/day) while ranging from 1.4 to 9.9 nm/day (2.6 to 18.3 km/day). Short-term rates over periods of one to two weeks varied between 0.7 and 11.8 nm/day (1.3 and 21.9 km/day). In the Chukchi, the average monthly drift rate was 4.0 nm/day (7.4 km/day) with maxima and minima of 2.9 and 6.3 nm/day (5.4 and 11.7 km/day). The short-term rates ranged from 0.2 to 9.7 nm/day (0.4 to 18.0 km/day).

During the past year (2011-12), eight multi-year ice floes were tracked for various periods between mid-November and the end of February. Of the five that entered the Chukchi, two remained north of Point Barrow while three moved to the south. As shown in Table 7, the monthly drift rates in the Beaufort varied between 1.6 and 8.3 nm/day (3.0 and 15.4 km/day). The average of 4.1 nm/day (7.6 km/day) was the lowest among the past three years, apparently reflecting the relatively low frequency of easterly winds (40%; Table 16) and low number of easterly storm days (16; Table 18). Short-term drift rates ranged from 0.1 to 13.3 nm/day (0.2 to 24.6 km/day).

The monthly drift rates in the Chukchi in 2011-12 (Table 13) were consistent with those in the prior two years: 0.3 to 7.9 nm/day (0.6 to 14.6 km/day) with an average value of

4.3 nm/day (8.0 km/day). The short-term rates varied from 0.4 to 8.3 nm/day (0.7 to 15.4 km/day).

Trend: The average drift rate measured for pack ice in the Beaufort Sea was 6 nm/day (11 km/day) in 2009-10, 4.8 nm/day (8.9 km/day) in 2010-11, and 4.1 nm/day (7.6 km/day) in 2011-12. The first of these is comparable to the rates obtained in the 1980s, but the second and third are lower. Additional years of observation will be necessary to determine whether the reduced values in 2010-11 and 2011-12 reflect normal fluctuations or a long-term trend. In either case, the lower speeds recorded during the past two years run counter to the findings of Walsh and Eicken (2007), who suggested that thinner sea ice in the winter may lead to increased ice movement.

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The average drift speeds measured in the Chukchi over the past three years have remained nearly constant: 4.0 nm/day (7.4 km/day) in both 2009-10 and 2010-11, and 4.3 nm/day (8.0 km/day) in 2011-12.

7. SUMMARY AND CONCLUSIONS

Study Methods

1. ***Remote Sensing:*** RADARSAT-2 images, when combined with AVHRR images, MODIS images, and publicly-available ice charts, 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. Nevertheless, remote sensing must be supplemented with on-site observations to detect and quantify local ice features and processes.

2. ***Aerial Reconnaissance Missions:*** Reconnaissance flights provide invaluable opportunities to refine the findings derived from remote sensing, and to identify small-scale features and processes that otherwise would escape detection. The flights conducted in late November 2011 not only provided insight into the early stages of freeze-up, but also fostered a realistic understanding of the conditions that might be encountered when responding to a drilling incident that occurred at the end of the open-water season. The flights conducted in February 2012 were instrumental in characterizing the features that had formed during freeze-up, such as the landfast ice zone and ice pile-ups. In addition, these missions led to the discovery of extraordinary ice features that had become grounded off the Chukchi Sea coast.

Findings for Entire Study Area

1. ***Air Temperatures***: In contrast to 2009-10 and 2010-11, which were among the warmest winters since 1970-71, last winter was the coldest since 1999-2000 and colder than 23 others in the 42-year period of record. Nevertheless, the drop in air temperatures probably reflected normal interannual variability rather than a reversal of the long-term trend toward warming.

2. ***First-Year Ice Growth***: The computed thickness of undeformed first-year ice at the end of the 2011-12 winter season was 176 cm in the Alaskan Beaufort Sea and 167 cm in the Chukchi, based on accumulations of 8,275 and 7,556 FDD at Deadhorse and Barrow Airports, respectively. In keeping with the relatively cold temperatures that prevailed in 2011-12, these thicknesses were about 10% greater than those computed for the previous two winters.

Findings for Beaufort Sea

1. ***Late Summer:*** The last vestiges of nearshore ice disappeared from the Alaskan Beaufort Sea in mid-August 2011. Subsequently, the pack ice reached its seasonal minimum extent on September 9th. The average extent in September was the second lowest since record-keeping began in 1979, and only 7% larger than the all-time low in 2007. At the end of September, the ice edge was located approximately 110 nm (204 km) off Barter Island and 240 nm (445 km) off Point Barrow.

2. ***Freeze-Up***: Freeze-up began during the second week in October, when ice began to form adjacent to the coast. Complete ice coverage in the nearshore region occurred on October 26th, after 102 FDD had accumulated at Deadhorse Airport. This timing is four days later than in 2009 and 15 days later than in 2010, producing an average date of October 20th for the past three freeze-up seasons. Complete freeze-up in the Alaskan Beaufort Sea occurred on November 1st, at which time 201 FDD had accumulated.

