COASTAL
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16-m High Ice Pile-Up on Shoal off Narwhal Island in Beaufort Sea (February 6, 2010)

2009 FREEZE-UP STUDY
OF THE
ALASKAN BEAUFORT AND CHUKCHI SEAS

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2009 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 2009 freeze-up season and early portion of the 2009-10 winter 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. Minerals Management Service ("MMS") by Coastal Frontiers Corporation and Vaudrey & Associates, Inc.

The 2009 Freeze-Up Study was developed with the intent of addressing six specific objectives:

1. Describing the ice conditions that evolve during the freeze-up and early winter seasons;
2. Documenting the development of landfast ice and the early shear zone;
3. Locating and mapping ice features of interest for the design and operation of offshore facilities, including ice movement lines, leads (linear openings in the sea ice), polynyas (areal openings in the sea ice), grounded rubble piles, first-year ridges, and multi-year (MY) floes;
4. Locating and mapping ice pile-up and encroachment on the shoreline and on man-made structures, and quantifying the dimensions and ice block thicknesses associated with such features;
5. Correlating ice movement events with the corresponding meteorological conditions, including wind speed and direction, and air temperature; and
6. Comparing the 2009 freeze-up season with those in the early and mid-1980's.

The study was conducted using a combination of publicly-available data, proprietary data made available by Shell, RADARSAT-2 satellite images, and aerial reconnaissance missions. The acquisition of publicly-available meteorological data, ice charts, and satellite imagery began in October, 2009, and continued through March, 2010. To provide higher-resolution images of the sea ice, three RADARSAT scenes of the Chukchi and two of the Beaufort were purchased for the period from mid-December through late January. In addition, the tracks of five Iridium telemetry buoys deployed on the sea ice in Camden Bay were acquired from Shell. Shell's willingness to provide these proprietary data along with high-resolution RADARSAT-2 images obtained in October, November, and December is gratefully acknowledged.

Five aerial reconnaissance missions were conducted near the end of the study period to investigate and expand upon the information acquired from the satellite images. Three of these, consisting of two fixed-wing flights and one helicopter flight, took place in the Beaufort Sea between February 4 and 7. The remaining two flights were made in the Chukchi on February 8 and 9 using a fixed-wing aircraft.

The principal study findings are summarized below:

Study Methods

1. ***Satellite Imagery:*** Geo-referenced RADARSAT-2 images with a nominal resolution of 100 m can be used to investigate individual ice features as well as regional ice conditions. Weekly images are ideal for correlating changes in the ice cover with meteorological events. Images obtained at longer intervals, although less suitable for tracking individual ice features, nevertheless provide useful information. In contrast, the low-resolution RADARSAT mosaics compiled by the Canadian Ice Service (CIS) are unsuitable for the analysis of individual features.

2. ***Aerial Reconnaissance Missions:*** Reconnaissance flights provide invaluable opportunities to confirm and refine the findings derived from satellite imagery, and to expand upon those findings with respect to small-scale features and processes. If budgetary constraints permit, two sets of aerial reconnaissance missions are recommended:

    Late November/Early December: Flights in the Beaufort Sea to enhance the interpretation of satellite imagery obtained early in the freeze-up process;

    Late January/Early February: Flights in the Beaufort and Chukchi Seas (analogous to those undertaken in 2010) to document the ice conditions at the end of the freeze-up process and investigate features identified in the satellite imagery.

3. ***Reconnaissance Aircraft***: In the Beaufort Sea, where distances offshore are comparatively small, the use of an intermediate-size helicopter to augment the missions conducted with a fixed-wing aircraft is warranted by the helicopter's ability to land at features of interest. In the Chukchi, where the distances offshore tend to be large, the cost of a long-range helicopter capable of visiting sites of interest (other than those along the coast) likely would be prohibitive.

Findings for Entire Study Area

1. ***Ice Regimes***: The ice regimes in the Beaufort and Chukchi Seas differ markedly due to factors that include geography, meteorology, and oceanography. In 2009-10, as in prior years, the easterly winds that prevailed in both regions tended to push the ice along the Beaufort Sea coast and away from the Chukchi coast. In the western Beaufort, the alongshore ice movement produced an extensive zone of landfast ice contained within a well-established shear zone. In the Chukchi, the offshore ice movement produced a recurring coastal flaw lead that repeatedly removed all but a narrow strip of landfast ice. These patterns are consistent with those noted in the past.

2. ***Air Temperatures***: The daily mean air temperatures from September 2009 through May 2010 were the fifth warmest out of the last 40 years, based on freezing-degree days accumulated at Barrow. The total of 6,608 freezing-degree days (relative to the Fahrenheit scale) was 16% less than the average value obtained for the six winters from 1980-81 through 1985-86.

3. ***First-Year Ice Growth***: The computed ice thickness at the end of the 2009-10 winter season was 155 cm, based on the freezing-degree days accumulated at Barrow. This value is about 10% less than the average from 1980-81 through 1985-86.

4. ***Multi-Year Ice***: Significant numbers of multi-year ice floes invaded both the Beaufort and Chukchi Seas during the 2009-10 freeze-up and early winter seasons. The floes consisted primarily of multi-year ice from the polar pack rather than second-year ice formed in the nearshore zone. Many were of large diameter and contained embedded ridges. The invasion constituted the first such occurrence since 2001.

Findings for Beaufort Sea

1. ***Late Summer:*** The total area covered by the pack ice at its minimum extent in mid-September 2009 was the third lowest since 1979. In late September, the ice edge was located about 60 nm (111 km) north of the central and eastern Beaufort Sea coast, close to its median location for this time of year during the period from 1979 through 2000.

2. ***Freeze-Up***: In 2009, the approximate date of freeze-up in the nearshore region of Beaufort Sea was October 22. This timing is comparable to the average date for the five-year period from 2002 through 2006, but 18 days later than the average computed for the 11 years from 1980 through 1985, and 1987 through 1991.

3. ***Landfast Ice:*** Warm air temperatures and a lack of sustained easterly winds produced an unusually narrow landfast ice zone that persisted from the initiation of freeze-up

through most of December 2009. An intense easterly storm in late December created a grounded shear zone and a typical offshore boundary for the landfast ice west of Prudhoe Bay that remained intact through midwinter. However, westerly winds in early to mid-January 2010 removed most of the landfast ice offshore of the barrier islands east of Prudhoe Bay, and the ice remained very dynamic through mid-February. This instability is consistent with the finding of a prior study that the probability of midwinter ice movement on the Sivulliq pipeline route is 50%.

4. ***Multi-Year Ice:*** The multi-year floes that invaded the Beaufort Sea in 2009-10 remained 10 to 20 nm (19 to 37 km) offshore as they migrated to the west under the influence of the Beaufort Gyre (a wind-driven current that flows from east to west off the north coast of Alaska). The highest concentrations, 7 to 8 tenths, were noted between Smith Bay and Point Barrow. Typical diameters ranged from hundreds of meters to several nautical miles.

5. ***Ice Pile-Ups:*** Ice pile-ups were observed on or adjacent to six natural barrier islands and Northstar Production Island during the aerial reconnaissance flights conducted in early February. The estimated pile-up heights ranged from 1-2 m on Flaxman Island to 16 m on a shoal west of Narwhal Island, while the ice blocks comprising the piles ranged from 25 to 75 cm thick. The pile-up off Narwhal Island was unique in that it consisted of a grounded ridge rather than an assemblage of individual ice blocks, and resulted from ice movement inside rather than outside the barrier islands. Also noteworthy was the fact that it exceeded 1 nm (2 km) in length.

Findings for Chukchi Sea

1. ***Freeze-Up***: A combination of unseasonably warm air temperatures and persistent easterly winds delayed the onset of ice growth in most regions of the Chukchi Sea until the first week in November. Freeze-up proceeded more slowly than in the Beaufort, with the ice edge advancing to the south and west through late November. By the end of November, the entire Chukchi Sea was ice-covered north of Cape Lisburne and east of 169°W.

2. ***Landfast Ice:*** With the exception of Peard Bay, Kasegaluk Lagoon, and protected areas east of Point Franklin and Icy Cape, the early-season ice off the coast between Barrow and Point Lay never had an opportunity to stabilize before it was dislodged by a series of easterly winds that caused freeze-up to start anew. At times, westerly winds drove the young ice against the shoreline and created pile-ups or offshore rubble fields. When a coastal reconnaissance flight was conducted on February 9, the edge of the fast ice zone was located only 1 to 2 nm (2 to 4 km) off Barrow, 0.5 to 1 nm (1 to 2 km) off Point Belcher, 2 to 3 nm (4 to 6 km) off Wainwright, and 3 to 4 nm (6 to

7 km) off Point Lay. Most of the coast lacked a shear zone with sufficient grounding to stabilize the offshore boundary of the fast ice. As a result, the ice was susceptible to removal during subsequent easterly storms.

3. ***Coastal Flaw Lead:*** Seaward of the landfast ice, a coastal flaw lead opened and closed repeatedly in response to easterly (offshore) and westerly (onshore) winds. Whenever it was open, the lead generated new ice as it refroze. 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. Because the coastal flaw lead reduces confinement, it leaves the ice in the nearshore zone susceptible to rapid movement and substantial deformation.

4. ***Nearshore vs. Offshore Ice Cover:*** The ice cover in the nearshore and offshore regions differed markedly at the time of the aerial reconnaissance missions in early February 2010. The former consisted primarily of heavily-deformed ice with small, undisturbed first-year pans between ridges. The latter was smoother, with fewer and smaller ridges, and was composed of vast first-year pans with diameters as large as several nautical miles. These contrasting characteristics indicate that the differential motion between floes was substantially smaller in the offshore zone, where the influence of the coastal flaw lead was minimal.

5. ***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 into Shell's Crackerjack and West Prospects to the west of the 165°W meridian, and (2) a southern or coastal branch that extended southwest from Barrow to the vicinity of the 70°N parallel. Concentrations as high as 4 to 5 tenths were observed in the northern branch between 72°N and 73°N, and as high as 7 tenths in the southern branch off Barrow. As in the case of the Beaufort Sea, the diameters typically ranged from hundreds of meters to several nautical miles, and many of the floes contained embedded ridges.

6. ***Ice Pile-Ups:*** Sixteen ice pile-ups and three ice ride-ups were observed on the Chukchi Sea coast during the February 9 reconnaissance mission, with thirteen of these located in the exposed stretch between Point Franklin and Point Belcher. 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, while the ice blocks comprising the piles ranged from 20 to 45 cm thick. The three ride-ups all encroached 5 to 6 m onto the beach in the vicinity of Point Belcher.

Comparison of Freeze-Up in the 1980's and 2009

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

2. ***First-Year Ice Growth:*** Based on air temperatures alone, the first-year ice thickness attained during an average winter has decreased by about 10% since the early to mid-1980's. However, increased snowfall accompanied by greater snow accumulation on the landfast ice sheet may be causing a more significant reduction in ice thickness. Other temperature-related factors, including reduced ice production in leads and decreased consolidation of ridges, probably exert a greater impact on the ice dynamics than a thinner ice cover.

3. ***Landfast Ice Development and Stability*:** The locations and shapes of the landfast ice zones and their associated leads and polynyas tended to follow the same general patterns in 2009-10 as noted in previous decades, but the landfast ice zone developed more slowly while the lead widths and polynya areas tended to increase. An additional difference in the Beaufort Sea in 2009-10 was the absence of a stable, grounded shear zone between Cross Island and Camden Bay.

4. ***Multi-Year Ice:*** Despite the invasion of multi-year pack ice that occurred in 2009-10, the probability of such an invasion in any given year is less than in the 1980's. This conclusion follows in part from the location of the ice edge, which has retreated farther to the north in recent summers, and in part from warmer air temperatures and increased storminess, which have reduced the likelihood that remnants of the Beaufort Sea shear zone will survive the summer melt season to become second-year floes. Nevertheless, as demonstrated in 2009-10, the possibility of encountering multi-year ice floes and ice gouges inflicted by such floes cannot be ruled out for developments in either the Beaufort or Chukchi Sea.

5. ***Pack Ice Movement:*** The average drift rate measured for pack ice during the 2009-10 freeze-up season was 6 nm (11 km) per day. This value is comparable to that obtained in the 1980's, suggesting that the drift rate has remained unchanged.

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2009 FREEZE-UP STUDY OF THE ALASKAN BEAUFORT AND CHUKCHI SEAS

1. INTRODUCTION

This report describes an investigation of the ice conditions that prevailed during the 2009 freeze-up season and early portion of the 2009-10 winter 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. Minerals Management Service ("MMS") 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 72.5°N parallel, and the 168°W meridian. The boundaries in the Beaufort Sea were selected to encompass Shell's prospects in Camden and Harrison Bays as well as all existing oil and gas developments operated by others, while those in the Chukchi were selected to encompass Hanna Shoal and other prospects that included Burger and Crackerjack.

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

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

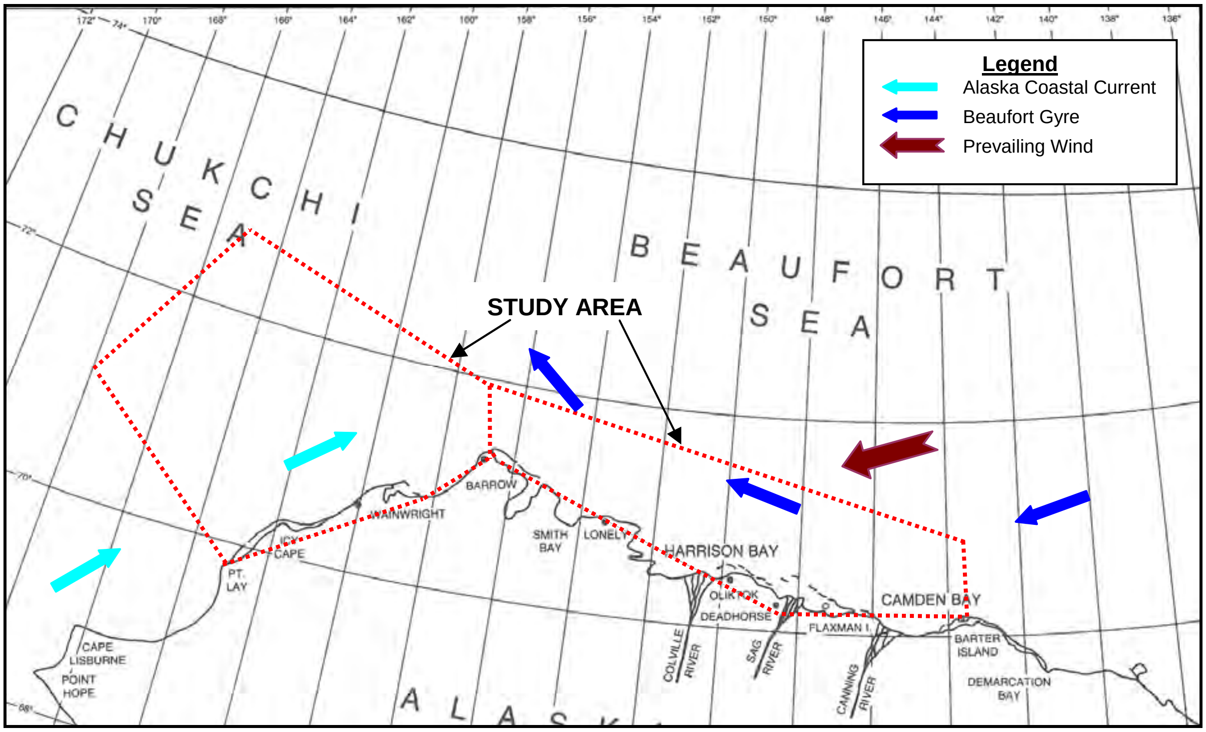


Figure 1. Study Area

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

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

During the 25 years that followed the last joint-industry study, freeze-up processes were investigated primarily through the analysis of satellite imagery (Vaudrey, 1988-1992; Eicken, *et al*., 2006). The resulting information, although useful in its own right, lacked some of the detail provided by the earlier observational studies. Specifically, items such as the age and character of multi-year floes and the locations and composition of ice ride-ups and pile-ups could not be extracted from the satellite-based data. To remedy this deficiency, Shell (a participant in the original freeze-up studies) requested a joint-industry study that would blend remote sensing with on-site observations.

The 2009 Freeze-Up Study was developed in response to the Shell request, with the intent of addressing six specific objectives:

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

5. Correlating ice movement events with the corresponding meteorological conditions, including wind speed and direction, and air temperature; and
6. Comparing the 2009 freeze-up season with those documented in the 1980's.

The acquisition of publicly-available meteorological data, ice charts, and satellite imagery began in October, 2009, and continued through March, 2010. To provide higher-resolution images of the sea ice, three RADARSAT-2 scenes of the Chukchi and two of the Beaufort were purchased for the period between mid-December and late January. In addition, the tracks of five Iridium telemetry buoys deployed on the sea ice in Camden Bay on January 11 were acquired from Shell. Shell's willingness to provide these proprietary buoy data as well as high-resolution RADARSAT-2 images obtained in October, November, and December is gratefully acknowledged.

Five aerial reconnaissance missions were conducted near the end of the study period to investigate and expand upon the information acquired from the satellite images. Three of these, consisting of two fixed-wing flights and one helicopter flight, took place in the Beaufort Sea between February 4 and 7. The remaining two flights were made in the Chukchi on February 8 and 9 using a fixed-wing aircraft.

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

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

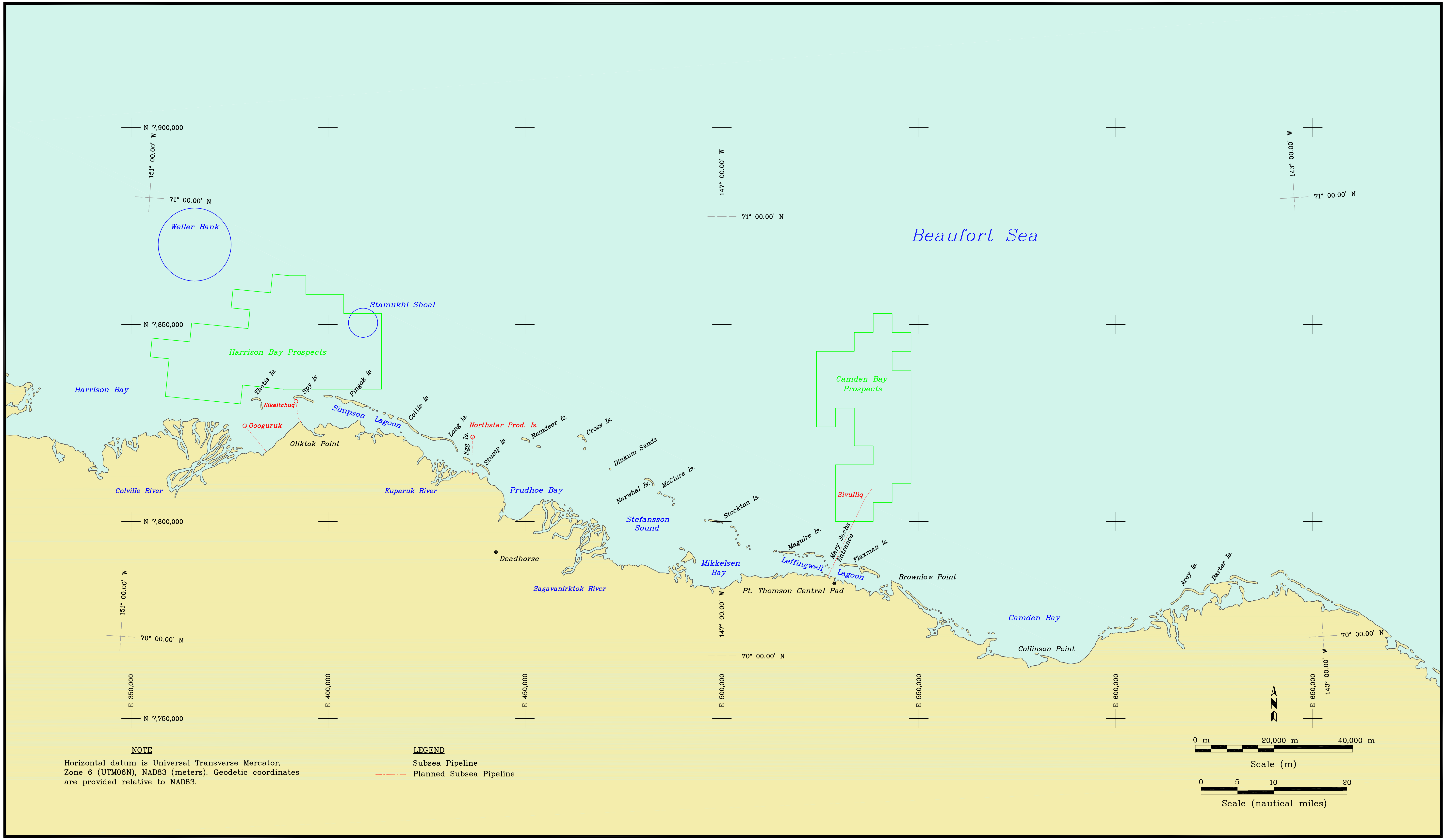
The remainder of this report provides a detailed account of the 2009 Freeze-Up Study. To provide historical context, the findings of the six prior joint-industry studies (1980-1985) are summarized in Section 2. Data acquisition and analysis are discussed in Section 3, which covers the aerial reconnaissance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

The vertical datum is Mean Sea Level (MSL). MSL lies only 8 cm above Mean Lower Low Water (MLLW) at Point Hope, which represents the closest National Ocean Service (NOS) tide station in the Chukchi Sea, and 10 cm above MLLW at Prudhoe Bay, which represents the only NOS tide gauge in the Beaufort Sea (National Ocean Service, 2010). For purposes of this report, the differences between MSL and MLLW (which represents the vertical datum for all NOS nautical charts of the area) are assumed to be negligible.

Units are provided in the SI system, with three exceptions: (1) distances offshore, onshore, and alongshore 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's) are provided using the Fahrenheit rather than Celsius scale to provide greater resolution and maintain consistency with past freeze-up reports. In the case of nautical miles and knots, the corresponding values in SI units are provided in parentheses.

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



NOTE
Horizontal datum is Universal Transverse Mercator, Zone 6 (UTM06N), NAD83 (meters). Geodetic coordinates are provided relative to NAD83.

LEGEND
Subsea Pipeline
Planned Subsea Pipeline

Figure 2. Geographic Points of Interest in Central Beaufort Sea

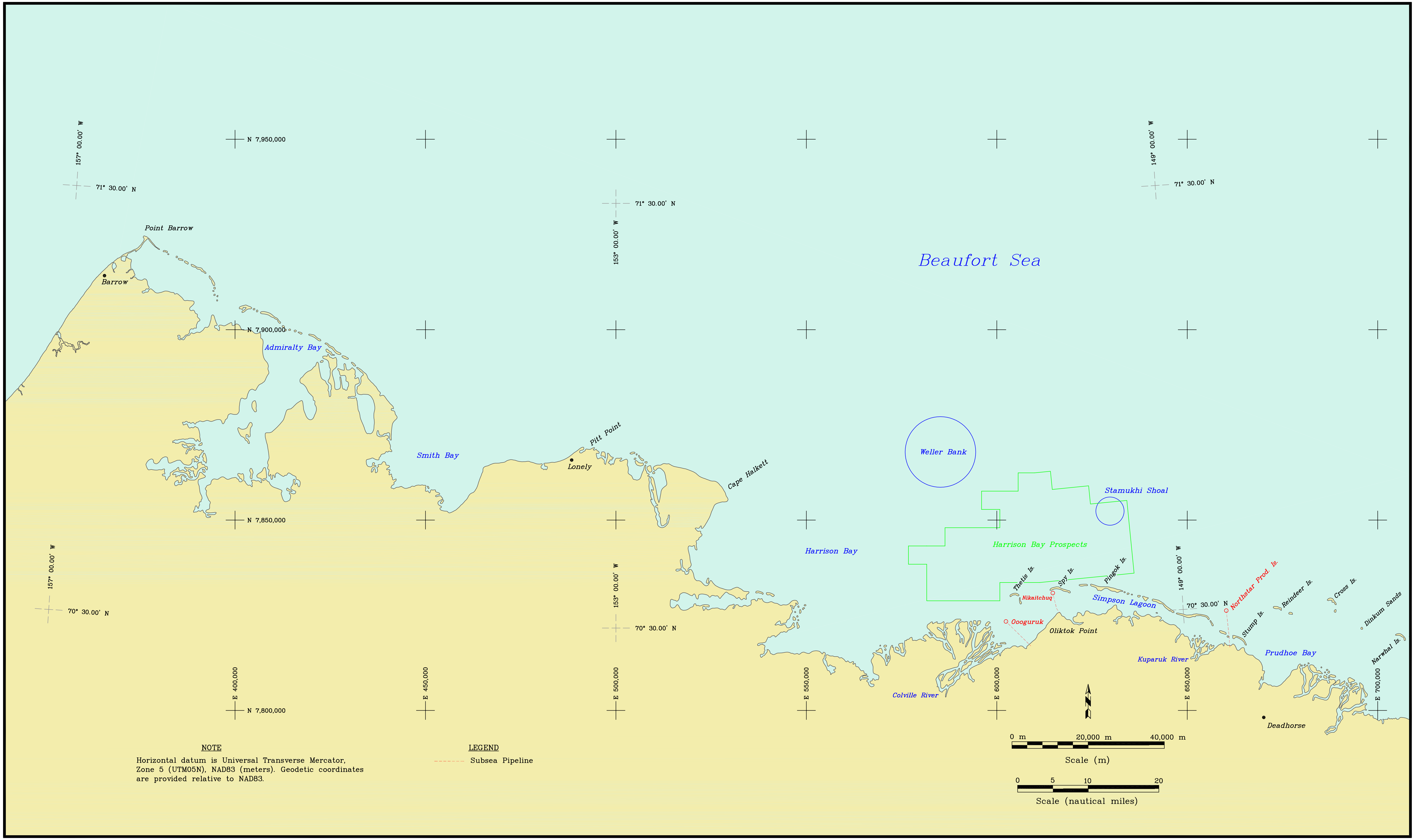


Figure 3. Geographic Points of Interest in Western Beaufort Sea

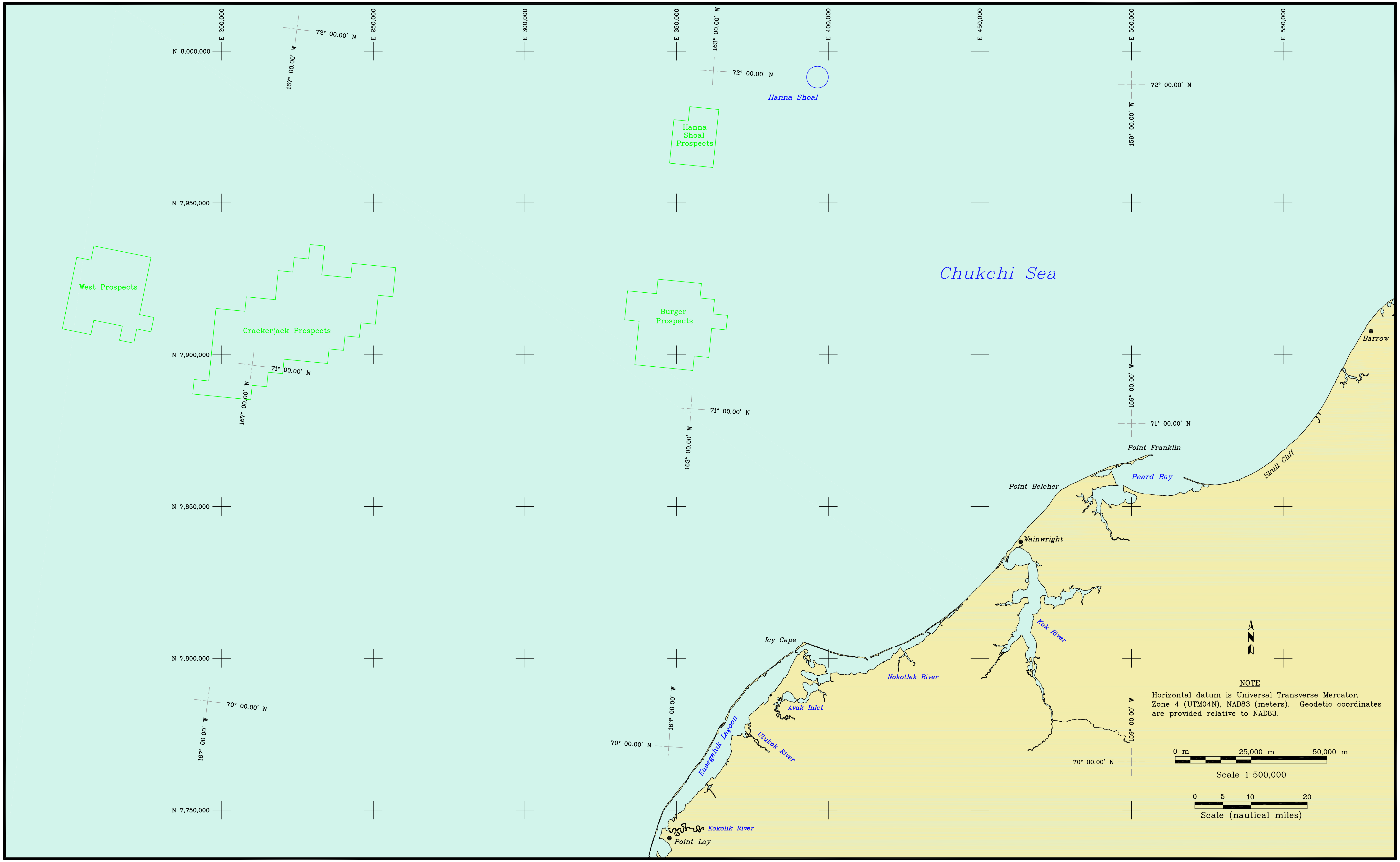


Figure 4. Geographic Points of Interest in Chukchi Sea

2. PRIOR STUDIES

As indicated in Section 1, six freeze-up studies were conducted as joint industry programs from 1980 through 1985 (Vaudrey & Associates, 1981; 1982; 1983; 1984; 1985; 1986). The findings were made available to the present project through the courtesy of Shell (Reece, 2009), which was a participant in each of the studies.

The primary objectives of the 1980's freeze-up studies were twofold: (1) to observe and record major ice movement events and their effects on man-made islands and structures, and (2) to 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 through 1982) were limited to the central Beaufort Sea, from Cape Halkett on the west to Flaxman Island on the east. The last three studies (1983 through 1985) were expanded significantly to include the entire region between Icy Cape in the Chukchi Sea and Barter Island in the Beaufort Sea. Occasionally, the eastern boundary of the reconnaissance flights was extended to points east of Barter Island, sometimes going as far as the Canadian border. Each of the three freeze-up studies between 1983 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 the Deadhorse airport, the NOAA facility at Barrow, and the Barter Island DEW station.

Based on the observations made during the reconnaissance flights, the chronology of the freeze-up season was developed. Areas of emphasis included the first occurrence of sea ice, the ice growth, and the various ice types (first-year, second-year, and multi-year) present during the various stages of the freeze-up process. Ice pileup and encroachment events on man-made structures and islands and on natural barrier islands and the mainland shore were documented. 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.

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

Beaufort Sea

- **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 freezing-degree days. Warming trends in October retarded initial ice growth by 7 to 10 days in 1983 and 1985 and by almost three weeks in 1984.

- **Multi-Year Ice.** Multi-year ice was present in varying concentrations in the nearshore zone of the central Beaufort Sea during each of the six freeze-up periods studied. The most extensive multi-year ice invasion occurred in late September, 1980, with a 3- to 5-tenths concentration located 2 to 3 nm (4 to 6 km) offshore of the barrier islands from Cross to Flaxman. Multi-year ice presence in 1981, 1982, and 1984 was limited to localized belts and patches of small floes and isolated ridge fragments grounded in the shear zone. During the summer of 1983, mild winds and cold air temperatures produced a significant concentration of second-year ice in the nearshore region in early October. Two years later, in October, 1985, most of the multi-year ice lay north of a line that roughly paralleled the coast 15 to 20 nm (28 to 37 km) offshore.

- **Ice Pile-Up and Rubble Pile Formation.** The potential for significant shoreline pile-up or ice encroachment 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, one in November, 1981, caused by a westerly that loosened or cracked the landfast ice followed by an easterly that drove the sheet ice back into the shoreline, and the other in mid-October, 1982, caused by 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 and the momentum of the moving ice.

  The storm reversals that caused shoreline pile-ups often created significant rubble piles offshore, especially on shoals like Stamukhi Shoal and Weller Bank. Several large rubble piles were observed in 10 to 12 m of water, 10 to 15 nm (19 to 28 km) northwest of Seal Exploration Island (the current location of Northstar Production Island), during a strong southwesterly in late December, 1983.

- **Landfast Ice and Shear Zone Development.** Persistent easterly winds in the Beaufort Sea were found to create a grounded shear zone that provided stability for the landfast ice. In contrast, intermittent westerly winds during freeze-up maintained the dynamics of the ice cover and prevented landfast ice stability. Freeze-up seasons without westerlies tended to have a well-established shear zone and stable landfast ice.

Chukchi Sea

- **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.
- **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 71st 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 71st parallel through late January 1985, and was located well offshore of the prevailing 10-20 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 2 nm (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.
- **Ice Pile-Up and Rubble Pile Formation.** As in the Beaufort Sea, it was noted that storm reversals during the freeze-up season can lead to shoreline pile-ups along the Chukchi coast, especially near the village of Barrow and near Pt. Belcher north of Wainwright. However, an absence of strong winds in 1983 and a lack of storm reversals in both 1984 and 1985 reduced the number of pile-ups observed along the Chukchi coast.
- **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 the coastal flaw lead, which, in turn, promoted ice production by refreezing of the lead.

Data from the 1980-86 freeze-up studies and their companion break-up studies have been used extensively in developing design and operational criteria and in planning operations for the existing coastal and offshore developments in the Alaskan Beaufort Sea.

3. DATA ACQUISITION AND ANALYSIS

As indicated at the outset, the 2009 Freeze-Up Study was conducted using a combination of remote-sensing data and on-site measurements and 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 field reconnaissance missions (Section 3.5). Digital files of the underlying data are provided on the CD that constitutes Appendix B.

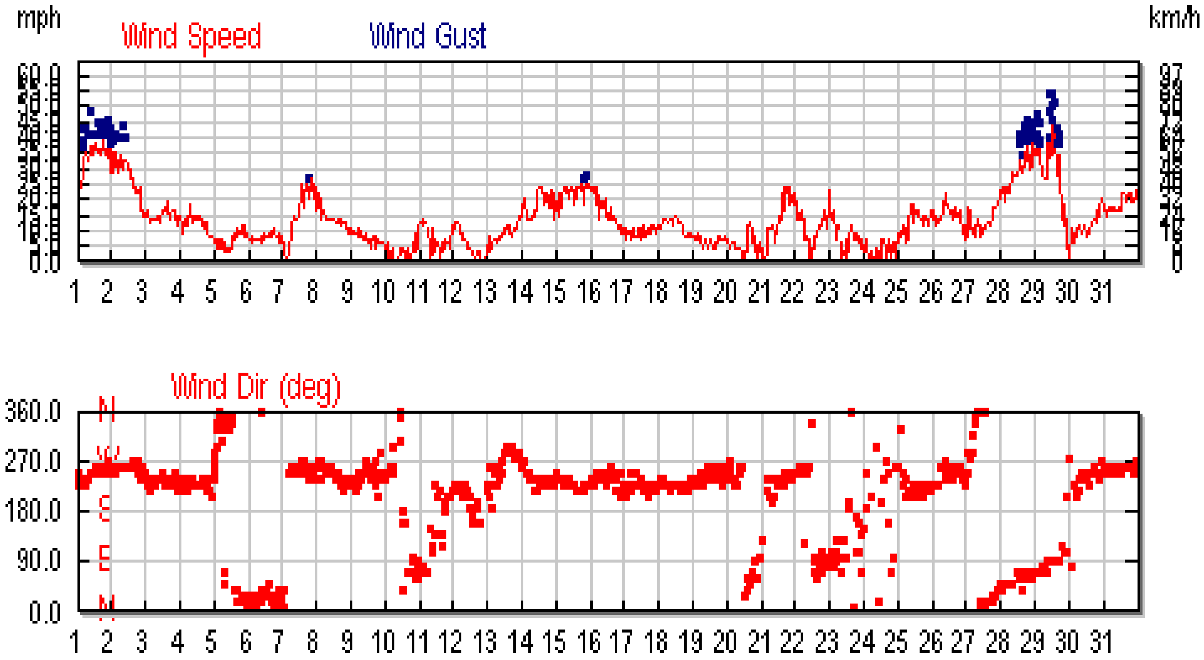
3.1 Meteorological Data

Meteorological data were obtained from two publicly-available sources: Weather Underground (2010) and the National Ocean Service (2010). The following data were downloaded from the Weather Underground website for the Barrow and Deadhorse Airports:

- Monthly plots of air temperature, barometric pressure, wind speed, and wind direction for the period from October 2009 through March 2010 (included as *.gif files in Appendix B);
- Daily maximum, minimum, and mean values of air temperature (and other meteorological parameters of secondary importance) for the period from October 2009 through May 2010 (compiled in Excel files in Appendix B).

The monthly plots of wind speed and direction served as the primary means of identifying wind shifts and storm sequences that caused ice movement events. A representative example that shows the conditions at Deadhorse during the month of January 2010 is provided in Figure 5. Of particular note is the easterly storm that caused an abrupt change in wind direction on January 27th followed by several days of increasing wind speeds.

The air temperature data were used to derive freezing degree days, 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 eight month period from September 2009 through May 2010, with “negative” freezing-degree days (when the mean daily air temperature exceeded 29°F) subtracted from the total. The results for both Barrow and Deadhorse are shown in Table 1.



Source: Weather Underground, 2010

Figure 5. Wind Speed and Direction at Deadhorse Airport in January 2010

Table 1. Cumulative Freezing-Degree Days (<29°F)
at Barrow and Deadhorse in 2009-10

Site	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Barrow	6	125	981	1988	3391	4479	5687	6312	6608
Deadhorse	25	208	1161	2192	3675	4830	6129	6725	6975

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 (STP) were downloaded from the National Weather Service website for the period from October 2009 through March 2010. The plots are included as PNG or BMP files in Appendix B.

3.2 Ice Charts

Ice charts were downloaded from two publicly-available sources: the Canadian Ice Service ("CIS"; 2010) and the National Ice Center ("NIC"; 2010). Although the charts from both organizations provide similar information regarding ice coverage, concentration, and stage of development, the CIS products tend to incorporate greater detail. However, coverage is limited to the entire Beaufort and only the extreme northeast portion of the Chukchi. The NIC produces separate charts for the Beaufort and entire Chukchi.

Eighteen ice charts were obtained from the CIS for the period from October 5, 2009, through March 1, 2010. The charts, which were issued on a weekly basis in October, November, and December, and bi-weekly thereafter, are provided as GIF files in Appendix B.

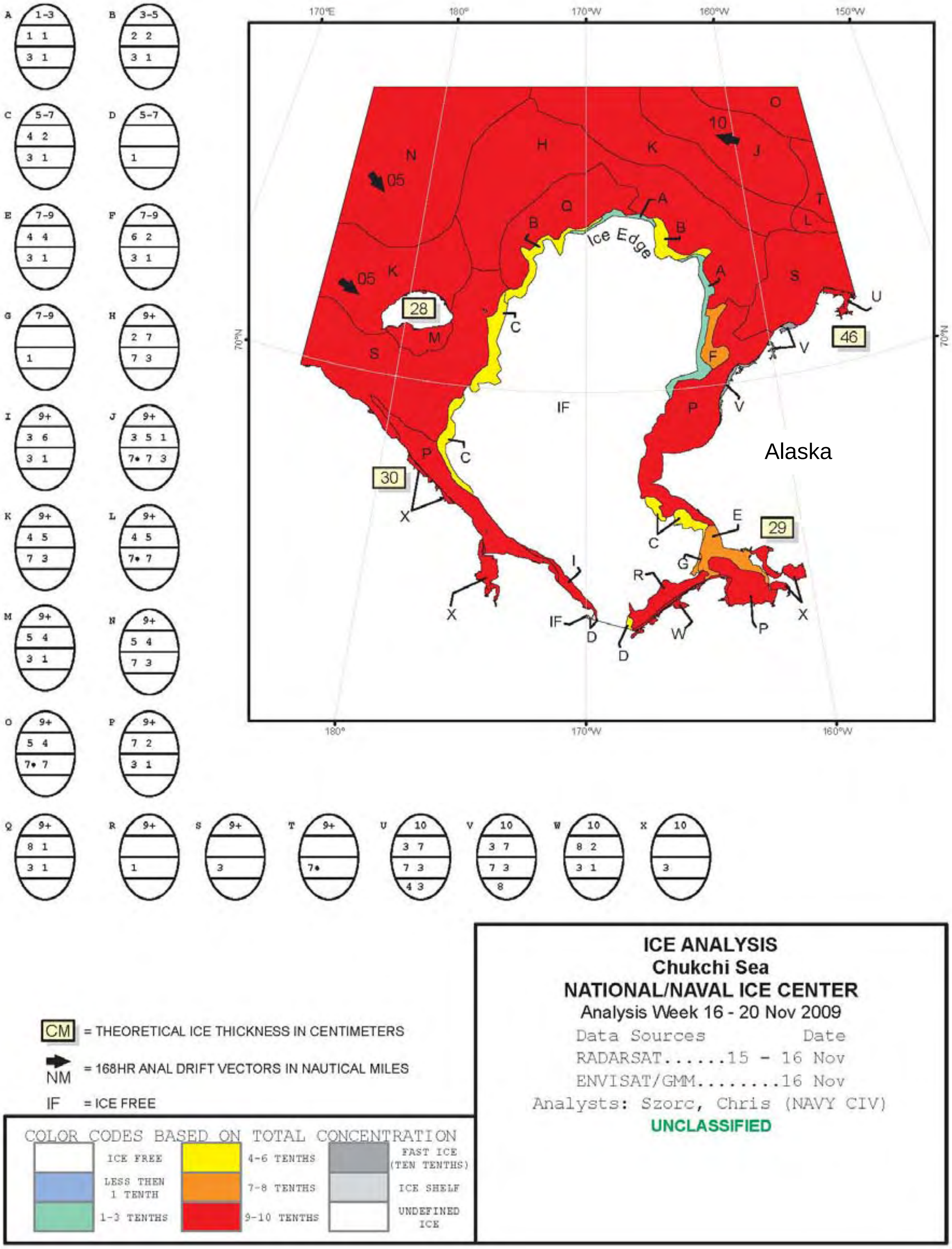
Twenty three ice charts were obtained from the NIC, consisting of eleven Beaufort Sea charts covering the period from November 23, 2009, through March 1, 2010, and twelve Chukchi Sea charts covering the period from November 16, 2009, through March 1, 2010. Although the NIC charts were available on a weekly basis, it was deemed unnecessary to acquire all of the charts produced after January 25 for the purpose of this project. The charts that were acquired are provided as PDF files in Appendix B. A representative example that displays a large expanse of open water in the Chukchi Sea in mid-November is provided in Figure 6.

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 items such as the location and nature of multi-year ice floes.

3.3 Satellite Imagery

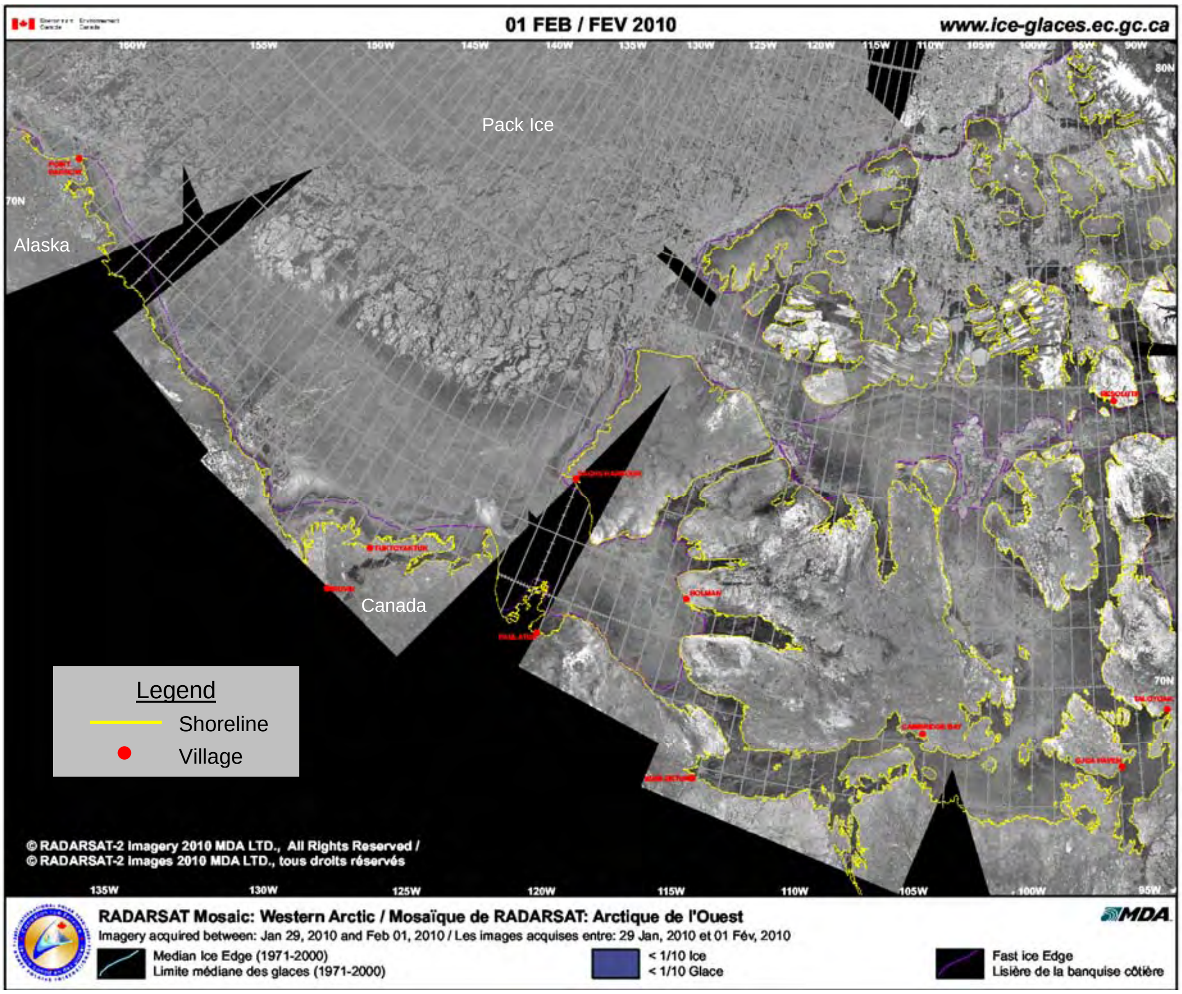
Three different types of satellite imagery were used to study the ice conditions that prevailed during the 2009 freeze-up season: RADARSAT, AVHRR (Advanced Very High Resolution Radiometer), and MODIS (Moderate Resolution Imaging Spectroradiometer). The RADARSAT imagery served as the primary source of information, while the AVHRR and MODIS imagery were used in supplemental roles.

At the outset, it was hoped that publicly-available RADARSAT mosaics compiled by the CIS (2010) would support detailed investigations of ice features. The resolution proved to be inadequate for detailed analysis, however, and the coverage proved to be sporadic in the western Beaufort and non-existent in the central and southern Chukchi. Notwithstanding these severe limitations, 16 images were obtained for the period spanning October 5, 2009 and March 15, 2010 to facilitate assessments of synoptic-scale ice conditions. The images, which were available on the CIS website at typical intervals of one to two weeks, are provided as GIF files in Appendix B. A representative example that illustrates the relatively low resolution and incomplete coverage of these mosaics is shown in Figure 7.