3. ***Wind Regime:*** Based on the average daily wind directions recorded at Deadhorse Airport, westerlies outnumbered easterlies by a ratio of three to two (60% vs. 40%) during the six-month period from October 2011 through March 2012. Storm events with average daily wind speeds exceeding 15 kt occurred on 14 occasions. Eight of the storms were easterlies that produced 16 days of storm conditions ("storm-days"), while the remaining six storms were westerlies that produced 18 storm-days. Both the total number of storms (14) and total number of storm days (34) were lower than those in either of the prior two freeze-up seasons.

4. ***Landfast Ice:*** As in 2009-10 and 2010-11, the landfast ice zone tended to expand during periods of easterly winds and contract during periods of westerly winds. After remaining narrow in November, a month dominated by westerlies, the landfast ice zone grew dramatically in December in response to three easterly storms. At the beginning of January, it extended past the 18-m isobath and exceeded 20 nm (37 km) in width over the entire region between Point Barrow and Barter Island. It remained firmly grounded on Weller Bank and Stamukhi Shoal through mid-winter, but narrowed off Smith Bay and from Prudhoe Bay to Camden Bay in January. Easterly winds and an easterly storm triggered another period of expansion in February, but the landfast ice failed to achieve stability to the east of Prudhoe Bay and retreated to the 11-m isobath in March.

5. ***Multi-Year Ice Floes:*** Except in the immediate vicinity of Point Barrow**,** multi-year ice remained well offshore in the Alaskan Beaufort Sea throughout the 2011-12 freeze-up season. Since 2000-01, large multi-year floes have invaded the nearshore region on

only two occasions, 2001-02 and 2009-10. This finding suggests that the probability of an invasion in any given freeze-up season currently is less than 20%.

6. ***Ice Pile-Ups:*** Ten ice pile-ups occurred in central portion of the Alaskan Beaufort Sea during the 2011-12 freeze-up season. Nine were located on natural barrier islands (including four on Narwhal Island) and one on Northstar Production Island. The heights ranged from 2 to 7.6 m, the encroachment distances from 0 to 20 m, the alongshore lengths from 200 to 1,200 m, and the ice block thicknesses from 20 to 30 cm.

Findings for Chukchi Sea

1. ***Freeze-Up:*** Freeze-up in the Chukchi Sea began during the first week in October with initial ice formation in Kasegaluk Lagoon. Complete coverage in the nearshore region followed on November 20th, after 601 FDD had accumulated at Barrow Airport. This date is four days later than in 2009 and 16 days later than in 2010, yielding an average of November 13th for the past three freeze-up seasons. Complete coverage of the Chukchi Sea north of Cape Lisburne occurred on November 30th, concurrent with the accumulation of 1,022 FDD.

2. ***Wind Regime:*** Easterly winds occurred with a frequency of 71% at Barrow Airport during the 2011-12 freeze-up season, versus 29% for westerlies. As in the case of the Beaufort, both the number of storms (11) and number of storm-days (27) were less than those recorded in either of the prior two freeze-up seasons. Eight of the storms were easterlies that accounted for 21 storm-days, while the remaining three were westerlies that accounted for six storm-days.

3. ***Landfast Ice:*** The characteristically narrow landfast ice zone in the northeast Chukchi Sea remained unstable and discontinuous until January, when a predominance of westerly winds coupled with two westerly storms produced a continuous, quasi-stable strip between Point Lay and Barrow. When a coastal reconnaissance flight was conducted on February 6th, the edge of the fast ice was located 0.9 nm (1.7 km) off Barrow, 0.1 nm (200 m) off Point Belcher, and 6.0 nm (11.3 km) off Point Lay. This strip persisted for the remainder of February despite the frequent occurrence of easterly winds.

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 present during a significant portion of the 2011-12 freeze-up season, including more than half of the months of December and February. The width typically ranged from 10 to 30 nm (19 to 56 km) but expanded to as much as 60 nm (111km) in December and 50 nm

(93 km) in January. The length typically varied between 120 and 180 nm (222 and 334 km) but equaled or exceeded 200 nm (371 km) on several occasions. In both mid-December and late March, the lead extended northeast of Point Barrow to such an extent that it entrained multi-year ice floes arriving from the Beaufort Sea.

5. ***Nearshore vs. Offshore Ice Cover:*** As in 2010 and 2011, a distinct change in the nature of the offshore ice canopy was noted approximately 40 to 50 nm (74 to 93 km) off the coast during the aerial reconnaissance flights conducted in February 2012. Inshore of this location, the ice evidenced significant deformation with ridge and rubble heights to 8 m. Farther offshore, the ice tended to be relatively flat. Ridges and rubble fields were more widely spaced, with heights typically less than or equal to 3 m. This difference reflects the influence of the coastal flaw lead, which causes the nearshore ice to lose confinement. The rapid movements that result can produce extensive ridging and rafting as floating pans of ice collide with, or rotate about, one another.