After: National Ice Center, 2010

Figure 6. Ice Chart of Chukchi Sea in Mid-November



After: Canadian Ice Service, 2010

Figure 7. CIS RADARSAT Image of Beaufort Sea for February 1, 2010

When the limitations of the CIS mosaics became apparent, Shell offered to supply proprietary, high-resolution RADARSAT-2 images of both the Beaufort and Chukchi Seas. Fourteen images of the Beaufort and eighteen of the Chukchi were provided for the three-month period encompassing October, November, and December, 2009. Although the images were not geo-referenced, they proved to be useful in assessing the progression of ice conditions through freeze-up and facilitating estimates of ice drift over extended time periods.

The most useful RADARSAT-2 images, consisting of two geo-referenced scenes in the Beaufort and three in the Chukchi, were purchased directly from MDA Geospatial Services, Inc. Each image was obtained using the ScanSAR Wide beam mode, which provides a nominal resolution of 100 m over a nominal area of 270 x 270 nm (500 x 500 km; MacDonald, Dettweiler and Associates Ltd., 2009). These characteristics were sufficient to support detailed investigations of major ice features, to facilitate the identification of multi-year ice and estimation of multi-year ice concentrations, and to measure ice movement over extended periods of time.

The purchased images of the Beaufort Sea were obtained on January 5 and 25, while those of the Chukchi were obtained on December 17, January 10, and January 27. As illustrated in Figures 8 through 12, they provided excellent coverage of the study area. The only significant drawbacks were the cost, which averaged about U.S. $5,000/scene inclusive of satellite programming, image acquisition, and processing, and the licensing agreement, which prohibited the distribution of the original geo-referenced TIF images. Accordingly, each image is provided in Appendix B in JPG format.

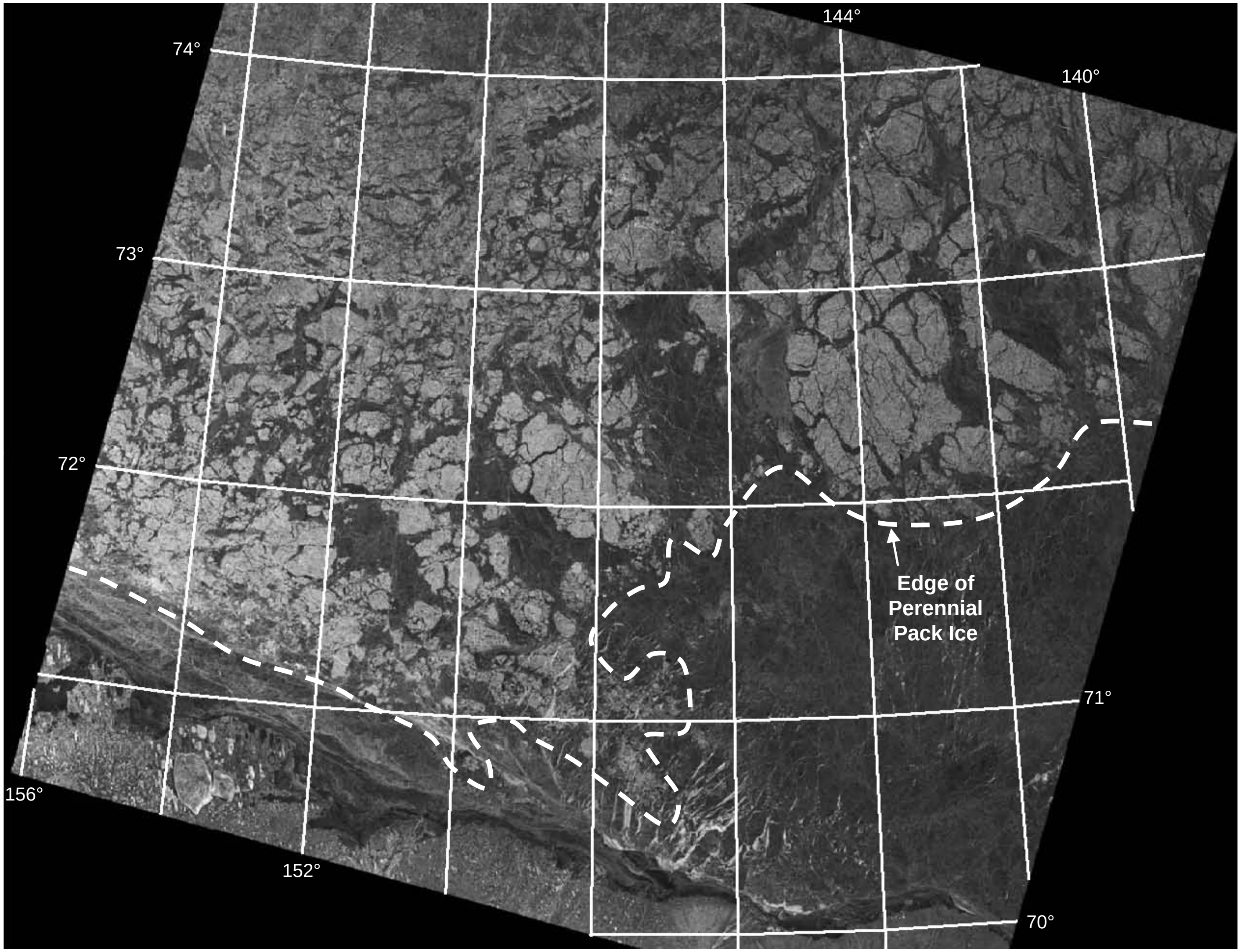
Numerous AVHRR images were downloaded from the National Weather Service Alaska Region Headquarters (2010) for the primary purpose of bridging the chronological gaps between RADARSAT images. The images, which were obtained on an as-needed basis from October 2009 through May 2010, are provided as JPG files in Appendix B. A sample scene in Figure 13 illustrates the formation of a vast coastal flaw lead in the Chukchi Sea and the boundary between the temporary fast ice and the pack ice in the Beaufort Sea.

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

MODIS imagery, like AVHRR imagery, was acquired to supplement the RADARSAT scenes. Unfortunately, the sensor's maximum resolution of 250 m was outweighed by its inability to penetrate cloud cover, its dependence on light in the visible spectrum, and its inability to image the region north of the 72° parallel. As a result, limited numbers of useful scenes were acquired prior to the onset of darkness in early November, and subsequent to the return of daylight in mid-February. The images, downloaded from the MODIS Rapid Response website (NASA, 2010a), are provided as JPG files in Appendix B.

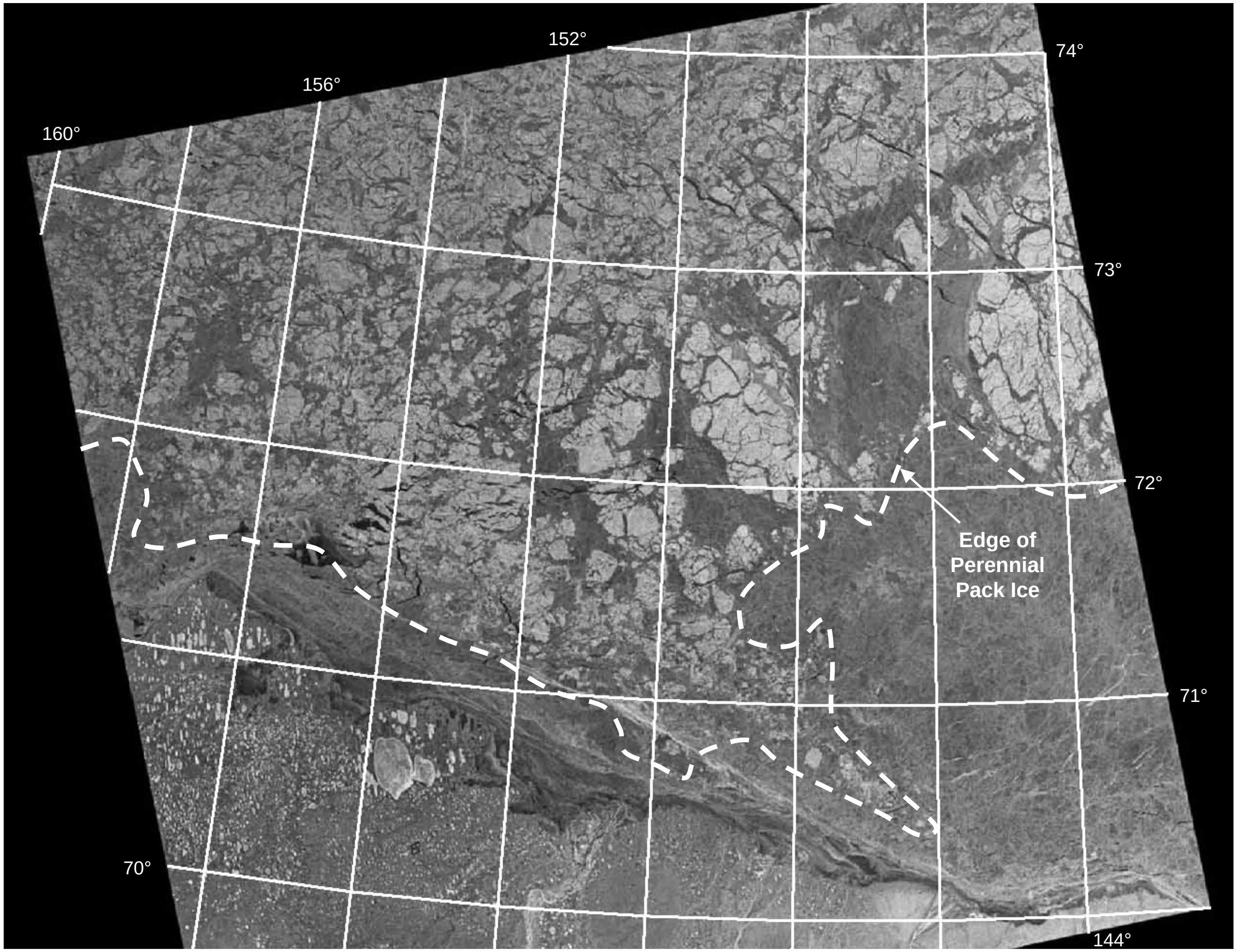
3.4 Iridium Telemetry Buoys

On January 11, 2010, Shell installed five Iridium telemetry buoys on the ice north of Flaxman Island to document ice movement in the Sivulliq Development project area. The



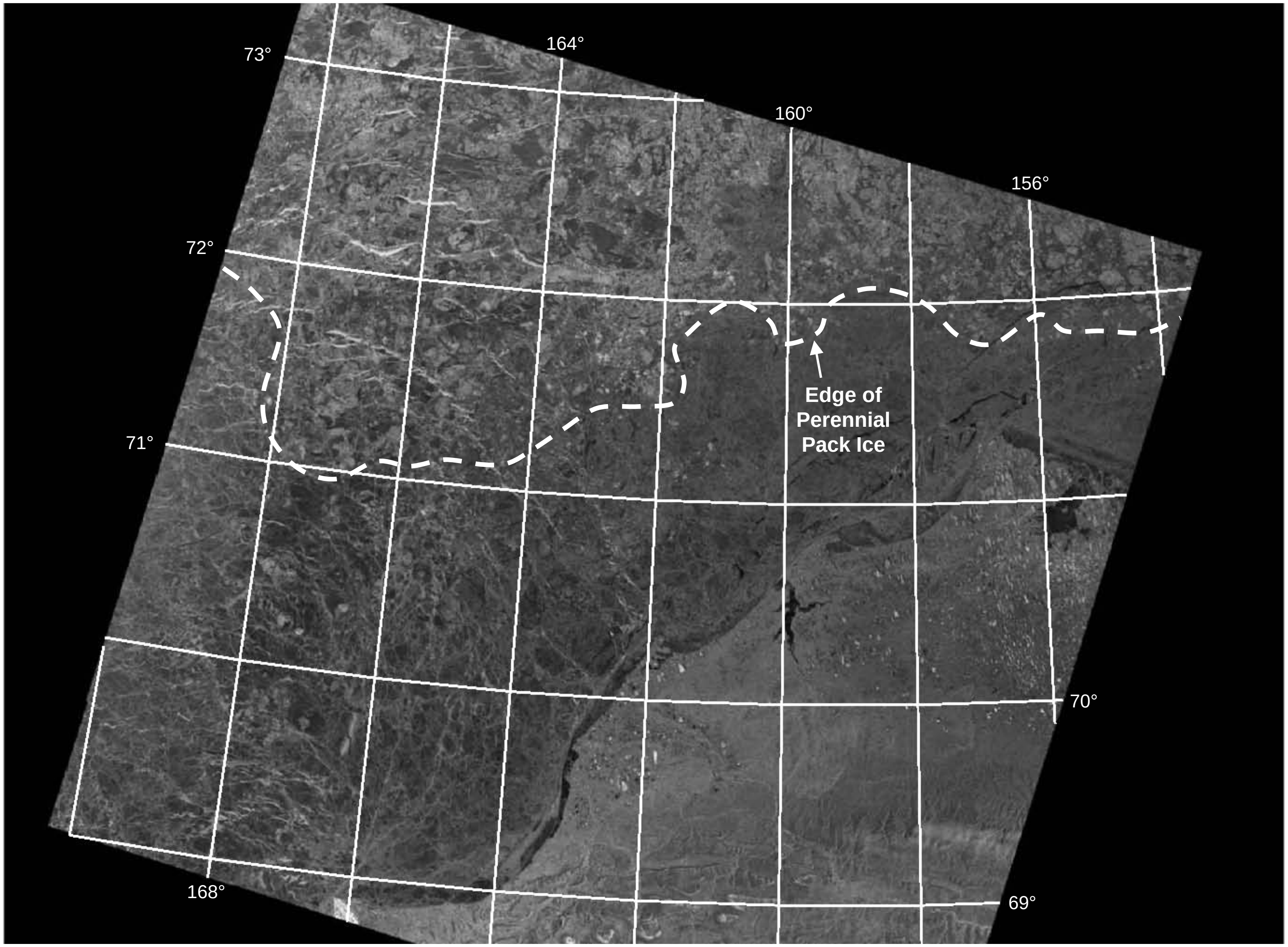
Source: RADARSAT-2 Data and Products © MacDonald Dettweiler and Associates Ltd., 2010 – All Rights Reserved

Figure 8. RADARSAT-2 Image of Beaufort Sea on January 5, 2010



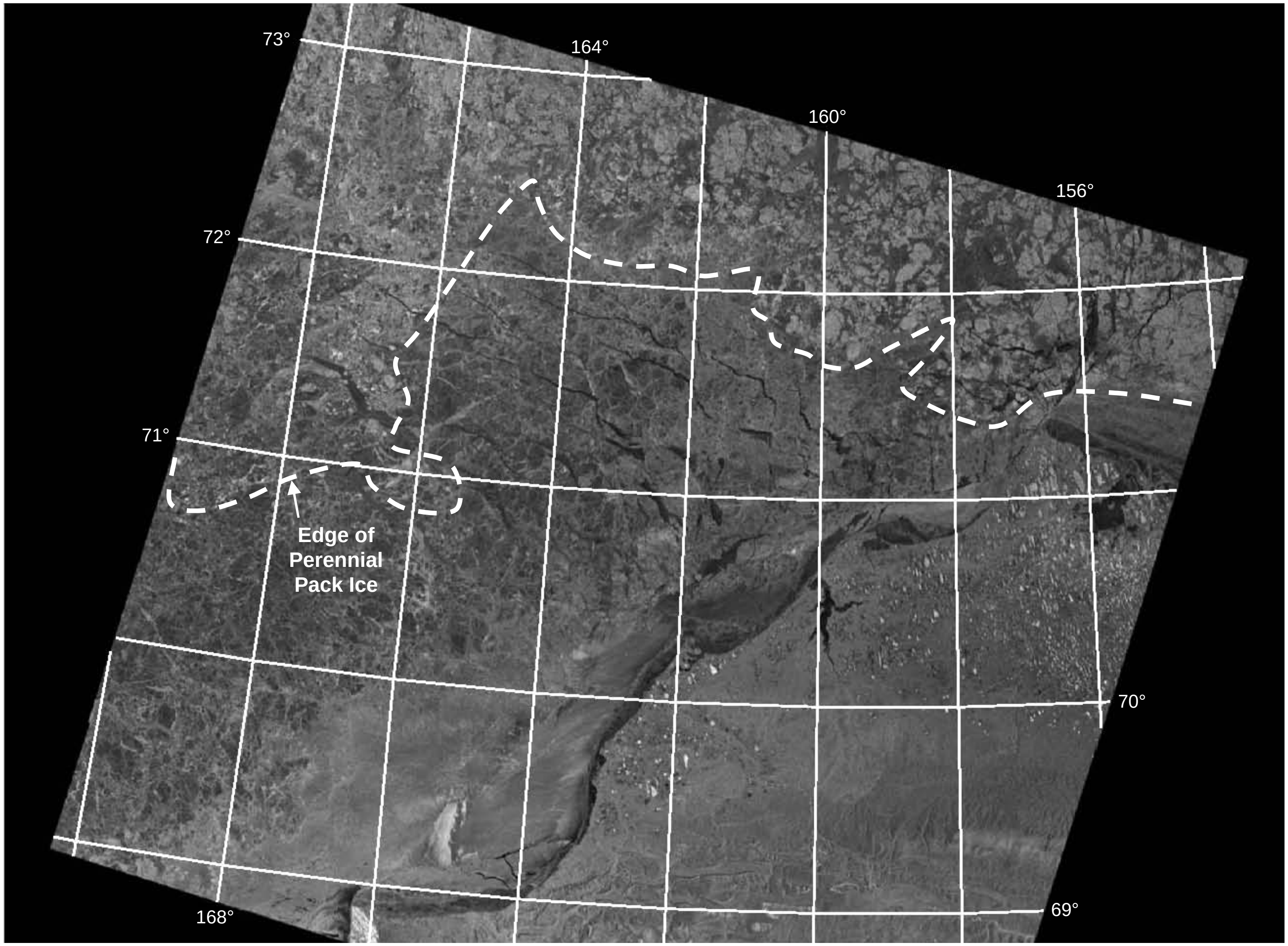
Source: RADARSAT-2 Data and Products © MacDonald Dettweiler and Associates Ltd., 2010 – All Rights Reserved

Figure 9. RADARSAT-2 Image of Beaufort Sea on January 25, 2010



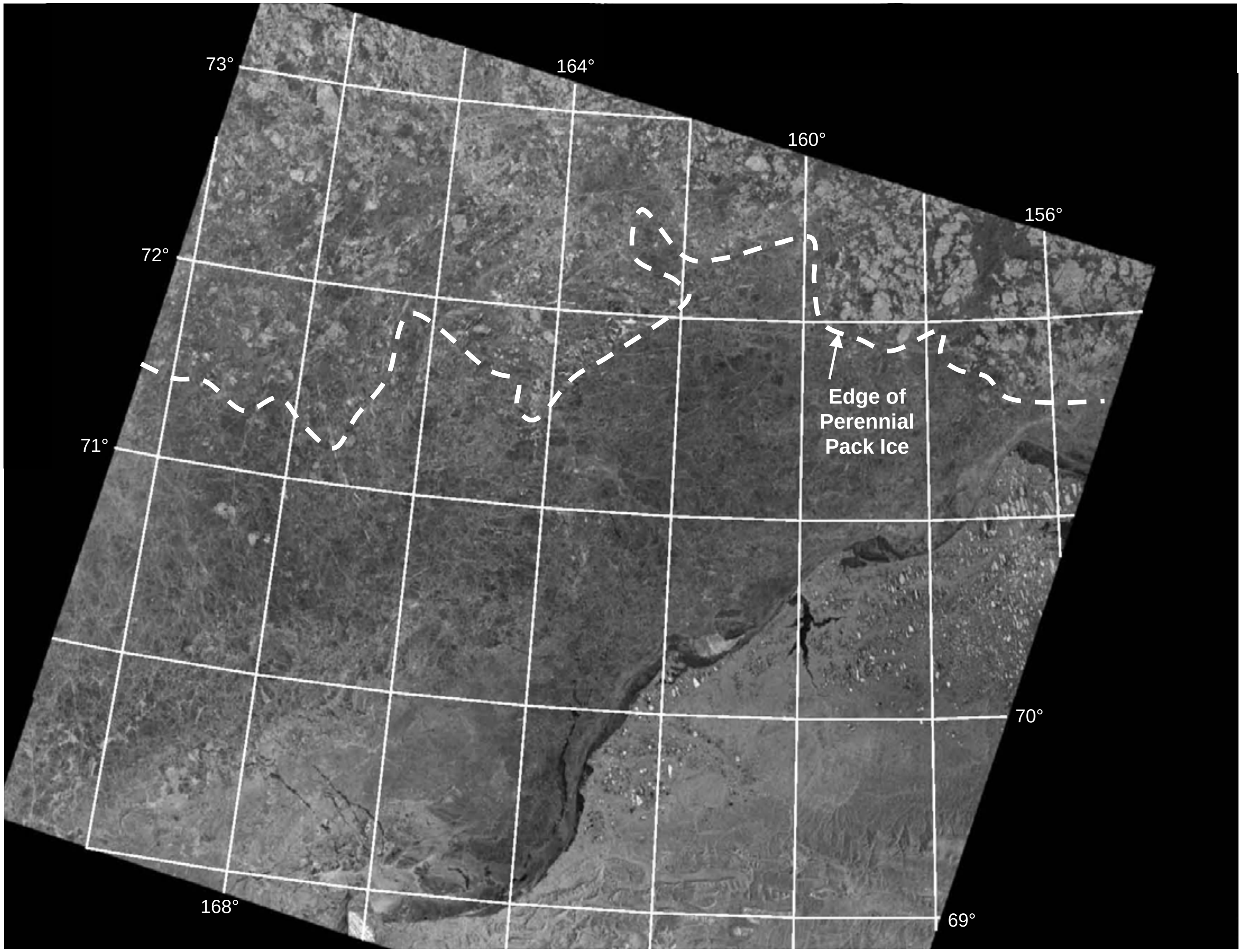
Source: RADARSAT-2 Data and Products © MacDonald Dettweiler and Associates Ltd., 2010 – All Rights Reserved

Figure 10. RADARSAT-2 Image of Chukchi Sea on December 17, 2010



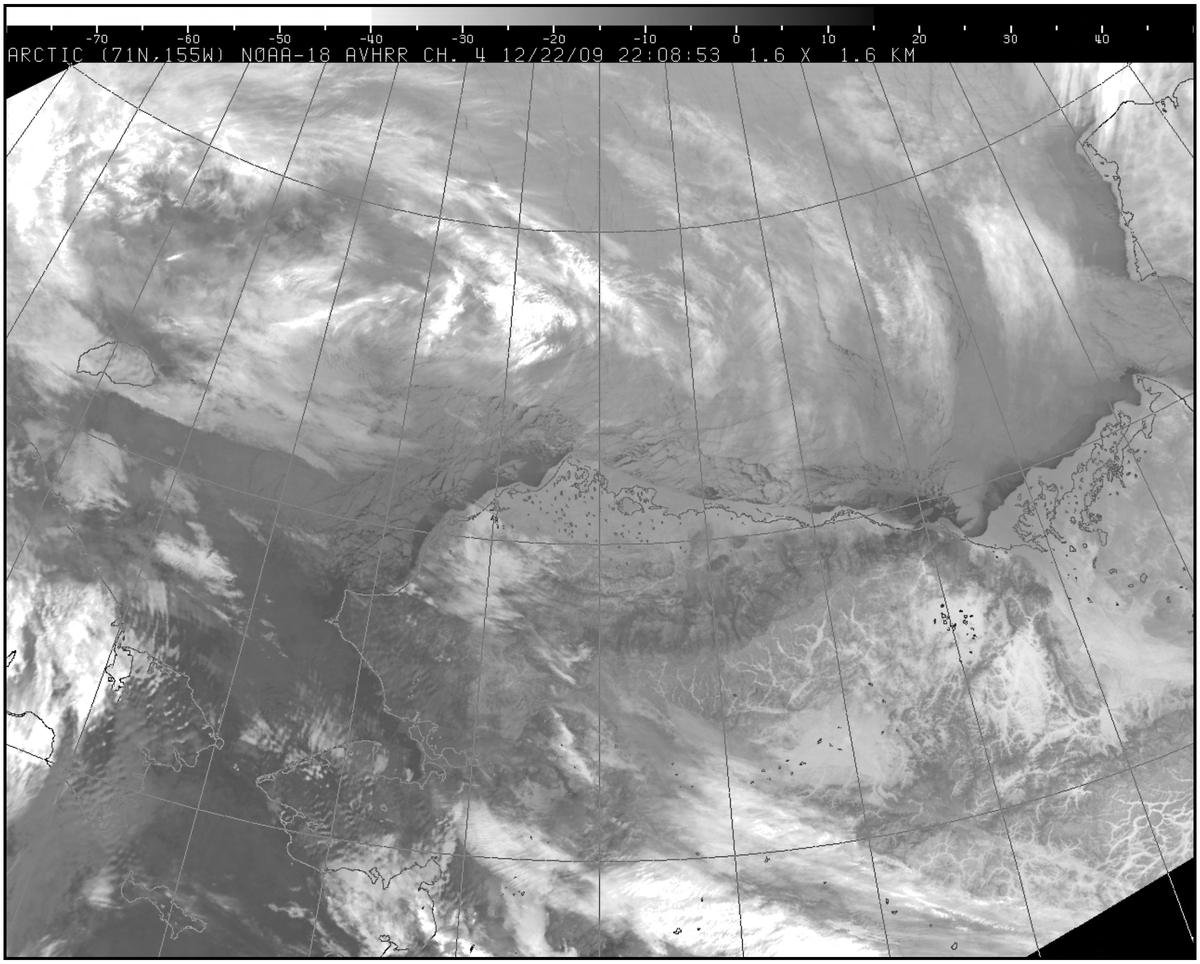
Source: RADARSAT-2 Data and Products © MacDonald Dettweiler and Associates Ltd., 2010 – All Rights Reserved

Figure 11. RADARSAT-2 Image of Chukchi Sea on January 10, 2010



Source: RADARSAT-2 Data and Products © MacDonald Dettweiler and Associates Ltd., 2010 – All Rights Reserved

Figure 12. RADARSAT-2 Image of Chukchi Sea on January 27, 2010



Source: National Weather Service, 2010

Figure 13. AVHRR Image of Beaufort and Chukchi Seas on December 22, 2009

buoy positions, which were transmitted hourly via satellite, were compiled on a proprietary website on a near-real-time basis (Hansen, 2010). As indicated in Section 1, Shell made the data available to this project in the interest of developing a more complete understanding of ice dynamics during the early-winter period. The information proved to be extremely useful both in correlating storm events with ice movements and in defining the boundary between landfast ice and pack ice.

Four of the buoys (Buoys 1, 2, 4, and 5) remained in motion until February 20, when they became stationary. The fifth buoy (Buoy 3) continued to record displacements until March 21, when it too became stationary. An overview of the buoy trajectories is provided in Figure 14, while the hourly position data are tabulated in Appendix B in the form of Excel spreadsheets.

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

Figure 14. Iridium Buoy Trajectories, January 11 – March 21, 2010

3.5 Aerial Reconnaissance Missions

Five aerial reconnaissance missions were conducted in early February, 2010, with the intent of acquiring on-site information to supplement the remote-sensing data obtained from other sources. The specific objectives were as follows:

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

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

Plate 2. de Havilland Twin Otter at Barrow

Plate 3. Bell 212 Helicopter on Multi-Year Ice Floe

Each flight path was mapped using a Trimble Pathfinder Pro XR GPS unit with the receiving antenna mounted in one of the aircraft's windows. To improve the accuracy of the position data, differential corrections broadcast in real time via satellite by the U.S. Government's Wide Area Augmentation System (WAAS) were received by the GPS unit. Static position checks conducted at North Slope survey monuments in the past have indicated that the accuracy attainable with WAAS typically is on the order of 1 to 2 m. On some occasions, GPS positioning was lost due to shadowing by the aircraft or inadequate satellite coverage. In such instances, positions were interpolated between fixes of acceptable quality.

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

The five flight paths are shown in Drawing CFC-800-01-001 (Appendix A). The drawing also displays the locations of representative photographs and of ice features observed during the flights. Each photo has been assigned a unique identification number such as "B2-19". The first portion, "B2" indicates the image was obtained during the second flight in the Beaufort Sea ("B" indicates Beaufort; "C" indicates Chukchi); the second portion, "19", indicates the image represents the 19th obtained during that flight. The photographs are provided in digital form in Appendix B, with the file names corresponding to the identification numbers shown on the drawing. The ice features observed during the flights are indicated on the drawing using the abbreviations defined in Table 2.

Table 2. Abbreviations for Ice Features

Ice Feature	Abbreviation
Active Shear Line	ASL
Inactive Shear Line	ISL
Lead	LD
Ridge	RDG
Refrozen Lead	RFL
Rubble	RBL
Multi-Year Ice (concentration)	MY (_%)
Pile-Up (height, m)	P/U (_m)
Ride-Up (distance onshore, m)	R/U (_m)

The objective and path of each flight are summarized below:

Beaufort Sea Flight No. 1 ("B1" on Drawing CFC-800-01-001, Sheet 1)

Beaufort Sea Flight No. 1 was undertaken with the Twin Otter on February 4 to observe the ice conditions in the central and eastern portions of the Beaufort Sea. The flight originated in Deadhorse, proceeded north to Cross Island, and then southeast along the barrier islands to Flaxman Island. It encompassed the Point Thomson Central Pad and the prospective pipeline route of the Sivulliq Development before heading east across Camden Bay to Barter Island. From Barter Island, the aircraft flew 6.5 nm (12 km) north before heading back to the offshore terminus of the Sivulliq pipeline route and continuing northwest over the pack ice to a point 25 nm (46 km) north of Stamukhi Shoal. The remainder of the flight consisted of a leg to the southwest to Weller Bank; a leg to the southeast that passed over the northern portion of Shell's Harrison Bay Prospects, Stamukhi Shoal, and a series of multi-year floes noted in the satellite imagery; and a circle around Northstar Production Island before returning to Deadhorse. The total flight time was 3.1 hr.

Beaufort Sea Flight No. 2 ("B2" on Drawing CFC-800-01-001, Sheet 1)

Beaufort Sea Flight No. 2, the sole helicopter mission, was undertaken on February 6 after a one-day delay due to a ground blizzard. The intent was to investigate features of interest noted during Beaufort Sea Flight No. 1 to the extent permitted by the limited range of the helicopter. The flight originated in Deadhorse and proceeded northwest past Prudhoe Bay West Dock and Northstar Production Island to a landing on one of the multi-year ice floes observed on February 4 at the east edge of Shell's Harrison Bay Prospects (Plate 4). The floe was inspected to verify its multi-year status, and its maximum sail height of 4.3 m was measured with a hypsometer. The flight resumed with a leg to the southeast to visit a massive ice pile-up noted off the west end of Narwhal Island. The peak of the pile was measured at 16 m above the ice surface, while the individual blocks comprising the pile were found to be 50 to 60 cm thick (Plate 5). The longitudinal axis of the pile-up trended east-west for a distance exceeding 1 nm (2 km).

After departing the pile-up site, the flight continued east to the offshore terminus of the Sivulliq Development pipeline route, southwest along the pipeline route to the Point Thomson Central Pad, and east along the mainland shoreline to the center of Mikkelsen Bay. The helicopter landed in an area of undisturbed first-year ice to allow the field crew to measure its thickness, which was accomplished using a portable drill motor adapted to accommodate a 5-cm diameter, stainless steel ice auger (Plate 6).

Plate 4. Multi-Year Ice Floe near Shell's Harrison Bay Prospects

Plate 5. Massive Ice Pile-Up West of Narwhal Island

Plate 6. Measurement of Ice Thickness in Mikkelsen Bay

The ice thickness was found to be 109 cm. Due to the limited fuel remaining, the flight then proceeded directly to Deadhorse Airport. The total flight time (excluding stops) was 2.2 hr.

Beaufort Sea Flight No. 3 ("B3" on Drawing CFC-800-01-001, Sheet 2)

Beaufort Sea Flight No.3 took place on the afternoon of February 7 following a half-day delay that resulted from a power outage in the vicinity of the airport. The objective was to document the ice conditions in the western Beaufort Sea between Deadhorse and Barrow. After flying from Deadhorse to Northstar Production Island, the Twin Otter continued west along the barrier islands to Spy Island, south along the Nikaitchuq Development flowline route to Oliktok Point, southwest along the shoreline of Harrison Bay, and northwest along the Oooguruk Development flowline route to the Oooguruk Offshore Drillsite. The aircraft then headed north through Shell's Harrison Bay Prospects until the active shear zone was reached approximately 30 nm (56 km) north of Oliktok Point. At that point, the aircraft turned to the west northwest and proceeded to Point Barrow on a coast-parallel course located 15 to 25 nm (28 to 46 km) offshore. The flight duration was 2.1 hr.

Chukchi Sea Flight No. 1 ("C1" on Drawing CFC-800-01-001, Sheet 3)

Chukchi Sea Flight No.1 was conducted on February 8 to observe the ice conditions in the northern portion of the Chukchi Sea. Emphasis was placed on visiting Shell's four areas of interest in this region, consisting of the Burger, Crackerjack, Hanna Shoal, and West Prospects. The Twin Otter flew from Barrow to Hanna Shoal, where an absence of ice rubble was noted at the site typically occupied by Katie's Floeberg (Barrett and Stringer, 1978). The aircraft then headed west southwest through the Hanna Shoal and Crackerjack Prospects, northwest through the West Prospects, east to circle the Burger Prospects, and east again to return to Barrow. The total flight time was 4 hrs. Of particular interest was the discovery of multi-year floes along much of the flight path, including regions within the Hanna Shoal, Crackerjack, and West Prospects.

Chukchi Sea Flight No. 2 ("C2" on Drawing CFC-800-01-001, Sheet 3)

The final aerial reconnaissance mission, Chukchi Sea Flight No.2, occurred on February 9. The objective was to observe nearshore ice conditions and shoreline pile-ups and ride-ups between Barrow and Point Lay, a region where pipelines from the offshore prospects conceivably could make landfall. The Twin Otter followed the coast to the southwest from Barrow to Point Lay, turned offshore at Point Lay, and then headed back toward Barrow while maintaining a distance of 5 to 10 nm (9 to 19 km) offshore. In the vicinity of Point Franklin, the aircraft turned to the northwest until 25 nm (46 km) offshore and then turned back to the east to return to Barrow. As in the case of the prior day's flight, a significant percentage of multi-year ice was noted in the region west of Barrow. The flight duration was 2.6 hrs.

The five reconnaissance flights provided invaluable opportunities to confirm and refine the findings derived from satellite imagery, and to expand upon those findings with respect to small-scale features and processes. The operational lessons learned from the flights included the following three points:

1. In the Beaufort Sea, where distances offshore are comparatively small, the cost of chartering an intermediate-size helicopter such as a Bell 212 or 412 is warranted by the ability to land at features of interest. Additional helicopter time during the 2009 Freeze-Up Study would have allowed more detailed investigations of the multi-year ice floes near the Harrison Bay Prospects, and the massive ice pile-up off Narwhal Island.

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

3. If studies of this nature are conducted in the future, and if budgetary constraints permit, a second set of aerial reconnaissance missions conducted in late November or early December and limited to the Beaufort Sea would greatly enhance the ability to interpret the early-season satellite imagery.

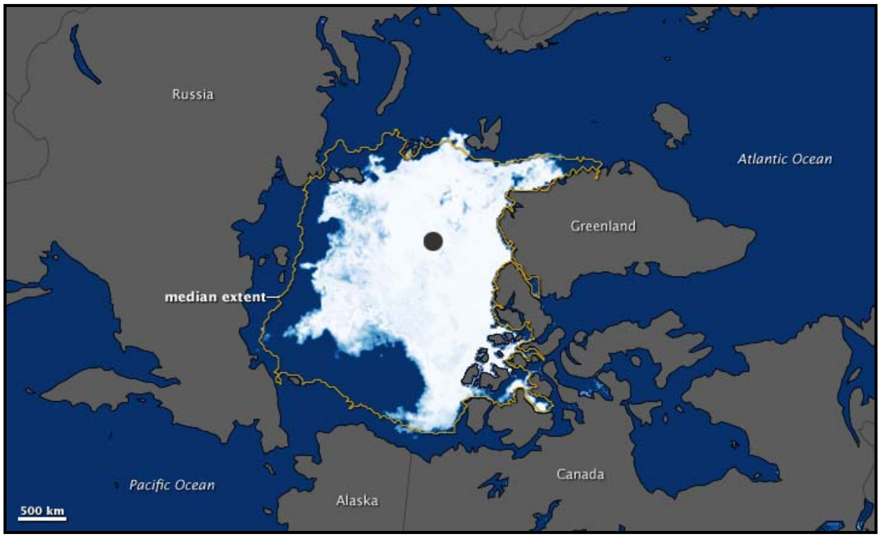
4. BEAUFORT SEA FREEZE-UP

4.1 Freeze-Up Development

4.1.1 Late Summer

Break-up and the subsequent retreat of the ice cover occurred quickly in 2009. By mid-July, the Beaufort Sea was essentially ice-free within 50 nm (93 km) of the coast between Barter Island on the east and Cape Halkett on the west (143°W to 152°W). Persistent westerly winds in mid-August prevented the ice from retreating further and maintained its position relative to the coast. The only conspicuous difference between mid-July and late August was the disappearance of ice in the western Beaufort Sea, which occurred when the northbound warm water current in the Chukchi Sea was deflected to the east by the westerly winds and caused melting.

Strong easterly winds in September and early October, coupled with the rotation of the Beaufort Gyre (Figure 1) , produced a rather compact southern ice edge and caused a westerly ice drift of 5 to 6 nm (9 to 11 km) per day according to the National Ice Center ice charts (2010). Typically, the pack ice reaches its minimum summer extent in the Beaufort Sea about a month prior to freeze-up (Figure 15). The total area covered by the Arctic pack ice at its minimum in mid-September 2009 was the third lowest since 1979. In late September 2009, the ice edge was located about 60 nm (111 km) north of the central and eastern Beaufort Sea coast, close to its median location for this time of year during the period from 1979 through 2000.



Source: NASA, 2010

Figure 15. Sea Ice Minimum Extent on September 12, 2009.

4.1.2 Freeze-Up and Early Winter

Initiation of Freeze-Up: A combination of unseasonably warm temperatures and persistent easterly winds delayed new ice growth in the nearshore Beaufort Sea until the beginning of the third week of October 2009, about two to three weeks later than freeze-up typically occurred in the early 1980's. Although some new ice formed in early October, it was limited to the brackish water near river deltas and to some shallow bays and lagoons.

During the freeze-up studies conducted in the 1980's, 40 to 50 freezing-degree days (FDD's) were required to initiate freeze-up along the central Beaufort Sea coast. In 2009, however, nearly 100 FDD's were required. This change probably resulted from the longer open-water season and correspondingly warmer sea water temperatures.

October Ice Conditions: A MODIS image obtained on October 6 (Figure 16) and a RADARSAT image obtained on October 8 indicate that the edge of the pack ice was located 70 nm (130 km) north of Prudhoe Bay and Flaxman Island (at approximately 71°45'N). Between October 20 and 22, a 30- to 40-kt (15- to 21-m/s) easterly storm caused the ice edge to retreat to a distance of 90 nm (167 km) north of Prudhoe Bay and 75 nm (139 km) north of Flaxman Island. This strong storm, which occurred during the initiation of freeze-up, disturbed the surface waters to such an extent that new ice did not completely cover the nearshore Beaufort Sea until the end of October.

Source: NASA, 2010a

Figure 16. MODIS Image Obtained on October 6, 2009.

November Ice Conditions: Shortly after freeze-up, on November 4 and 5, a 20- to 30-kt (10- to 15-m/s) easterly storm created a prominent shear (ice movement) line that extended from Cross Island westward along the north shore of Reindeer Island to Northstar Production Island, and then continued to the west along the barrier island chain from Long Island to Thetis Island. The movement caused the 25-cm thick ice (computed from accumulated freezing-degree days) to form a low rubble field on the east side of Northstar and shoreline pile-ups on the barrier islands. These features were noted during the field investigation conducted in early February 2010, and are discussed in more detail in the next section.

In the western Beaufort Sea, the ice movement line created by the early-November storm was located 1.5 to 2 nm (3 to 4 km) off Cape Halkett. It extended to the west parallel to the coast off Lonely (Pitt Point) and across the mouth of Smith Bay. In the eastern Beaufort, the ice movement line ran parallel to the barrier island chain from Cross Island to Flaxman Island, about 0.5 nm (0.9 km) offshore. A vast polynya was located in eastern Camden Bay from the shoreline out to a water depth of 18 m, from Collinson Point on the west to Arey Island on the east.

Another easterly storm occurred on November 11 and 12, creating new leads and lines of ice movement near the Beaufort Sea coast. The width of the open-water leads ranged from 0.5 to 2 nm (0.9 to 4 km), according to a RADARSAT image acquired on November 11. The widest openings occurred in eastern Camden Bay, where the ice remained very dynamic. Other leads were located at the following sites:

- 0.5 nm (0.9 km) north of the Stockton Islands;
- From 1 nm (2 km) north of Cross Island west to 3 nm (6 km) north of Northstar Production Island;
- From the north shore of Thetis Island west off the Colville River delta, about 3 nm (6 km) north of the Oooguruk Offshore Drillsite.

The active ice movement line that resulted from the November 11-12 storm lay seaward of that from the November 4-5 event, reflecting the greater thickness of the ice sheet due to both deformation and growth. The line was located 1 to 3 nm (2 to 6 km) offshore of the Beaufort Sea coast and barrier islands at most locations, in the general vicinity of the 9-m isobath. Whereas Northstar Production Island was located on the active movement line on November 4, it was 3 nm (6 km) inside the fast ice one week later. The most significant exception to the seaward migration of the ice movement line occurred in the region occupied by Shell’s Sivulliq Development. There, the location of the boundary between the fast ice and pack ice remained unchanged at 0.5 nm (0.9 km) off Flaxman Island.

During the week of November 4-11, the old pack ice drifted to the west under the influence of the Beaufort Gyre. Two extremely large multi-year floes evident on RADARSAT imagery near 74°N about 200 nm (370 km) north of Harrison and Camden Bays, respectively, each moved 63 nm (117 km) during this period (as indicated by the red cross and black asterisk in Figure 17).

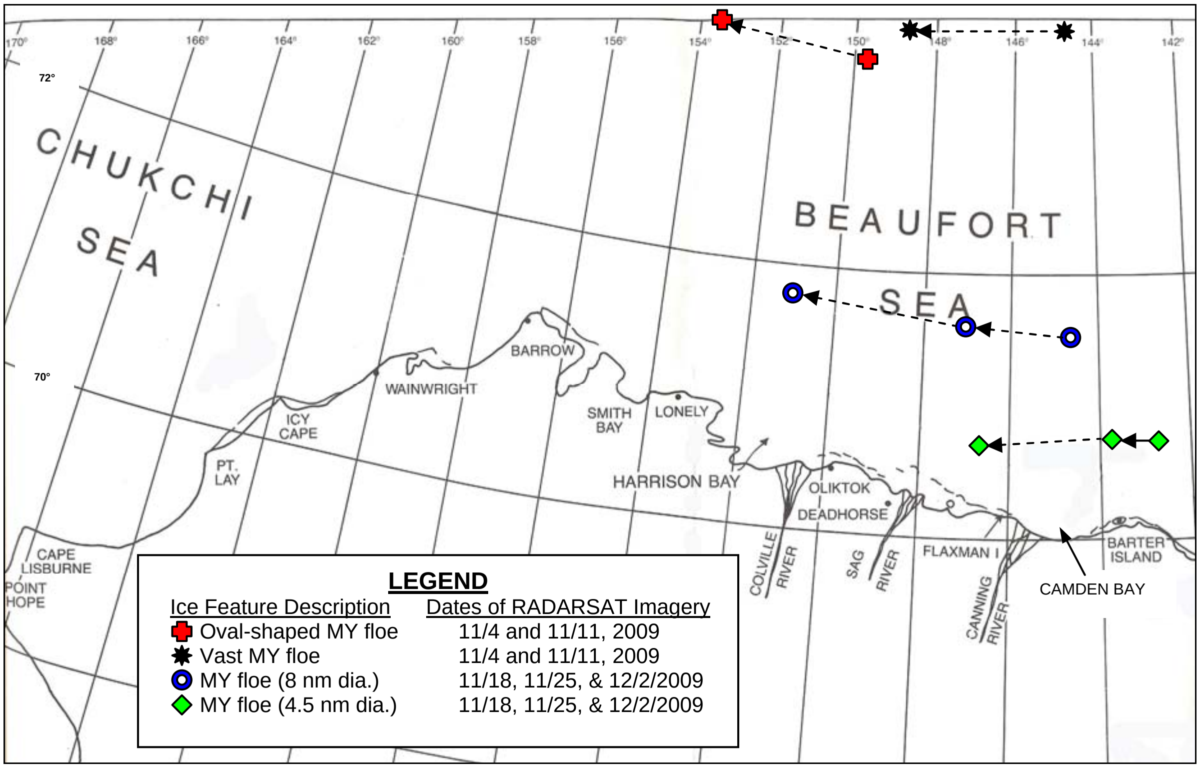


Figure 17. Ice Movement in Beaufort Sea during November 2009

Steady, moderate (15-kt; 8-m/s) westerly winds prevailed during the week of November 11-18, producing a lead 0.5 to 1 nm (0.9 to 2 km) wide from Cross Island to western Camden Bay. The fast ice boundary was located 4 nm (7 km) offshore off the McClure Island chain and 4 to 5 nm (7 to 9 km) north of Mary Sachs Entrance (on the Sivulliq pipeline route) near the 14-m isobath, but only 1 nm (2 km) north of Brownlow Point (east of Flaxman Island) near the 9-m isobath. Many cracks and small, refreezing leads, generally oriented in a north-south direction, were present in outer Camden Bay based on a RADARSAT image acquired on November 18.

By mid-November, the multi-year ice had moved closer to the Beaufort Sea coast, at a distance of 30 to 40 nm (56 to 74 km) north of Barter Island, Flaxman Island, Prudhoe Bay, and Cape Halkett.

The week of November 18-25 was relatively quiet, with little or no wind. Based on a RADARSAT image acquired on November 25, the nearshore Beaufort Sea ice canopy remained stable between Cross Island and Point Barrow. During the following week, however, a sequence of moderate westerly and easterly winds reactivated the ice movement line across central Harrison Bay and north of the barrier island chain from Spy Island to Cross Island in water depths of 9 to 12 m. A 2-nm (4-km) wide lead opened up offshore of the temporary fast ice that extended about 2 nm (4 km) offshore of the barrier islands from Reindeer Island on the west to Flaxman Island on the east. The lead continued across Camden Bay, based on a RADARSAT image acquired on December 2.

While the winds remained light to moderate during the last half of November, the Beaufort Gyre continued to displace the old pack ice to the west. Offshore of Camden Bay, a large multi-year floe (8-nm or 15-km diameter) near 71.5°N moved 44 nm (82 km) to the west-northwest between November 18 and 25 and an additional 74 nm (137 km) between November 25 and December 2 (as indicated by the blue circle in Figure 17). The corresponding displacements for another large multi-year floe (4.5-nm or 8-km diameter) located closer to shore were 18 nm (33 km) to the west during the week of November 18-25 and 56 nm (104 km) during the week of November 25-December 2 (as indicated by the green diamond in Figure 17). The concentration of multi-year ice during this period was 1 to 2 tenths in the eastern portion of the Beaufort Sea and as much as 5 to 6 tenths in the western portion.

Although well-defined ice movement lines were evident in the RADARSAT images acquired in November 2009, a shear zone with significant grounded rubble was not detected. This situation probably arose from the combination of brief easterly storms early in the month and moderate southwesterly winds in the last half.

The thickness of the first-year fast ice at the end of November is estimated to be 56 cm, based on the relationship of Bilello (1960) with an accumulated total of 1,161 freezing-degree days at Deadhorse Airport (Table 1).