6. ***Multi-Year Ice Floes:*** Large multi-year ice floes began streaming into the region south and west of Barrow in mid-December when they encountered an extension of the coastal flaw lead off Point Barrow that caused them to turn to the southwest. This pattern of southwesterly movement, which persisted through mid-winter, included another episode of the flaw lead entraining multi-year floes in late March. Floes with diameters from 100 m to more than 20 km attained concentrations as high as 90%, and moved as far south as the 68°N parallel. Large multi-year ice floes have invaded the region south and west of Barrow in six of the past twelve freeze-up seasons: 2000-01, 2001-02, 2003-04, 2005-06, 2009-10 and 2011-12. This finding suggests that the probability of an invasion in any given freeze-up season currently is about 50%.

7. ***Ice Pile-Ups:*** Thirty-one ice pile-ups were observed on the coast of the northeast Chukchi Sea during the 2011-12 freeze-up season. The highest concentrations were located on the spit that ends at Point Franklin and on the barrier islands that bracket Icy Cape. The heights ranged from 3 to 18 m, the encroachment distances from 0 to 40 m, the alongshore lengths from 100 to 5,400 m, and the ice block thicknesses from 30 to 60 cm. All of the maximum dimensions were associated with a massive pile-up that overtopped the 15-m high bluff at Skull Cliff and spilled 3 m onto the tundra.

8. ***Grounded Ice Features:*** Two grounded ice features believed to be ice island fragments from Ellesmere Island were discovered off the Chukchi Sea coast in February 2012. The larger of the two, located approximately 3 nm (6 km) off Point Belcher in a charted water depth of 32 m, was estimated to be 80 m long, 40 m wide and 20 m above sea level.

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 42 per year. Nevertheless, as demonstrated in 2011-12, a substantial deviation from this trend can occur in any given year.

2. ***Winds:*** Since the mid-1970s, the frequency of storm events during freeze-up has increased by more than 50%. The frequency of storm events in mid-winter (January through April) also may have increased, but additional data will be required to quantify the extent of the change.

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 since the 1980s. Freeze-up in the nearshore region currently tends to occur during the third week in October in the Beaufort, and during the second week in November in the northeastern 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 8% (14 cm) since the early to mid-1980s. However, a significant increase in 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 and rubble fields, probably exert greater impacts 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 during the past three freeze-up seasons as in previous decades, but the landfast ice developed more slowly while the lead widths and polynya sizes tended to increase. An additional difference in the Beaufort Sea was the absence of a stable, grounded shear zone to the east of Prudhoe Bay. In the Chukchi, the data acquired during late freeze-up and mid-winter suggest that the coastal flaw lead tends to attain greater widths and persist longer than in the 1980s.

6. ***Multi-Year Ice in the Alaskan Beaufort Sea:*** The probability of large multi-year ice floes invading the nearshore portion of the Alaskan Beaufort Sea in any given year is substantially less than in the 1980s. Nevertheless, as demonstrated in 2009-10, the possibility of multi-year ice encounters cannot be ruled out for developments in the nearshore region. Furthermore, fragments of old ice analogous to those observed in 2010-11 can be present even if large multi-year floes remain well offshore.

7. ***Multi-Year Ice in the Chukchi Sea:*** The probability of multi-year ice entering the Chukchi Sea to the south and west of Barrow also appears to have decreased since the 1980s, but the validity of this conclusion is challenged by the invasions that occurred in two of the past three freeze-up seasons. If northward extensions of the coastal flaw lead beyond Point Barrow become commonplace, as occurred in 2011-12, a rebound in the frequency of multi-year ice incursions into the Chukchi is likely to ensue.

8. ***Pack Ice Movement:*** The average drift rate measured for pack ice in the Beaufort Sea was 6 nm/day (11 km/day) in 2009-10, 4.8 nm/day (8.9 km/day) in 2010-11, and 4.1 nm/day (7.6 km/day) in 2011-12. The first of these is comparable to the rate obtained in the 1980s, but the second and third are lower. Additional years of observation will be necessary to determine whether the reduced values in 2010-11 and 2011-12 reflect normal fluctuations or a long-term trend. In either case, the lower speeds recorded during the past two years run counter to the findings of Walsh and Eicken (2007), who suggested that thinner sea ice in the winter may lead to increased ice movement.

Operational Considerations

1. ***Multi-Year Ice Invasions:*** If the coastal flaw lead that frequently opens in the northeast Chukchi Sea extends sufficiently far north of Point Barrow to intersect the southern boundary of multi-year ice, it can convey a large quantity of multi-year floes into the region south and west of Barrow in a relatively short time. Early warning of such invasions can be obtained by monitoring satellite imagery for evidence of an extended flaw lead. It should be noted, however, that other circumstances also may lead to multi-year ice floes entering the region south and west of Point Barrow.

2. ***Ice Reconnaissance:*** Ice features analogous to the presumed ice island fragments that were discovered off the Chukchi Sea coast in 2011-21, while too small to be identified in satellite imagery, nevertheless can impart substantial loads on offshore structures and incise massive gouges in the sea bottom. As such features are likely to travel with old rather than first-year ice, the analysis of satellite imagery should be supplemented with aerial reconnaissance flights when old ice approaches an operating area containing facilities susceptible to damage.

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