December Ice Conditions: A brief southwesterly wind of moderate intensity occurred on December 3, followed by an equally brief but stronger easterly (25-30 kt; 13-15 m/s) two days later. Such a reversal in wind direction, from southwest (which pulls the ice loose) to east (which provides the driving force), usually produces significant movement in the nearshore, first-year pack ice. This instance was no exception; RADARSAT imagery indicates that between December 2 and 9, the pack ice (represented by a vast first-year floe shown as a yellow square in Figure 18) moved 25 nm (46 km) to the west at 71°N near Weller Bank off Harrison Bay.

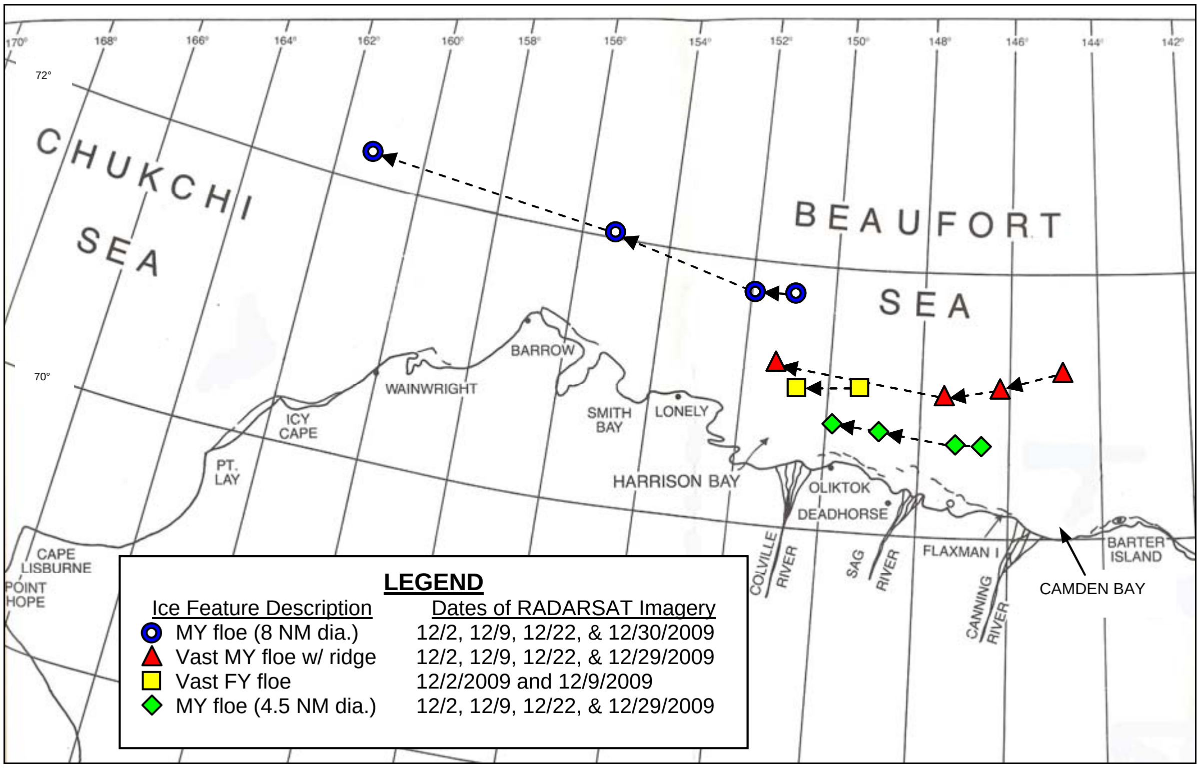


Figure 18. Ice Movement in Beaufort Sea during December 2009.

Movement of the pack ice in December was measured using four multi-year floes. Two of these were identified in four successive RADARSAT images acquired by Shell on December 2, December 9, December 22, and December 29, the third was identified in the first three of these images, and the fourth was identified in the first two. Two of the floes, with diameters of 8 and 4.5 nm (hereafter referred to as the "8-nm floe" and "4.5-nm floe"; diameters of 15 and 8 km, respectively), were identical to those tracked during the month of November (Figure 17).

The results for December are shown in Figure 18. During the week of December 2-9, the vast multi-year floe shown as a red triangle moved 27 nm (50 km) to the west – a displacement similar to that of the first-year floe depicted as a yellow square. Both of these floes were located in close proximity to the 71st parallel. However, the other two multi-year floes (shown as a green diamond and blue circle) moved significantly less during the same period. The 4.5-nm floe located closest to the shore (denoted by a green diamond) advanced 11 nm (20 km) to the west, while the 8-nm floe located farthest offshore (denoted by a blue circle) moved 18 nm (33 km). The differing displacements indicate that either ridge-building or lead formation was occurring within the pack.

The middle two weeks of December were marked by steady but moderate westerly winds, while the final week of December was dominated by a strong easterly storm that peaked at 30 to 35 kt (15 to 18 m/s) on December 26.

The landfast ice edge remained nearly stationary between December 9 and 22, and was located only slightly farther offshore than it had been in mid-November. The boundary tended to follow the 9-m isobath in the western Beaufort Sea, from Harrison Bay to Pingok Island, moved offshore to water depths of 12 to 15 m in the central Beaufort from Northstar Production Island eastward to the Stockton Island chain, and then returned to the 9-m isobath in the eastern Beaufort from Flaxman Island across Camden Bay to Barter Island.

Although the two-week period between December 9 and 22 was dominated by westerly winds, the multi-year floes embedded in the pack ice moved steadily to the west, against the prevailing wind, due to the influence of the Beaufort Gyre. As shown in Figure 18, the 8-nm floe (blue circle) in the western Beaufort Sea moved 64 nm (119 km) during this period. The other two floes (red triangle and green diamond), which began the period well offshore of the Sivulliq Development, moved 25 to 30 nm (46 to 56 km).

The fast ice boundary changed dramatically between December 22 and December 29 due to an intense, long-duration northeasterly storm that persisted from December 24 to 29. During the one-week period between images, a substantial shear zone (seen clearly in the RADARSAT image acquired on December 29) formed along the 18-m isobath, thereby significantly increasing the area of temporary fast ice along the Beaufort Sea coast. The shear zone east of Cross Island was not as pronounced on the imagery, perhaps indicating that the shear rubble was not extensive or well-grounded. Figure 19 illustrates the offshore progression of the fast ice boundary during the first two months after freeze-up by depicting the ice movement lines evident on November 4, November 11, December 22, and December 29.

The big easterly storm in late December produced significant westerly ice movements. The 8-nm floe designated by the blue circle in Figure 18 entered the northern Chukchi Sea and moved 108 nm (200 km) to the west northwest, based on a RADARSAT image of the Chukchi Sea acquired on December 30. The vast multi-year floe depicted as a red triangle in Figure 18 moved 79 nm (146 km) to the west northwest, while the 4.5-nm floe (shown as a green diamond and located closer to the coast) moved 23 nm (43 km) to the west northwest and became lodged on windward side of Weller Bank, with the shear zone developing along the north side of the floe.

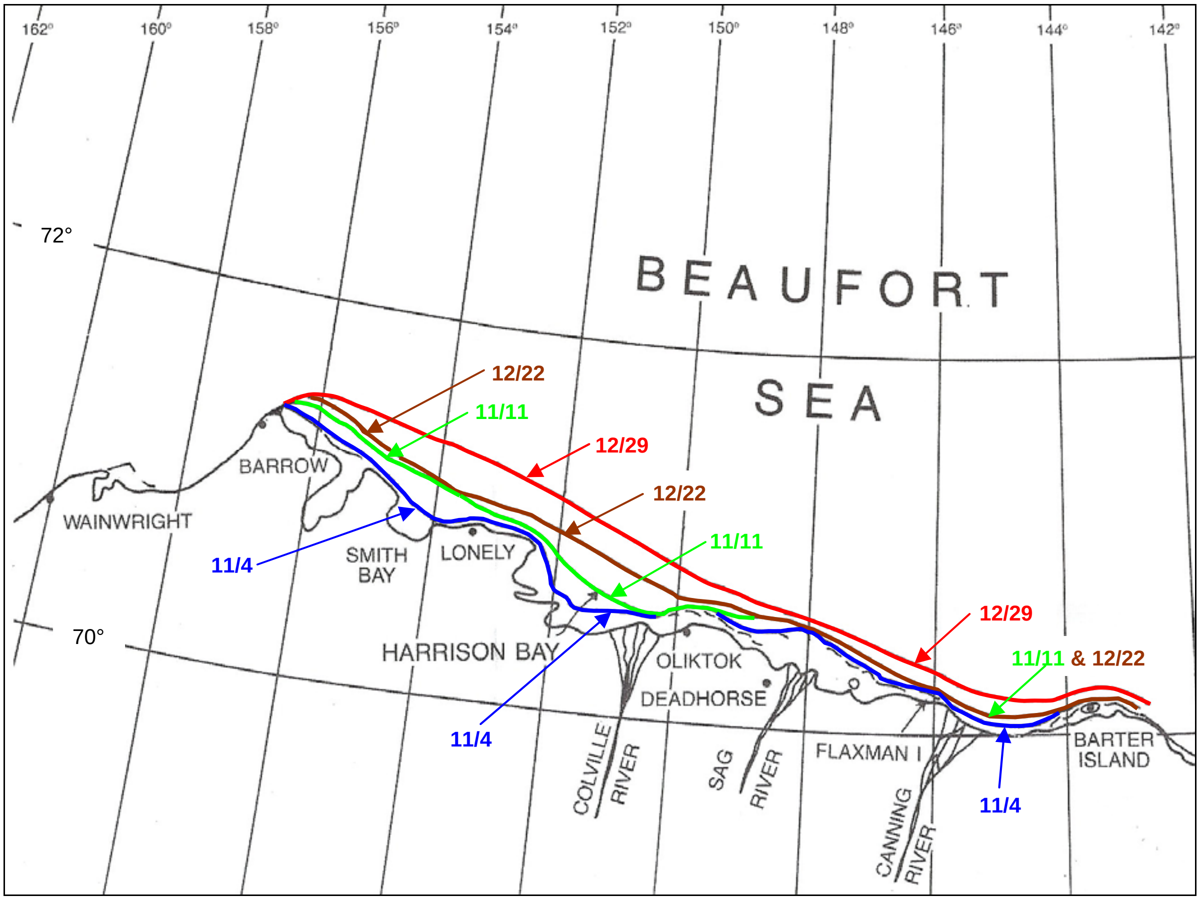


Figure 19. Seaward Progression of Landfast Ice Edge, November-December 2009.

On December 29, the southern limit of multi-year ice was located far offshore in the eastern Beaufort Sea (east of the Stockton Island chain). Farther west, in the region offshore of Harrison and Smith Bays, the multi-year ice concentration increased to as much as 8 tenths in some areas. Based on the RADARSAT image obtained on December 29, almost all of the multi-year ice lay offshore of the newly-formed shear zone (which is bounded by the red line in Figure 19). A notable exception occurred to the east of Harrison Bay between the 149 and 150° meridians. Numerous multi-year floes (including the 4.5-nm floe shown by a green diamond in Figure 18) invaded this area during the early stages of the late-December storm and became lodged on the east side of Weller Bank. The storm then created a new shear zone along the northern perimeter of these floes, leaving them trapped in the landfast ice.

As indicated in Table 1, 2,192 freezing-degree days had accumulated at Deadhorse Airport at the end of December. The corresponding ice thickness is computed to be 81 cm.

January Ice Conditions: A 35-kt (18 m/s) westerly storm on January 1 and 2, 2010, produced a divergence in the pack ice just north of the shear zone between 149° and 150°W. Based on RADARSAT imagery acquired on December 29, 2009, and January 5, 2010, the two multi-year floes shown in Figure 20 as a red triangle and a yellow circle moved in opposite directions. The former moved 15 nm (28 km) to the northwest, while the latter moved 20 nm (37 km) to the south southeast. The 4.5-nm floe represented by the green diamond in Figure 20 remained stationary, embedded in the fast ice just shoreward of the shear zone. A fourth multi-year floe, which was tracked using RADARSAT imagery and is shown as a blue circle in Figure 20, exited the Beaufort Sea under the influence of the Beaufort Gyre. It moved 108 nm (200 km) to the west northwest between December 22 and 30 before backtracking 31 nm (57 km) to the southeast between December 30 and January 10.

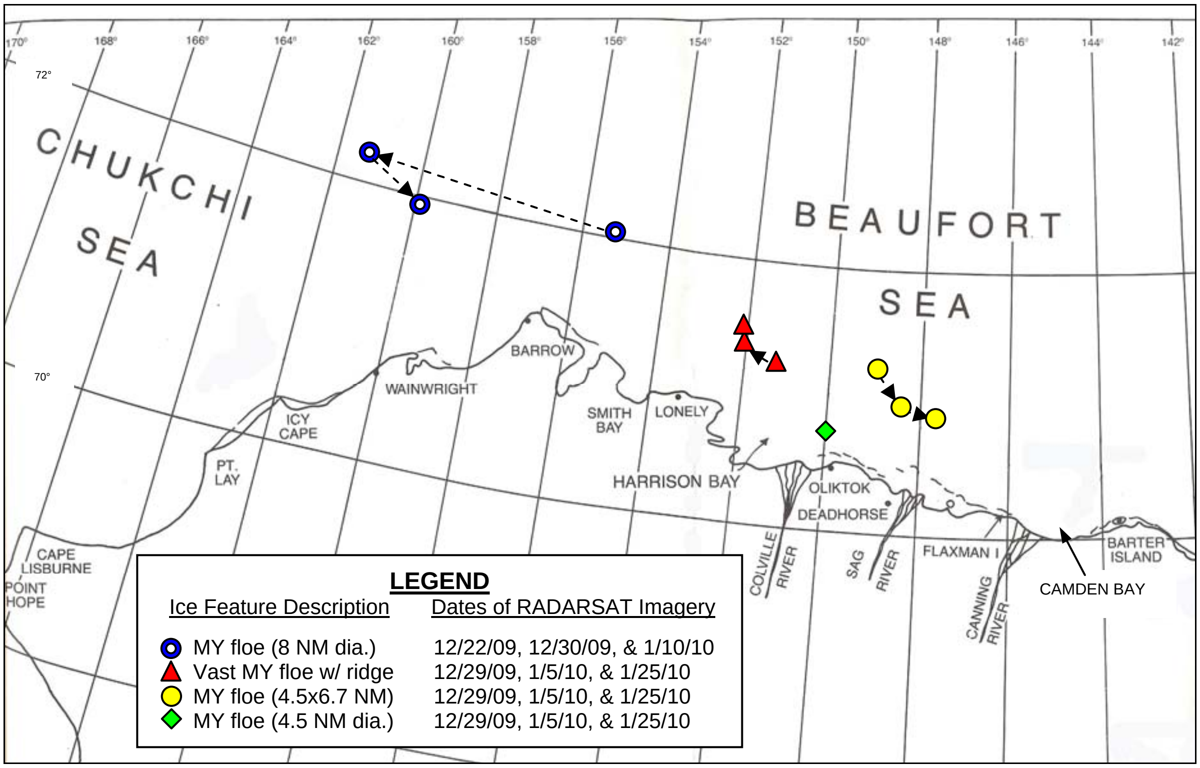


Figure 20. Ice Movement in Beaufort Sea during January 2010.

The westerly storm on January 1 and 2 was sufficiently strong and oriented such that it carved a large scallop from the first-year fast ice inside Stefansson Sound between Cross and Narwhal Islands. The displaced ice ran aground about 1 nm (2 km) west of the western tip of Narwhal Island, thereby creating the 16-m high grounded ridge described in

Section 3.5. The ridge was documented during the helicopter reconnaissance flight on February 6, 2010, and will be described in greater detail during the discussion of the field investigation presented in Section 4.2.

Although the extent of the landfast ice zone increased dramatically in late December between Cross and Barter Islands, the ice remained unstable because the shear zone was not grounded. The westerly storm on January 1 and 2 breached the newly-formed shear zone in several places, producing significant ice movement offshore of the barrier islands and in Camden Bay. The new boundary between fast and pack ice formed along the 9-m isobath offshore of the Stockton and Maguire Island chains, and in western Camden Bay off the mouth of the Canning River.

Following the westerly storm of January 1 and 2, southwesterly winds predominated until a 35 to 40 kt (18 to 21 m/s) easterly storm occurred on January 28 and 29. During the long period of mild-to-moderate southwesterlies, little pack ice movement occurred (based on a comparison of RADARSAT images acquired on January 5 and January 25). What movement did occur reflected a continuation of the divergence noted in late December. Specifically, the vast multi-year floe shown as a red triangle in Figure 20 moved a scant 4 nm (7 km) to the north while the multi-year floe shown as a yellow circle moved 13 nm (24 km) to the east-southeast. The multi-year pack in the western Beaufort Sea north of Admiralty Bay drifted about 15 nm (28 km) to the north-northeast over the 20-day period between January 5 and 25, indicating that the Beaufort Gyre was temporarily reversed by the near-constant southwesterly winds.

On January 11, 2010, Shell installed five Iridium telemetry buoys on the ice in various water depths in the vicinity of the Sivulliq Development. After remaining stationary for three days, they moved in unison about 16 nm (30 km) to the east-southeast in response to a 20-kt (10 m/s) southwesterly wind on January 14-16. For two weeks thereafter, the buoys logged minor displacements. They then moved uniformly in a contour-parallel direction to the west northwest in response to the 35 to 40 kt (18 to 74 m/s) easterly storm on January 28 and 29. The buoys moved 56 nm (104 km) over a 48-hour period at an average rate of 1.1 kt (0.6 m/s; about 3% of the sustained wind speed) and a peak rate of 1.7 kt (0.9 m/s).

The multi-year ice concentration and the southern limit of multi-year ice changed very little in the Beaufort Sea during January 2010. The first-year ice thickness at month-end is predicted to be 1.1 m based on an accumulated total of 3,675 freezing-degree days at Deadhorse Airport (Table 1).

4.2 Field Observations

As discussed in Section 3.5, aerial reconnaissance missions were undertaken in the Beaufort Sea on February 4, 6, and 7. Beaufort Sea Flight Nos. 1 and 2 (Flights “B1” and “B2” on Drawing CFC-800-01-001, Sheet 1) focused on nearshore ice conditions in the central and eastern Beaufort, while Beaufort Sea Flight No. 3 (Flight “B3” on Drawing CFC-800-01-001, Sheet 2) was used to observe ice conditions in the western Beaufort Sea.

Landfast Ice and Shear Zone Development: The ice in the smaller bays and lagoons, such as Prudhoe and Mikkelsen Bays and Simpson and Leffingwell Lagoons, became stable shortly after the initiation of freeze-up, leaving the sheet ice generally featureless and flat. Light rubbling was noted in the more exposed areas of Stefansson Sound, such as the region northeast of the Endicott Causeway, but the remainder of the Sound consisted of relatively smooth first-year sea ice. In addition, flat, undisturbed sea ice was observed in a large area north of Stump and Egg Islands and west of the West Dock Causeway.

Even after the aforementioned intense easterly on January 28-29 and a strong, westerly storm with a double peak in wind speed on February 2-5, there was no perceptible ice movement inshore of a well-established shear zone to the west of Prudhoe Bay. The grounded shear zone between Cross Island and Point Barrow (Plate 7) was observed to lie near the 18-m foot isobath – a location that differed only slightly from that established during the strong easterly storm on December 29 (Figure 19).

Based on RADARSAT imagery, the ice as close as 2 nm (4 km) to the north of the Jones Island chain between Pingok and Thetis Islands continued to move throughout November and December 2009 (Figure 18). This assessment was supported by the significant ridging observed during Beaufort Sea Flight No. 3. It is likely that the grounded ridges, each 6 to 9 m high, were formed by the westerly-easterly storm sequence that occurred in early December. Plate 8 shows one such ridge about 0.5 nm (0.9 km) north of Pingok Island. The ice in this region (including the eastern portion of Shell’s Harrison Bay Prospects) did not become part of the landfast ice zone until late December.

In sharp contrast to the well-developed shear zone observed to the west of Prudhoe Bay, a similar feature was conspicuously absent to the north and east at the time of the aerial reconnaissance missions. This situation resulted from the strong westerly storm between February 2 and 5, which removed any previously-established shear line and much of the temporary fast ice that lay to the south. Based on an AVHRR image acquired on February 5 and confirmed by aerial observations the next day, a 2-nm (4-km) wide lead was located

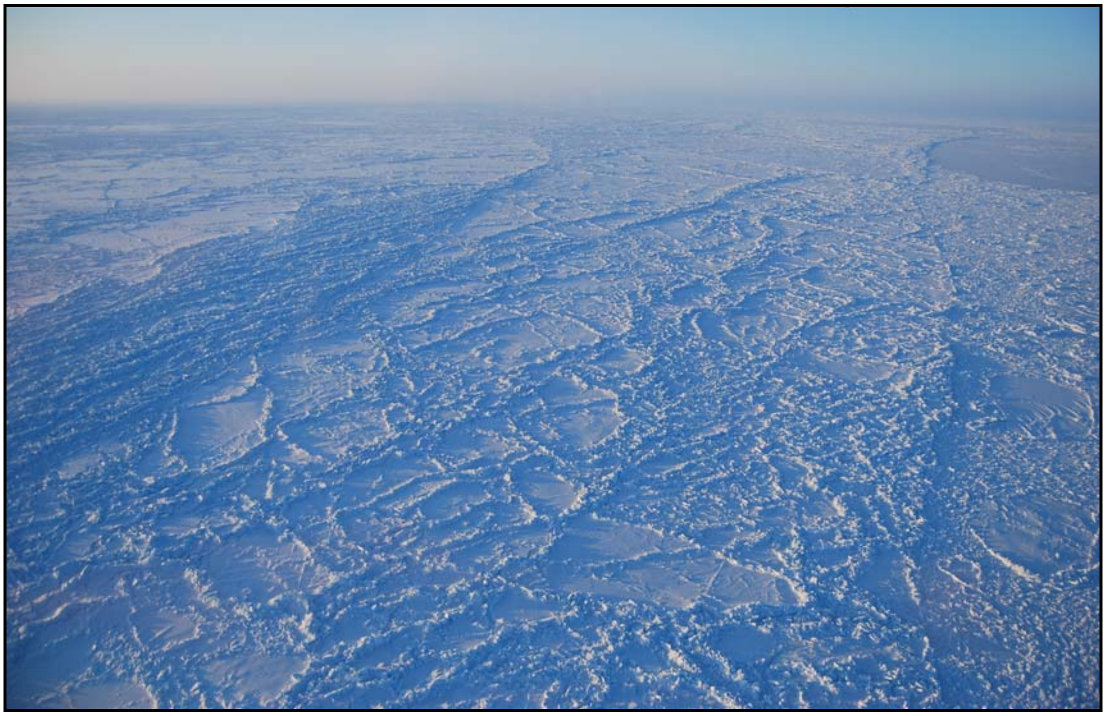


Plate 7. Grounded Shear Zone East of Weller Bank.

Plate 8. 9-m High Grounded Ridge Offshore of Pingok Island.

offshore of the barrier island chain from Cross Island to Camden Bay (3 nm or 6 km north of Cross Island; within 0.5 nm or 0.9 km of the Stockton Island chain; 2 nm or 4 km north of the west end of Flaxman Island; and 0.5 nm or 0.9 km north of Brownlow Point). In Camden Bay, a vast refreezing lead was noted with its southern boundary on the 9-m isobath and its northern boundary 1 to 2 nm (2 to 4 km) north of a line between Flaxman Island and Barter Island.

When the Sivulliq Development prospective pipeline route was inspected by helicopter on February 6, a wide lead running north-south was noted at the seaward end (Plate 9). Approximately 4 nm (7 km) to the south along the route, a large chunk of shear rubble (6-9 m high) was observed. The rubble was part of the old shear zone that had been detached by the recent southwesterly winds and carried into the pack ice. Over the next 5 nm (9 km), numerous refreezing leads oriented east-west were present with new ice less than 30 cm thick (Plate 10). The southernmost lead, estimated at 0.5 nm (0.9 km) wide, was approximately 5 nm (9 km) from the prospective shore crossing at Pt. Thomson. Landward of this lead, in the region that includes Mary Sachs Entrance and Leffingwell Lagoon, the ice appeared to be relatively fast. In summary, the ice on the prospective pipeline route was found to be relatively stable inside the 12-m isobath, and dynamic and unstable outside.

Multi-Year Ice: Throughout November and early December, the old pack ice in the high Canadian Arctic west of Banks Island moved southwest toward the central Beaufort Sea coast under influence of the Beaufort Gyre. This movement pattern drove the southern limit of multi-year ice southward until it was located 12 nm (22 km) north of the Sivulliq Development well site and 16 nm (30 km) north of Cross Island. However, during the middle of December, the direction of movement changed abruptly from southwest to west. The new movement pattern increased the concentration of multi-year ice in the western Beaufort Sea while removing virtually all of the multi-year ice from the region east of Prudhoe Bay and south of the 72°N parallel. The westerly set of the Beaufort Gyre remained in place from mid-December through the aerial reconnaissance missions in early February.

During the two reconnaissance flights in the central Beaufort Sea (Flights B1 and B2 on Drawing CFC-800-01-001, Sheet 1), small multi-year floe fragments 30 to 150 m in diameter were detected 30 to 40 nm (56 to 74 km) to the northwest of Prudhoe Bay in concentrations of one tenth or less. The concentration increased slightly and the floe size increased dramatically to the northeast of Weller Bank, where the diameters reached 600 to 1,000 m.

Plate 9. Wide North-South Lead at Seaward End of Sivulliq Pipeline Route

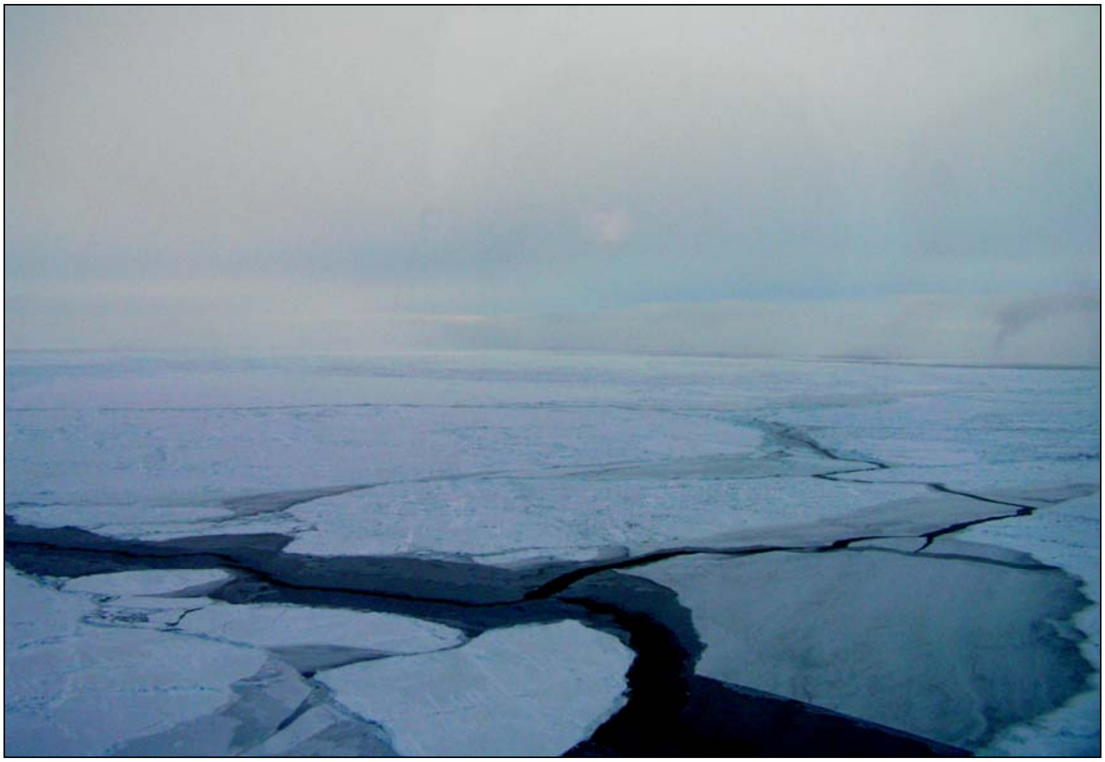


Plate 10. Dynamic Ice Conditions in Middle Portion of Sivulliq Pipeline Route in Early February 2010.

A 10-nm (19-km) wide band of multi-year floes located just south of the shear zone was observed between Weller Bank and Stamukhi Shoal (primarily between 149 and 150°W) in the northeast portion of Shell's Harrison Bay Prospects. Many individual floes were surrounded by or embedded in significant first-year ridges or shear rubble, and probably were grounded in 12 to 18 m of water. The multi-year floes had been driven into the nearshore region during the easterly storm in late December and thereafter became part of the landfast ice zone.

The multi-year ice concentration in the band was 1 to 2 tenths, with typical floe diameters ranging from 150 to 300 m. During the helicopter flight on February 6, the field crew landed on a particularly large floe with an estimated diameter of 2 nm (4 km). This floe, which had been identified previously in RADARSAT imagery and noted during the Twin Otter flight two days earlier, was located at 70° 41'N and 149° 18'W (17 nm or 32 km northwest of Northstar Production Island). The floe contained several embedded ridges, the tallest of which produced a maximum sail height of 4.3 m (Section 3.5), and had a hummocky, undulating surface that was partially obscured by wind-packed snow.

In the western Beaufort Sea, multi-year ice was observed 20 to 25 nm (37 to 46 km) off Cape Halkett and Smith Bay, just north of the shear zone. The multi-year ice concentration increased from east to west, ranging from 2 to 3 tenths offshore of central Harrison Bay to 7 to 8 tenths between Smith Bay and Point Barrow. Typical floe sizes ranged from 300 to 500 m (Plate 11), with several floes more than 2 nm (4 km) across (Plate 12).

Most of the multi-year floes observed in the western Beaufort Sea contained embedded ridges with estimated sail heights of 1 to 5 m. Some of the floes were characterized by relatively rough topography that suggested second-year rather than multi-year ice. The majority appeared to consist of multi-year sheet ice, which tends to be more rounded and hummocky than the sharp-featured, second-year ice. Most of the multi-year floes, although surrounded by first-year rubble, had remained intact rather than splitting into smaller fragments.

Ice Pile-Up Events: A number of ice pile-ups were observed in the central Beaufort Sea, along with one in the eastern portion (Table 3). The most significant of these was located in Stefansson Sound about 1 nm (2 km) west of the western tip of Narwhal Island, at 70°24'N, 147° 35'W (Drawing CFC-800-01-001, Sheet 1). Based on an analysis of weekly RADARSAT imagery, it appears that the pile-up formed during the westerly storm on January 1 and 2. As indicated in Section 4.1, the storm dislodged a large piece of the first-year fast ice between Cross and Narwhal Islands. The initial breakout to the east caused the

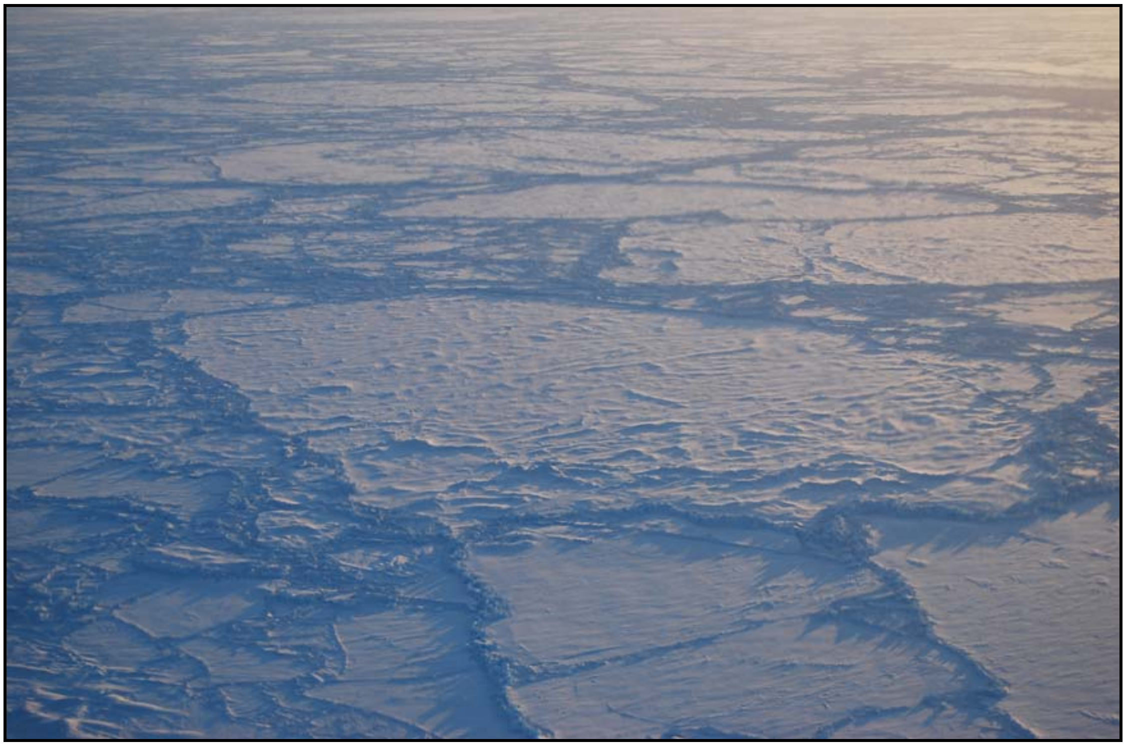


Plate 11. Typical Multi-Year Floe Located 25 nm Offshore in Western Beaufort Sea.

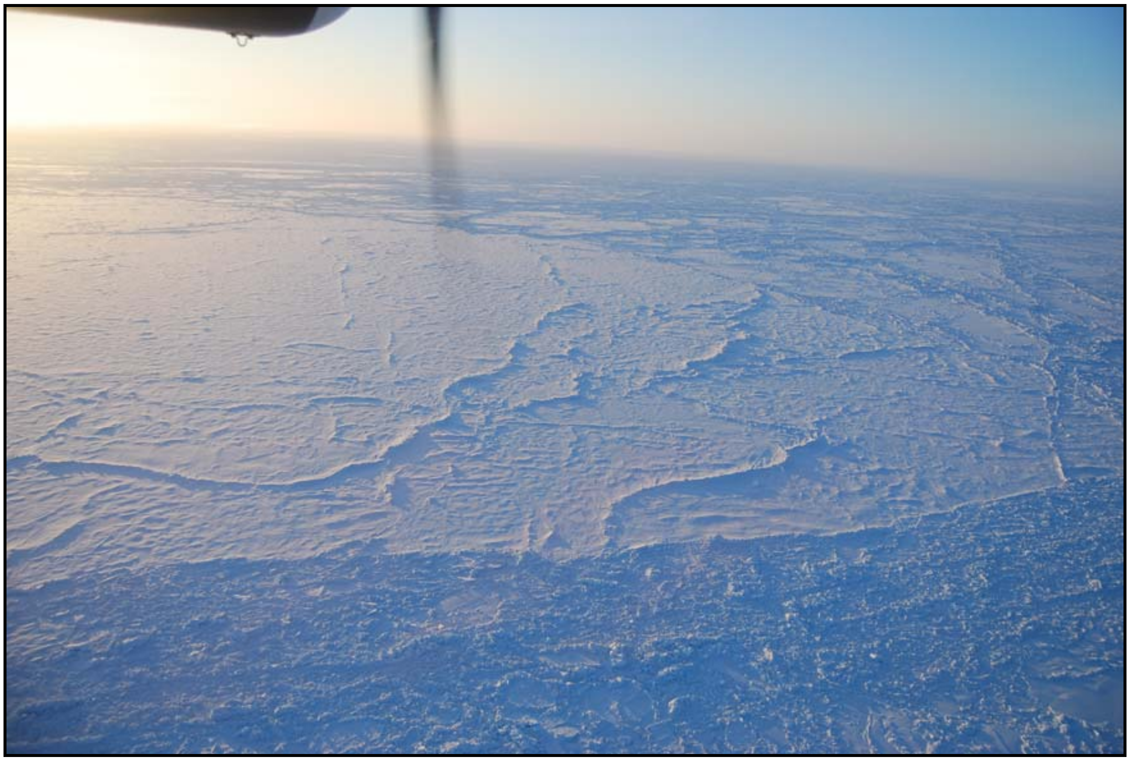


Plate 12. Vast Multi-Year Floe Located 5 nm Northeast of Weller Bank.

TABLE 3

ICE PILE-UP EVENTS OCCURRING IN 2009-10 AT MAN-MADE AND BARRIER ISLANDS IN CENTRAL BEAUFORT SEA

Site	*Location*	*Est. Pile-Up Height (m)*	*Ice Block Thickness (cm)*	*Length or Coverage (nm)*	*Storm Event Date*	*Storm Direction*
Narwhal I.	offshore	16	75	1	1/1/10	westerly
Northstar I.	offshore/ shoreline	2 to 3	25	0.1	11/4/09	easterly
Long I.	shoreline	2 to 3	25	1 – 2	11/4/09	easterly
Cottle I.	shoreline	3 to 5	25	0.15	11/4/09	easterly
Stockton I.	shoreline	2 to 3	25	0.3	11/4/09	easterly
Flaxman I.	shoreline	1 to 2	25	0.15	11/4/09	easterly
Arey I.	shoreline	6 to 9	60	0.5	12/10/09	westerly

moving ice to grind along the northern edge of the remaining fast ice, forming a shear ridge oriented in an east-west direction. A slight wind shift to the west northwest produced a grounded compression ridge over the top of the initial shear formation. The end product was a ridge containing a core of tumbled, fused ice chunks and an outer shell of individual ice blocks (Plate 5). The ice comprising the ridge bore a darkish color, indicating sediment entrainment induced by movement early in the freeze-up process.

The pile-up was unique in two ways: (1) it consisted of a grounded ridge rather than an assemblage of individual ice blocks, and (2) it resulted from the northerly transport of ice inside the barrier islands rather than the more common occurrence of southerly transport outside the islands. The ridge ran aground on a shoal between Narwhal Island and Dinkum Sands where depths of 5 to 7.5 m are indicated on NOAA Chart No. 16046 (National Ocean Service, 1990). It had a peak height of 16 m (Plate 5) and stretched more than 1 nm (2 km) in an east-west direction. The block thicknesses were variable due to extensive rafting and refreezing of the rafted layers. The largest blocks observed were about 1 m thick, whereas the undisturbed ice growth was computed to be 75 cm at the time the ridge formed (based on accumulated freezing-degree days).

Smaller pile-ups that appear to have resulted from the early-season storm of November 4 and 5 (Section 4.1) were observed at five sites. The ice thickness at the time of this easterly event is estimated at a modest 25 cm. Storm-induced ice movement created a low-relief rubble field off the east side of Northstar Production Island and a 2- to 3-m high pile-up at the shoreline on the north side (Plate 13). The ice did not encroach onto the above-water portion of the slope protection system, however.

Plate 13. Low-Relief Rubble Field on East Side of Northstar Production Island

The other four ice pile-ups that resulted from the November 4-5 storm occurred on natural barrier islands. To the west of Northstar, extensive ice piles were observed on the seaward shorelines of Long and Cottle Islands. The pile-up height on Long Island was estimated at 2 to 3 m, while that on Cottle was estimated at 3 to 5 m (Plate 14). The pile-up on Long Island extended 1 to 2 nm (2 to 4 km) along the shoreline, but there was no apparent encroachment onto the island itself. It was impossible to determine if any encroachment accompanied the Cottle Island pile-up, which extended about 0.15 nm (0.3 km) along the seaward shoreline.

To the east of Northstar, the same early-November storm produced a 2- to 3-m high by 0.3-nm (0.6-km) long pile-up on the seaward shoreline of the Stockton Islands, and a 1- to 2-m high by 0.15-nm (0.3-km) long pile-up on the western end of Flaxman Island. These characteristics are summarized in Table 3.

With the exception of the small pile-up on Flaxman Island, no such features were observed in the vicinity of the Sivulliq Development. Specifically, pile-ups were absent

Plate 14. Ice Pile-Up at Shoreline of Cottle Island.

from the barrier islands adjacent to Mary Sachs Entrance and inside Leffingwell Lagoon. Pile-ups also were absent from Mikkelsen Bay, including the shoreline and dock at the Badami Development.

The only ice pile up observed east of Flaxman Island was located on Arey Island, which lies to the west of Barter Island in eastern Camden Bay. During the Twin Otter flight on February 4, (Drawing CFC-800-01-001, Sheet 1), a 6- to 9-m high pile-up was noted on the north shore of the western portion of this barrier island. It is believed that the pile-up occurred in response to sustained 15-kt (8-m/s) west-northwesterly winds on December 10-12 following a 25-kt (13-m/s) easterly storm on December 5.

Ice Movement during Storms: Prior to Shell’s deployment of five Iridium telemetry buoys on January 11 (Section 3.4), average ice movement rates were estimated by measuring the displacements of ice features that could be identified in successive satellite images. Once the buoys became operational, both average and peak ice movement rates in the vicinity of the Sivulliq Development were derived directly from the hourly position data. The ice movement data obtained from the` buoys during storm events in January and February 2010 are presented in Table 4, while highlights pertaining to the prolonged westerly storm in early February are discussed below.

TABLE 4

ICE MOVEMENT DURING STORM EVENTS IN JANUARY AND FEBRUARY 2010

Dates	Storm Direction	Sustained Wind Speed (kt)	Ice Movement			
			Buoy No.	Distance (nm)	Avg. Rate (kt)	Peak Rate (kt)
January 14-16	westerly	15-20	1-5	16	0.33	not computed
January 28-29	easterly	35-40	2-5	56	1.10	1.7
February 1-4	westerly	35-40	1	19	0.80	not computed
			2	53	0.55	1.9
			3	49	0.51	1.6
			4	49	0.51	1.6
			5	19	0.56	1.9
February 4-5	westerly	20-25	1	0	0	0
			2	2.9	not computed	not computed
			3	3.6	not computed	not computed
			4	3.6	not computed	not computed
			5	2.3	not computed	not computed

At the beginning of February, Buoy 1 (located closest to shore) was trapped in the shear zone 4 nm (7 km) north of Flaxman Island. At the outset of the westerly storm on February 2-5, however, the grounded shear zone between Cross and Flaxman Islands floated free and moved offshore into the open lead. Buoy 1 moved quickly to the east-southeast, covering a distance of 19 nm (35 km) in 24 hours before becoming stationary again in northwestern Camden Bay.

Prior to the early-February storm, Buoy 2 was located in the pack ice about 40 nm (74 km) northwest of Flaxman Island and 5 nm (9 km) north of Cross Island. Over the four-day period between February 1 and 4, it moved 53 nm (98 km) to the east southeast and wound up only 3 nm (6 km) northwest of Buoy 1 in Camden Bay. However, whereas Buoy 1 became stationary, Buoy 2 continued to move with the pack ice – a finding that suggests as of February 4, the new landfast ice boundary lay between the two buoys.

Buoys 3 and 4 were located about 10 nm (19 km) north of Buoy 2 on February 1 (*i.e.*, 40 nm northwest of Flaxman Island and 15 nm (28 km) north of Cross Island). Each moved 49 nm (91 km) to the east southeast over the next four days, paralleling the barrier island chain before approaching their original deployment locations near the Sivulliq Development. Meanwhile, Buoy 5, located 70 nm (130 km) northwest of Flaxman Island and 25 nm (46 km) north northwest of Northstar Production Island, moved only 19 nm (35 km) to the east southeast over the first 34 hours of the storm. It then remained stationary for the remainder of the four-day period. This discrepancy in distance traveled between Buoys 2-4 and Buoy 5 indicates the occurrence of significant divergence in the pack ice. Additional evidence of divergence was provided by numerous north-south leads observed north of the barrier islands and east of Prudhoe Bay during the February 4 reconnaissance flight.

When the displacements cited above are converted into rates, Buoy 1 is found to have averaged 0.8 kt (0.4 m/s) during the 24-hr period in which it remained adrift. This relatively high speed probably reflects a lack of confinement in the lead in which it was moving. The remaining four buoys each averaged about 0.5 kt (0.3 m/s) over longer periods, with peak rates ranging from 1.6 to 1.9 kt (0.8 to 1.0 m/s) during the period of maximum storm intensity on the evening of February 2. The peak rates represent 4 to 5% of the sustained wind speed. Similar relationships were measured during storm events in the 1980s.

First-Year Ice Growth: As indicated in Section 3.5, the field crew measured the thickness of undisturbed first-year ice in Mikkelsen Bay during the helicopter reconnaissance flight on February 6. A key objective was to provide a basis for verifying or refining the ice thicknesses computed from accumulated freezing-degree days using the relationship of Bilello (1960). The measured fast ice thickness was 109 cm (excluding a 15-cm snow cover). This value agrees closely with the predicted ice thickness of 114 cm that was derived for the same date using accumulated freezing-degree days at Deadhorse Airport (Table 1).

4.3 Midwinter Ice Conditions

A prolonged period of northeasterly winds that began on February 10 continued for two weeks until February 25. From February 19 through 21, the winds intensified into a full-blown storm with sustained speeds of 30 to 35 kt (15 to 18 m/s). Light to moderate southwesterlies that began on February 25 prevailed until mid-March, followed by moderate to strong easterlies from March 16 to 25.

The multi-year ice in the pack near 73°N moved a total of 280 (519 km) to the west during February and March, based on RADARSAT mosaics compiled by the Canadian Ice Service at bi-weekly intervals. The average drift rate was 5 nm (9 km) per day, but the movement rate was much faster over shorter time periods. During the last two weeks in

February (which included the strong northeasterly storm), the ice moved 155 nm (287 km) to the west at an average rate of 11 nm (20 km) per day (almost 0.5 kt or 0.3 m/s). To estimate the ice movement that occurred during the three-day storm of February 19-21, it was assumed that long-term average of 5 nm (9 km) per day prevailed during the other 11 days. The inferred displacement of 100 nm (185 km) for the 3-day storm represents a rate of 1.4 kt (0.7 m/s), which is consistent with the range of 1.2 to 1.5 kt (0.6 to 0.8 m/s) obtained using 4 to 5% of the 30-kt (15-m/s) wind speed.

The westerly ice movement in February and March caused the multi-year ice to leave the Beaufort Sea and enter the northern Chukchi. The continuous easterly winds during the first two weeks in February enlarged the shear zone in the western Beaufort as the pack ice ground its way along the edge of the landfast ice. East of Prudhoe Bay, a more competent shear zone was established to the north of the barrier islands between Cross and Flaxman Islands and then across Camden Bay. The location of the landfast ice edge is evident in an AVHRR image obtained during southwesterly winds on March 11. The image shows a 2-nm (4-km) wide lead forming 10 nm (19 km) north of the Stockton and Maguire Islands and 15 nm (28 km) north of the Camden Bay shoreline.

The seaward progression of the landfast ice edge in February and March is confirmed by shear or ice movement lines observed on the RADARSAT mosaics and by the tracks of the five Shell buoys. Buoy 1 remained stationary after February 4, indicating that it was already trapped in the shear zone in Camden Bay. Buoys 2, 3, and 4 moved 9, 12, and 15 nm (28 km) to the west, respectively, between February 6 and 20 before becoming stationary at the peak of the storm. Buoy 5 moved 16 nm (30 km) to the west northwest. The fact that Buoys 4 and 5 ceased operation on February 20 suggests that they were impacted by ice deformation (shear formation or ridge-building) during the storm.

Based on 4,830 accumulated freezing-degree days at Deadhorse Airport at the end of February and 6,129 days at the end of March, the respective first-year ice thicknesses are computed to be 130 and 147 cm.

5. CHUKCHI SEA

5.1 Freeze-Up Development

5.1.1 Late Summer

In the Chukchi, like the Beaufort (Section 4.1.1), break-up occurred early and the ice edge retreated quickly in 2009. Causative factors included strong easterly winds (*i.e.*, offshore winds) in June and July, above-normal air temperatures in July and August, and the arrival of relatively warm water from the Mackenzie River due to the prevalence of easterly winds in early July. The north-setting Alaska Coastal Current (Figure 1), which transports warm water of low salinity through the Bering Strait, also contributed to the rapid melting and ice-edge retreat that occurred during the summer months.

By mid-July, open water prevailed in the Chukchi Sea south of 71°N. Less than a month later, on August 10, the Chukchi was ice-free and open water stretched north to the vicinity of 75° N.

Strong easterly winds along with warm air temperatures kept the Chukchi ice-free in September and early October. In mid-September, the ice edge was located near 77°N (about 350 nm or 650 km north of Point Barrow) – a location that was well north of the median value derived for the period from 1979 through 2000 (Figure 15). By early October, the ice edge had advanced to the vicinity of 73°N (roughly 100 nm or 185 km north of Point Barrow) due to the formation of new ice and the rotation of the Beaufort Gyre. However, the entire Chukchi Sea remained ice free.

5.1.2 Freeze-Up and Early Winter

Initiation of Freeze-Up: A combination of unseasonably warm temperatures and persistent easterly winds delayed new ice growth in the nearshore Chukchi Sea until the beginning of the third week in October. Even then, the new ice was restricted to Kasegaluk Lagoon between Point Lay and Icy Cape, and Peard Bay near Point Franklin. Open water prevailed at the coast around Barrow and Wainwright until early November.

November Ice Conditions: A RADARSAT image acquired on November 9, 2009 indicates that ice was present at only two locations in the Chukchi Sea: (1) a 20-nm (37-km) wide band of new ice along the coast between Icy Cape and Point Lay and (2) a band of old (multi-year) pack ice at a concentration of 4 to 5 tenths moving southwest from the Beaufort into the Chukchi. The band of pack ice extended 45 nm (83 km) due west of Barrow, where a multi-year floe with a diameter of 3.5 nm (6.5 km) was evident on the RADARSAT image. The new ice in the embayment north of Peard Bay and east of Point Franklin was in the process of being removed by a 15-kt (8 m/s) southeasterly wind when the image was obtained.

By November 16, new, unstable ice had formed from the shore out to a distance of 110 nm (204 km) west of Barrow, 60 nm (111 km) west of Wainwright, and 40 nm (74 km) off the coast between Icy Cape and Point Lay. Open water prevailed west of 162°W from 70.5°N to73°N, and west of 164°W from 69.5°N to 70.5°N. A RADARSAT image acquired on November 16 revealed the presence of polynyas offshore of Point Belcher and north of Point Barrow.

During the week of November 9-16, four very large, conglomerate multi-year floes (with diameters ranging from 2 to 4 nm or 4 to 7 km) became entrapped in the fast ice 3 to 5 nm (6 to 9 km) offshore of Skull Cliff near the 60-ft isobath. The grounding probably occurred in response to a 25-kt (13-m/s) easterly storm on November 11-12 followed by moderate northerly winds on November 14. The floes remained stationary for the rest of the month. Apart from this protected area and other sheltered bays and lagoons, landfast ice had not developed along the Chukchi shoreline by mid-November.

Wind speeds were less than 10 kt (5 m/s) during the week of November 16-23, with the direction shifting from east to southwest. The light winds, coupled with cold air temperatures, caused the ice edge to advance rapidly to the south and west. On November 23, it was located at 70.5°N. New ice was forming as far as 60 nm (111 km) offshore of Icy Cape and Point Lay, with many leads oriented perpendicular to the shoreline. As the ice moved to the northeast, an active shear line developed off the coast between Icy Cape and Barrow. The line extended from 3 nm (6 km) north of Icy Cape to the vicinity of Point Belcher, then paralleled the coast from Point Belcher to a shoal area north of Point Franklin at a distance of 1 to 2 nm (2 to 4 km) from shore, and finally turned east northeast toward the shoreline south of Barrow.

A comparison of RADARSAT images acquired on November 16 and 23 indicates a divergence in the ice movement occurring to the north and south of Point Barrow. To the north, a multi-year floe with a diameter of 1.8 nm (3.3 km, shown as a yellow cross in Figure 21) moved 14 nm (26 km) to the west (2 nm or 4 km/day). This upwind motion reflected the dominance of the Beaufort Gyre, which typically transports the ice to the west at a nominal rate of 5 to 6 nm (9 to 11 km) per day. In contrast, a multi-year floe with a diameter of 2.7 nm (5.0 km, shown as a red diamond in Figure 21) moved 25 nm (46 km) to the east northeast in the region between Barrow and Point Franklin. Because this region is

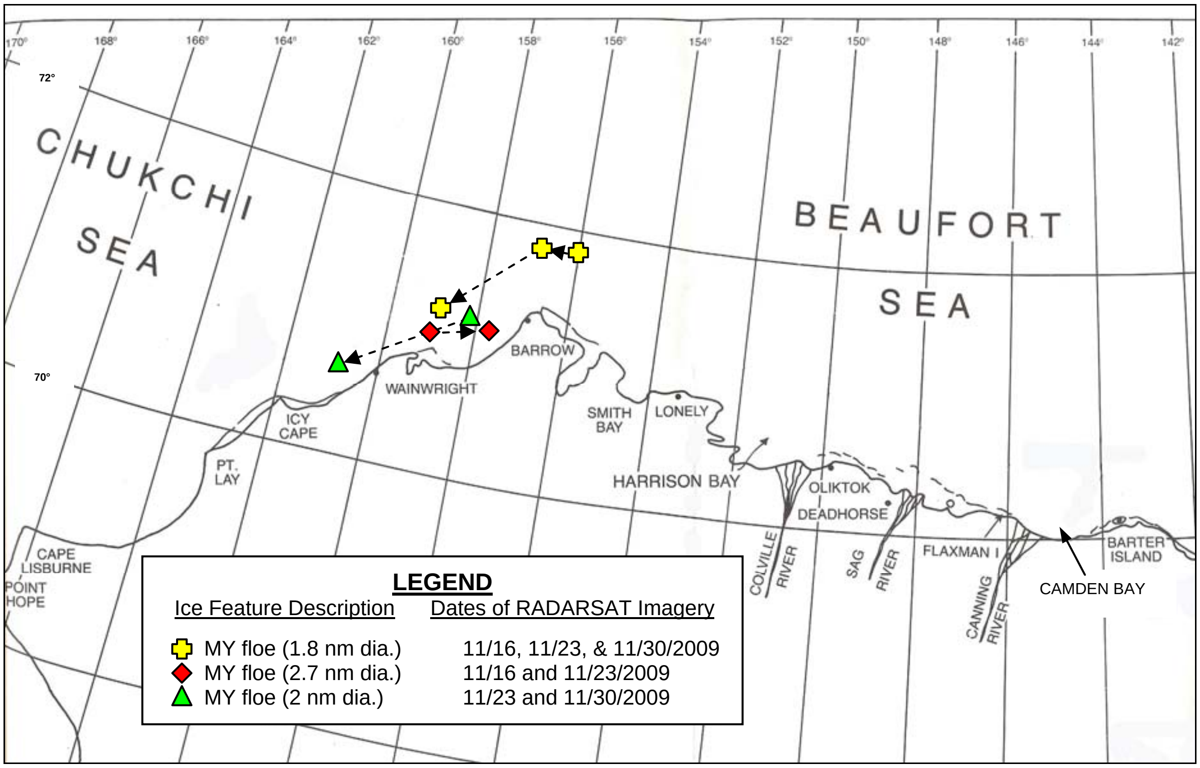


Figure 21. Ice Movement in Chukchi Sea during November 2009

sheltered from the influence of the Beaufort Gyre, the motion was driven by the light southwesterly winds and the Alaska Coastal Current (Figure 1).

A northeasterly storm on November 26 and 27 produced significant ice movement in the nearshore pack ice. Two multi-year floes (shown as the yellow cross and green triangle in Figure 21) moved 50 to 60 nm (93 to 111 km) to the southwest. In addition, the ice movement line first noted in the RADARSAT image of November 23 had become more prominent by November 30. Numerous leads were evident 20 to 30 nm (37 to 56 km) west of Wainwright and Icy Cape in the November 30 image. The leads were 2 nm (4 km) wide and oriented in a southeast-northwest direction.

By the end of November the Chukchi Sea was entirely ice-covered north of Cape Lisburne and east of 169°W, based on an AVHRR image and an NIC ice chart. Scattered multi-year floes were present in a 10-nm (19-km) wide band located just seaward of the ice movement line as far south as Wainwright. Multi-year ice with a concentration of 2 to 3 tenths also was present in 30-nm (56-km) diameter patch centered about 85 nm (158 km) northwest of Barrow.

December Ice Conditions: Light and extremely variable winds predominated during the first half of December. On December 5 and 6, however, this calm period was interrupted by a brief storm with sustained wind speeds of 25 kt (13 m/s) . During the course of the storm, the winds veered from east through south to west. The multi-year ice in the northwestern Chukchi Sea (north of 72°N and west of 164°W) wallowed around but did not experience significant displacement. However, the multi-year pack ice arriving from the western Beaufort Sea continued its steady-state march into the Chukchi. As shown in Figure 22, a multi-year floe with a diameter of 3 nm (6 km) moved about 50 nm (93 km) to the southwest during the 17-day period between RADARSAT images acquired on November 30 and December 17 (3 nm or 6 km per day).

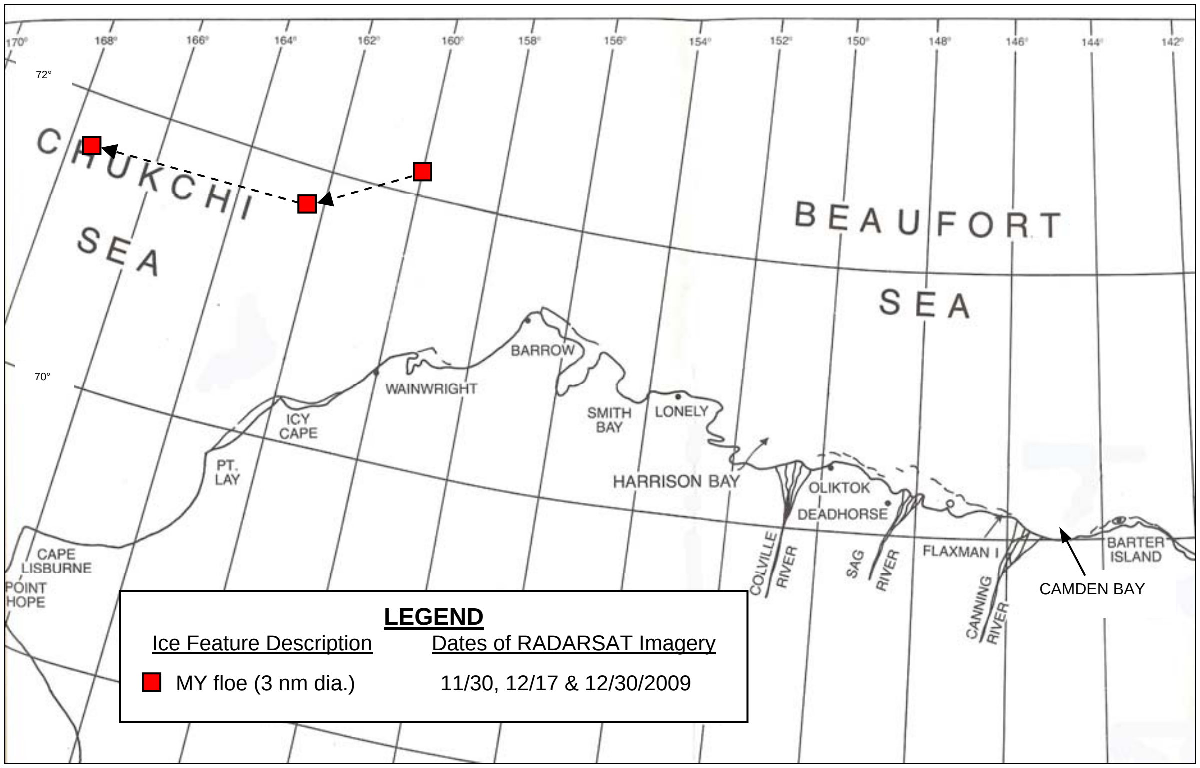


Figure 22. Ice movement in Chukchi Sea during December 2009.

The combination of easterly winds at the beginning of the December 5 storm and air temperatures as high as 30°F (-1°C) removed virtually all of the temporary fast ice along the Chukchi coast, including the ice in the protected embayments east of Point Franklin and Icy Cape and the multi-year floes that had been locked in the temporary fast ice near Skull Cliff since mid-November.

Moderate northwesterly winds on December 10-14 helped re-establish the temporary fast ice along the coast. These same winds may have created the ice pile-ups on the shoreline between Wainwright and Icy Cape that were observed during the aerial reconnaissance flight on February 9. Additional details regarding these pile-ups will be presented in the next section.

Major leads or polynyas were absent from the Chukchi Sea ice cover in mid-December, but many smaller leads, cracks, and fissures were evident in a sequence of AVHRR infrared images acquired from December 12 through 18. The only old shear line that remained in mid-December was located 0.5 to 1 nm (0.9 to 2 km) off the coast between Point Belcher and Point Franklin, based on the RADARSAT image acquired on December 17 (Figure 10). A new ice movement line extended from Point Franklin to the east northeast toward the coast south of Barrow. The southern limit of multi-year ice was located near 72°N to the east of the 160° meridian, and near 71.5°N to the west of the 162° meridian.

The last two weeks of December were dominated by strong easterly winds that drove the entire ice cover to the west. The multi-year floe shown as a red square in Figure 22 moved 95 nm (176 km) to the west, to the vicinity of the 168° meridian, between December 17 and December 30 (7 nm or 13 km per day). A wide coastal flaw lead developed off the Chukchi coast. Based on a RADARSAT image acquired on December 30 and an AVHRR image on December 31, the lead was 15 nm (28 km) wide at Barrow, 30 nm (56 km) wide at Wainwright, and 55 nm (102 km) wide between Icy Cape and Pt. Lay.

As the lead started to develop and widen in late December, the 25-kt (13 m/s) easterly winds removed the last of the fast ice along the shore at Wainwright. This sequence of events was evident in two AVHRR images acquired over a 9-hour period on December 26. The only fast ice remaining outside the coastal barrier islands at the end of December was located in the semi-protected embayments east of Icy Cape and Point Franklin. Each of the two fast ice remnants was 5 nm (9 km) wide at its widest point, narrowing to between 0.5 and 1 nm (0.9 and 2 km) near the coast 15 nm (28 km) south of Wainwright and along Skull Cliff 25 nm (46 km) south of Barrow.

January Ice Conditions: A 25-kt (13-m/s) westerly storm on January 1 and 2, 2010, produced a reduction in ice concentration along the edge of the pack, with individual floes moving into the refreezing flaw lead. Based on RADARSAT imagery acquired on December 30 and January 10, the two multi-year floes shown in Figure 23 as a red square and a blue circle moved 22 and 31 nm (41 and 57 km) to the southeast.

Two wind events occurred during the 17-day period between RADARSAT images acquired on January 10 (Figure 11) and January 27 (Figure 12): (1) a sustained 15-kt (8-m/s)

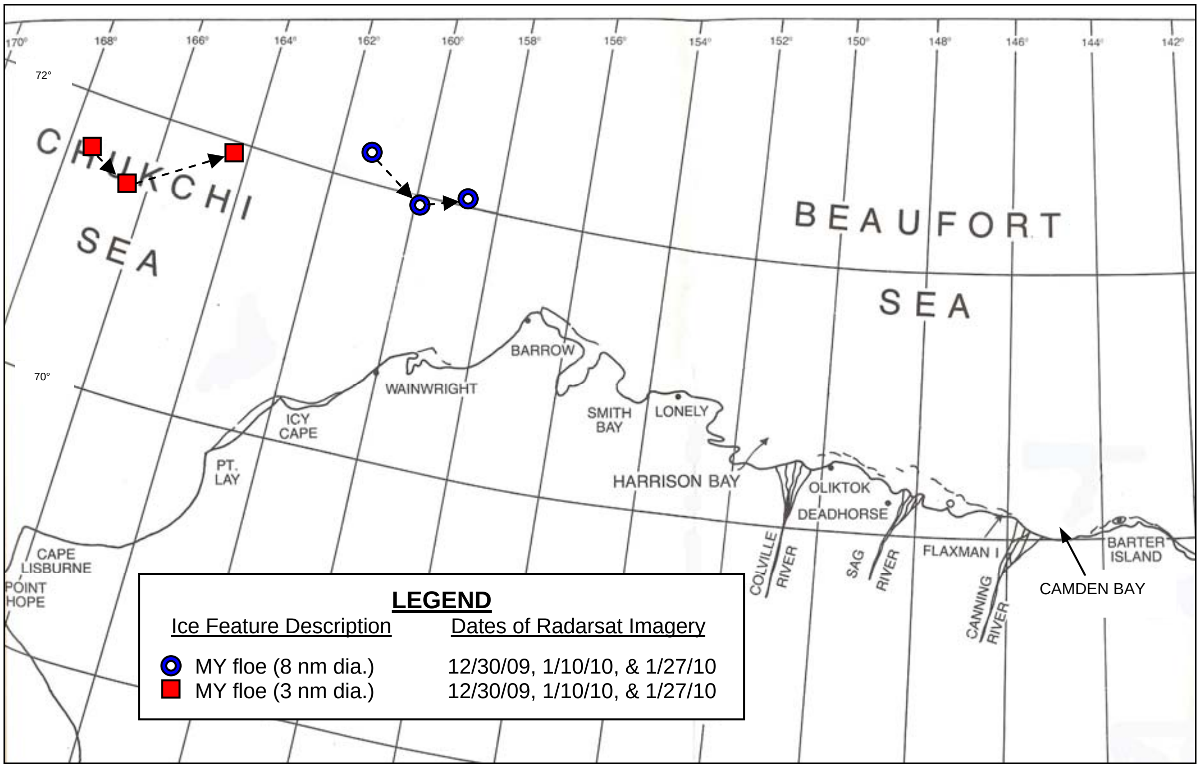


Figure 23. Ice Movement in Chukchi Sea during January 2010.

westerly from January 13 through 18 and (2) a short 30-kt (15-m/s) southeasterly on January 22. The net result was a northeasterly displacement of about 50 nm (93 km) for the multi-year floe shown as a red square in Figure 23, and 20 nm (37 km) for the multi-year floe shown as a blue circle.

Notwithstanding the displacement of individual floes, the concentration of multi-year ice in the Chukchi Sea remained relatively constant through January 27. The coverage ranged from 1 tenth or less between 71 and 72°N to the west of 164°W, to 5 tenths north of a line between 71.5°N, 156°W and 72°N, 160°W. Concentrations of 1 to 3 tenths prevailed in the northwestern portion of the Chukchi, in the area bounded by 72°-73°N and 164°-169°W.

On three occasions in January, the winds were light to moderate in intensity and variable in direction. During each of these periods, which ranged from three to seven days, the ice tended to wallow or move in small loops.

The fast ice zone continued to be almost nonexistent in January. It was located within 1 nm (2 km) of the shoreline off Barrow and Wainwright. A grounded shear line or permanent ice motion boundary between the fast ice and moving pack ice was conspicuously absent in the January 10 and 27 RADARSAT images, indicating that the fast ice edge was transient and unstable.

In the semi-protected embayment east of Point Franklin, the texture, hue, and relative locations of the ice features evident in the satellite imagery indicate that the somewhat wider accumulation of fast ice noted in December remained motionless through January 27. In the embayment east of Icy Cape, the second area in which a wider accumulation of fast ice was detected in December, the fast ice remained stable from December 30 to January 10. By the time of the next RADARSAT image was acquired on January 27, most of the fast ice had been replaced by a refreezing polynya. Judging from an AVHRR image acquired on January 24, the fast ice was dislodged by the 30-kt (15 m/s) southeasterly winds that occurred on January 22.

The coastal flaw lead that first appeared in late December and closed in early January reopened on January 10 in response to light-to-moderate easterly winds. The RADARSAT image acquired on this date (Figure 11) shows the initial opening of the lead running almost parallel to the coastline (northeast-southwest), while numerous smaller leads (up to 1.5 nm or 2.8 km wide) and fissures were present farther offshore trending perpendicular to the coast (northwest-southeast). Based on AVHRR imagery obtained on January 11 and 13, the flaw lead attained a width of 15 nm (28 km) between Point Lay and Icy Cape and 10 nm (19 km) off Wainwright before narrowing by about 50% in response to mild westerly winds on January 13. The lead subsequently closed and refroze, but was opened again by southeasterly winds on January 22-23 before closing on January 25-26 in response to northwesterly winds. When the RADARSAT image shown in Figure 12 was acquired on January 27, the lead was no longer present.

Late January and Early February Ice Conditions: The ice conditions changed significantly in late January and early February, prior to the aerial reconnaissance missions in the Chukchi Sea conducted on February 8 and 9. Based on daily AVHRR images acquired from January 28 through February 1, a 25-kt (13 m/s) northeasterly storm on January 28 and 29 stripped the ice away from the shoreline at Barrow and along the coast from Point Franklin to Wainwright, re-opened the coastal flaw lead to a width of 5 to 10 nm (9 to 19 km), and created many smaller leads and fissures in the ice cover north of the 71° parallel. The reduced confinement permitted a substantial concentration of multi-year ice to enter the Chukchi Sea from the western Beaufort and to move quickly to the southwest, both along and offshore of the coastal flaw lead.

By January 31, the flaw lead had attained its maximum width of 20 nm (37 km). The wind then shifted abruptly from northeast to northwest and freshened to sustained speeds of

20 to 30 kt (10 to 15 m/s) on February 2 and 3. During the next three days, the wind gradually backed to the west and then southwest while the speed diminished to between 10 and 20 kt (5 and 10 m/s). This sequence of events drove scattered multi-year floes to within several miles of the Chukchi Sea coast and created a concentrated band of such floes that extended more than 50 nm (93 km) southwest from the vicinity of Barrow. Additional information regarding the band, which was dubbed “Multi-Year Alley” during the aerial reconnaissance missions, will be provided in the next section. On February 5 and 6, immediately prior to the flights, unusually cold and relatively calm conditions caused most of the leads and fissures in the ice to refreeze.

5.2 Field Observations

As indicated above and discussed at greater length in Section 3.5, fixed-wing aerial reconnaissance missions were undertaken in the north Chukchi Sea on February 8 and 9. Chukchi Sea Flight No. 1 (Flight “C1” on Drawing CFC-800-01-001, Sheet 3) 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. Chukchi Sea Flight No. 2 (Flight “C2” on Drawing CFC-800-01-001, Sheet 3) was used to observe nearshore ice conditions between Barrow and Point Lay.

Landfast Ice and Shear Zone Development: The ice in Peard Bay and Kasegaluk Lagoon became stable shortly after the initiation of freeze-up, leaving the sheet ice generally featureless and flat. On the other hand, the early-season ice off the unprotected west-facing beaches at Barrow and Wainwright, as well as the more exposed locations in the vicinity of Point Belcher and between Icy Cape and Point Lay, never had the opportunity to stabilize before it was dislodged by a continuous series of easterly winds that caused freeze-up to start anew. At times, westerly winds drove the young ice into the shoreline and created pile-ups or offshore rubble. In those instances when the rubble became grounded, it provided stability to the refreezing nearshore ice.

A series of grounded shear lines and large rubble piles within 1 nm (2 km) of Barrow allowed the narrow landfast ice foot (less than 0.1 nm or 200 m wide) to resist displacement (Plate 15). In contrast, most of the landfast ice to the south of Barrow was observed to be unstable and temporary. A representative example is provided in Plate 16, which shows light ridging and scattered rubble fields without any grounded shear zone off the coast north of Point Lay.

When the coastal reconnaissance flight was made on February 9, the active ice movement line that defined the edge of the fast ice zone was located 1 to 2 nm (2 to 4 km)

Plate 15. Grounded Shear Zone 1 nm off Barrow.

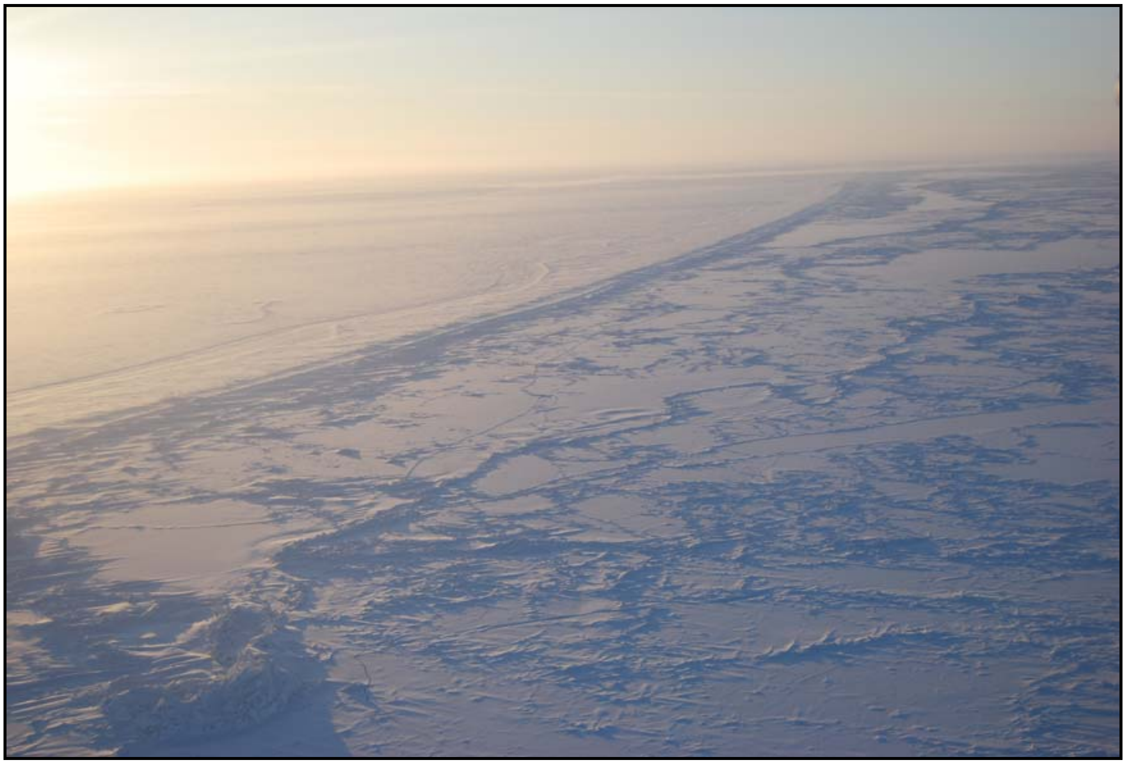


Plate 16. Temporary Fast Ice off Coast North of Point Lay.

off Barrow, 0.5 to 1 nm (0.9 to 2 km) off Point Belcher, 2 to 3 nm (4 to 6 km) off Wainwright, and 3 to 4 nm (6 to 7 km) off Point Lay. As indicated above, most of the coast lacked a shear zone with sufficient grounding to stabilize the offshore boundary of the fast ice. As a result, the ice remained susceptible to removal during the next easterly storm.

Ice Conditions in Shell Prospects: A key objective of the aerial reconnaissance trip on February 8 was to document the ice conditions in Shell's Hanna Shoal, Crackerjack, West, and Burger Prospects. The Hanna Shoal Prospects were found to contain 2 to 3 tenths multi-year ice, large first-year ice pans, moderate first-year ridging (Plate 17), and areas of active lead formation. While traveling west southwest from this region to the Crackerjack Prospects, noteworthy features included multi-year ice at a concentration of one tenth, recently-formed compression ridges at the perimeters of vast first-year ice pans, and finger rafting at refrozen leads indicative of significant ice movement.

Plate 17. Large First-Year Ice Pan and Moderate Ridging in Hanna Shoal Prospects.

Although a large multi-year floe with a diameter of 3 to 4 nm (6 to 7 km) was observed at the northeast corner of the Crackerjack Prospects (Plate 18), the multi-year ice concentration in this region was limited to around 5%. Occasional multi-year ridge

Plate 18. Large Multi-Year Floe with Embedded Ridge in Crackerjack Prospects.

fragments attained maximum heights of 6 m. As in the case of the Hanna Shoal Prospects, the presence of open leads, refrozen leads, and new compression ridging indicated that the region had experienced significant ice motion in the recent past. These features were intermingled with older first-year floes and rubble fields with a maximum freeboard of 6 m (Plate 19). The first-year ridge frequency varied from 2-3 ridges/nm (1-2 ridges/km) in areas where the ice had maintained its integrity to 10-20 ridges/nm (5 to 11 ridges/km) in areas where the ice had experienced rubbling and differential motion.

The West Prospects were dominated by refrozen leads and vast, nearly-featureless first-year pans (Plate 20). A 6-m high zone of shear rubble that extended more than 0.5 nm (0.9 km) in length was noted, along with occasional 5- to 8-m high first-year compression ridges. The ridge frequency ranged from as little as 1 to as many as 10 per nm (0.5 to 5/km), while the ice block thickness was estimated at 0.5 to 1 m. Like Crackerjack, the multi-year ice concentration was estimated at 5%, with several floes measuring 0.5 nm (0.9 km) in diameter.

While flying east from the Crackerjack to the Burger Prospects, no multi-year ice was sighted east of 165°W. The ice cover was unremarkable, consisting almost entirely of

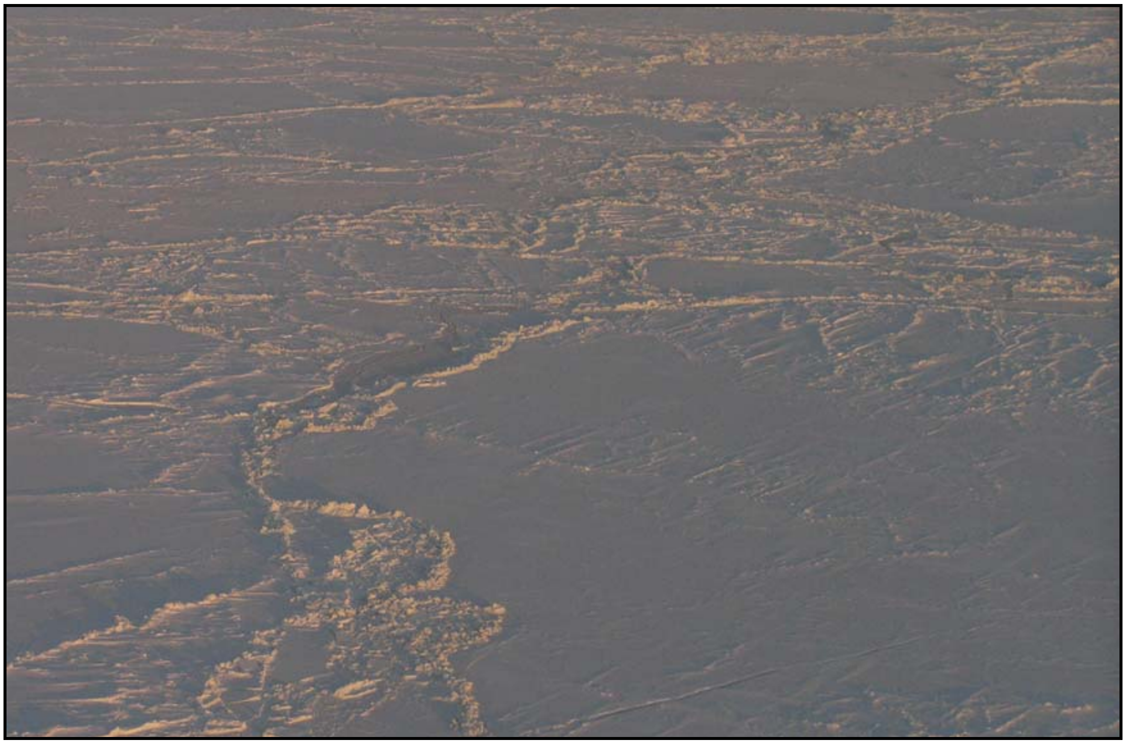


Plate 19. First-Year Ridging and Rubble Field in Crackerjack Prospects.

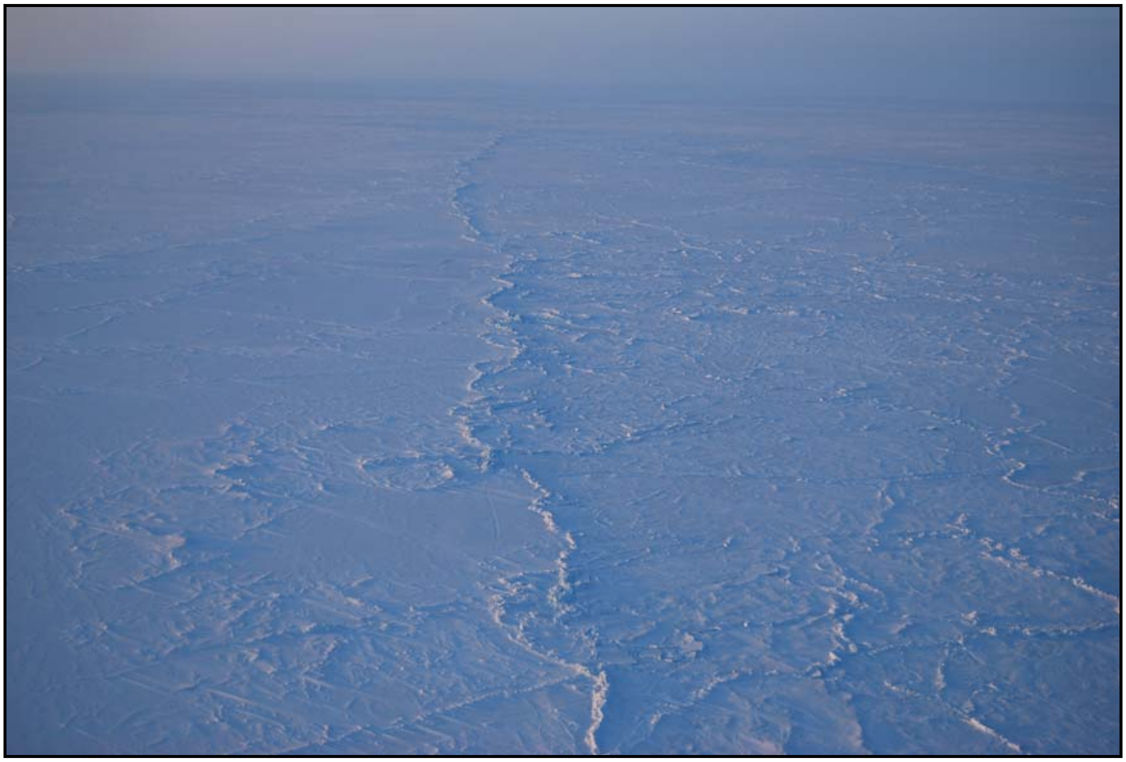


Plate 20. Vast, First-Year Ice Pans and Compression Ridge in West Prospects.

refrozen leads and large first-year floes. Ridging and rubbling were far less prevalent than in the Hanna Shoal and Crackerjack Prospects. As shown in Plate 21, these ice characteristics prevailed in the Burger Prospects as well.

Plate 21. Refrozen Lead and First-Year Ice Floes in Burger Prospects.

To the east of Burger, multi-year ice was conspicuously absent for a distance of 75 nm (139 km). It reappeared abruptly near the 159° meridian, however, and continued for more than 40 nm (74 km) to the vicinity of Barrow at concentrations of 1 to 2 tenths.

Katie's Floeberg Formation on Hanna Shoal: A secondary objective of the aerial reconnaissance trip on February 8 was to assess the development of Katie's Floeberg, a grounded rubble pile that forms each winter on Hanna Shoal (not to be confused with Shell's Hanna Shoal Prospects; see Drawing CFC-800-01-001, Sheet 3). The site is located 100 nm (185 km) northwest of Barrow, at 72°N by 162°W. The shallowest water depth on the shoal is 12 m, while the surrounding water 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 May 1980, the feature was found to consist of a vast oval of grounded first-year and multi-year ice rubble measuring 5 nm (9 km) long and 2.5 nm (4.6 km) wide (Vaudrey and Thomas, 1981). Its maximum elevation was 18 m above the ice surface. The long axis was oriented northeast-southwest, and the shallowest water depth was located at the southwest tip.

When the Hanna Shoal area was searched on February 8, 2010, numerous ridges and rubble fields indicative of significant ice movement were observed (Plate 22) but a vast grounded rubble pile was not. The absence of a grounded feature is consistent with the observations of Vaudrey and Thomas (1981), who found that in the 1970's, Katie's Floeberg frequently did not start forming until February. In fact, a significant grounded rubble pile did develop on Hanna Shoal later in February 2010 during a two-week period of intense easterly winds. Additional information regarding the growth of the Floeberg will be provided in the discussion of midwinter ice conditions that follows in Section 5.3.

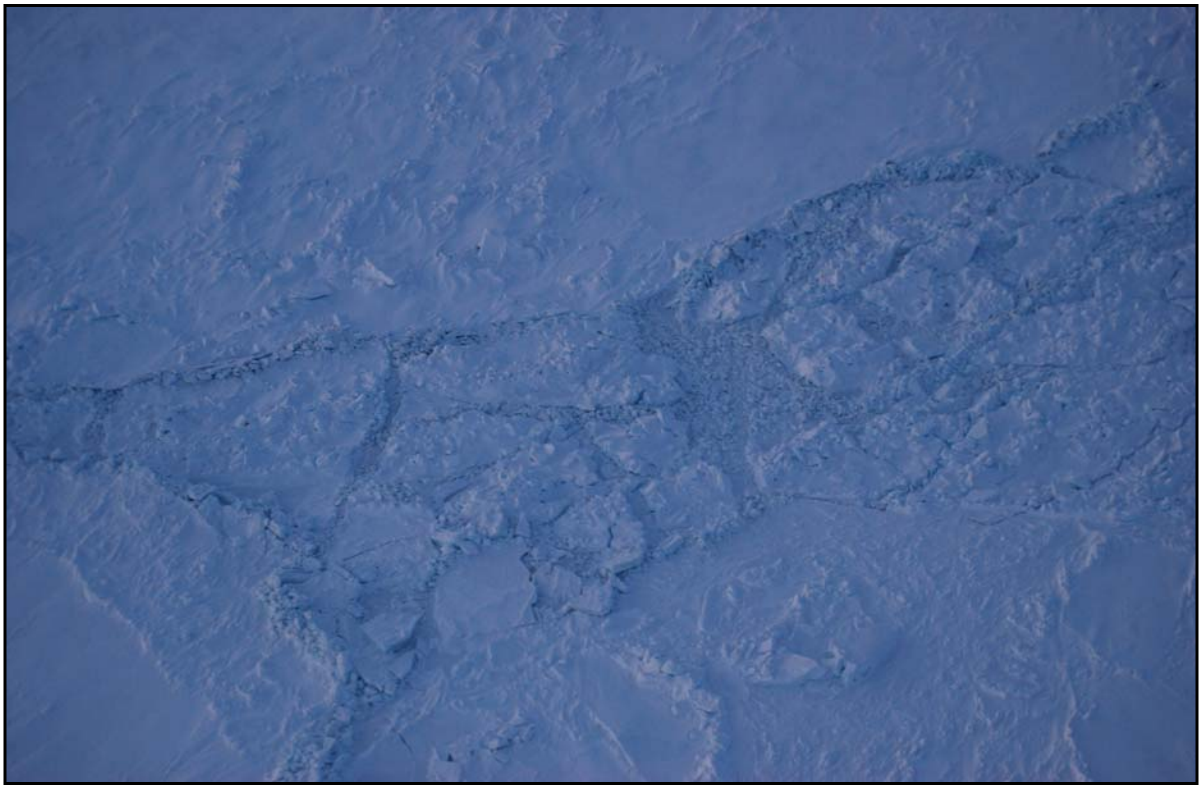


Plate 22. Rubble Field at the Site of Katie's Floeberg on February 8, 2010.

<u>Multi-Year Ice</u>: Multi-year ice entered the northern Chukchi Sea from the western Beaufort over an extended period that began in mid-November 2009 and continued through the time of the aerial reconnaissance missions in early February 2010. As indicated in

Section 5.1, the invading floes split into two separate branches that persisted throughout the winter.

The northern or offshore branch of multi-year ice remained above the 71.5° parallel in the eastern and central Chukchi Sea before dipping south into the Crackerjack (Plate 18) and West Prospects to the west of the 165° meridian. Most of the multi-year floes in the Crackerjack Prospects were expansive, with diameters of 1 to 3 nm (2 to 6 km), while those in the West Prospects were smaller, typically measuring 600 m across. All of the floes observed in both prospects contained embedded ridges with heights of 2 to 3 m. Occasional multi-year ridge fragments with attached shoulders were present as well, measuring 100 to 150 m in length and rising as much as 5 to 7 m above sea level. The concentration of multi-year ice in the northern branch tended to decrease from east to west, with values of 2 to 3 tenths observed in the Hanna Shoal Prospects and 5% in the Crackerjack and West Prospects. The heaviest concentrations (4 to 5 tenths) were located between 72°N and 73°N, judging from RADARSAT imagery acquired on January 27 and a CIS RADARSAT mosaic developed on February 1.

The southern or coastal branch of the multi-year ice consisted of a 20- to 30-nm (37- to 56-km) wide tongue that extended southwest from Barrow to the vicinity of the 70° parallel ("Multi-Year Alley" per Section 5.1). Multi-year ice concentrations ranged from 7 tenths in the vicinity of Barrow to widely-scattered floes off Icy Cape, with intermediate values of 1 to 3 tenths off Point Franklin. The floe sizes in Multi-Year Alley were similar to those observed in the western Beaufort Sea, with typical diameters of 600 to 900 m and extremes of 1 to 2 nm (2 to 4 km; Plates 23 and 24). Most of the floes contained large embedded ridges with maximum elevations of 3 to 5 m above the ice surface, indicating that they might be second-year rather than true multi-year features. Because Multi-Year Alley was located in the heavily-deformed nearshore region of the Chukchi Sea, most of the multi-year floes were surrounded by significant first-year ridging or rubble.

Ice Pile-Up and Rubble Pile Events: The most significant shoreline ice pile-up on the Chukchi Sea coast occurred on the west side of the spit at Icy Cape (Drawing CFC-800-01-001 Sheet 3). Based on an analysis of weekly RADARSAT imagery and Barrow weather conditions, it is likely that the pile-up resulted from northwesterly winds on December 10 through 14. The feature, composed of ice blocks 20 to 25 cm thick, extended approximately 150 m alongshore and attained a maximum height of 15 m (Plate 25). It encroached onto the frozen sand beach an estimated distance of 15 to 30 m.

As shown in Drawing CFC-800-01-001, Sheet 3, 18 other pile-ups/ride-ups were observed on the Chukchi Sea coast during the February 9 reconnaissance mission. All were

Plate 23. Typical Multi-year Floe Located 17 nm North of Point Franklin.

Plate 24. Vast Multi-year Floe Located 20 nm Northwest of Point Franklin.

Plate 25. 15-m High Ice Pile-Up on West Side of Icy Cape Spit.

composed of ice blocks 20 to 30 cm thick, and likely developed during the same mid-December period of northwesterly winds cited above. Fifteen of these features were judged to be pile-ups, with maximum heights of 4 to 6 m and negligible encroachment onto the beach. The other three, which were located in the immediate vicinity of Point Belcher, were predominantly ride-ups that encroached 5 to 6 m onto the beach. The most impressive ride-up stretched intermittently along the shoreline at Point Belcher for a distance of 9 nm (17 km). All of the other pile-ups and ride-ups were much shorter, with alongshore lengths less than 0.5 nm (0.9 km).

Fourteen of the eighteen coastal pile-ups/ride-ups noted during the aerial reconnaissance mission were concentrated between Point Franklin and Icy Cape. The shoreline surrounding Point Belcher is particularly susceptible to such events, in that the narrow strip of landfast ice tends to remain unstable during the early freeze-up period. When this strip is dislodged, the beach is exposed to ice approaching from the west and northwest.

In addition to the coastal pile-ups and ride-ups described above, numerous floating rubble fields were observed in the nearshore region during the February 9 reconnaissance flight. The most dramatic rubble pile, however, was grounded 4 nm (7 km) off Icy Cape in a water depth of 6 m (estimated from NOAA Chart No. 16005; National Ocean Service, 1976). As shown in Plate 26, the rubble pile was oval-shaped, several thousand meters long, and nearly 20 m high at several locations. The major axis was oriented west-southwest to east-northeast. Block thicknesses were estimated at 30 to 45 cm. The pile may have been formed during a storm sequence that began with intense easterly winds on December 20 and ended with a westerly storm on January 1.

Plate 26. Grounded Ice Pile-Up 4 nm North of Icy Cape.

Table 5 presents a summary of the nineteen ice pile-ups and ride-ups noted on the Chukchi Sea coast, with the data consolidated by region. The massive grounded rubble pile off Icy Cape also is included.

<u>Nearshore vs. Offshore Ice Conditions</u>: The Chukchi Sea ice cover tends to remain mobile due to the predominance of easterly winds, which push the ice away from the coast

TABLE 5

ICE PILE-UPAND RIDE-UP EVENTS OCCURRING IN 2009-10 ON OR ADJACENT TO THE CHUKCHI SEA COAST

Region	*Location*	*No. of Pile-Ups/ Ride-Ups*	*Pile-Up Ht./ Ride-Up Dist. (m)*	*Ice Block Thickness (cm)*	*Storm Dates*	*Storm Direction*
Barrow - Pt. Franklin	shoreline	2/0	5-10/na	25-30	12/10-14	westerly
Pt. Franklin - Pt. Belcher	shoreline	0/3	na/5-6	25-30	12/10-14	westerly
Pt. Belcher - Icy Cape	shoreline	10/0	5-6/na	25-30	12/10-14	westerly
Icy Cape - Utukok R.	shoreline	2/0	12-15/na	20-25	12/10-14	westerly
Utukok R. - Pt. Lay	shoreline	2/0	4-5/na	20-25	12/10-14	westerly
Icy Cape	offshore	1[1]/0	15-20/na	30-45	12/21&1/1	east/west

Note:

[1] Grounded rubble pile located 4 nm (7 km) offshore

and re-open the flaw lead to widths as great as 30 to 40 nm (56 to 74 km). Because the lead reduces confinement, it leaves the ice susceptible to rapid and large movements, especially when the wind shifts to the west. The nearly-continuous ice motion produces extensive first-year ridging and rafting, which occur at the boundaries of the floating ice pans as they collide with or rotate about one another. A significant contrast exists between the heavily-deformed ice in the nearshore pack (within 30 to 50 nm or 56 to 93 km of the coast) and the relatively undeformed ice in the offshore pack.

The distinct difference between the nearshore and offshore ice cover was clearly evident during the aerial reconnaissance missions in early February. As shown in Plates 27and 28, the nearshore zone contained a hodgepodge of compression ridges and rubble fields formed when the westerly winds preceding the field investigation closed the rapidly-refrozen coastal flaw lead and drove the thicker ice from offshore toward the coast. The resulting nearshore ice cover consisted primarily of heavily deformed ice, with small undisturbed first-year pans between ridges.

By contrast, the ice cover in the offshore zone (more than about 50 (93 km) from the coast) was smoother, with fewer and smaller ridges. The first-year pans were vast, with

Plate 27. Nearshore Ice Conditions 12 nm Northwest of Point Franklin.

Plate 28. Ice Conditions 10 nm Offshore between Icy Cape and Point Lay.

diameters as large as several nautical miles. These characteristics indicate that the differential motion between ice floes was far less than that in the nearshore zone. More specifically, the ice pans and floes appeared to have moved together in a manner analogous to a quasi-rigid body – an observation that applies to the ice in the Burger, Crackerjack, and West Prospects (Plates 29 and 30).

First-Year Ice Growth. If computed using accumulated freezing-degree days at Barrow airport (Table 1), the first-year ice growth in the Chukchi would be similar to but slightly less than that computed for the Beaufort Sea. In the nearshore zone, however, very little first-year ice remained intact from the initiation of freeze-up through the time of the reconnaissance flight (other than in protected bays and lagoons and within a short distance of the coast). Instead, repeated opening of the coastal flaw lead resulted in continuous ice production throughout the winter. In addition, the mobility of the ice cover produced a significant quantity of rafted ice. In consequence, the first-year ice thickness in the nearshore zone varied significantly from site to site on a given day, and from day to day at a given site.

5.3 Midwinter Ice Conditions

A long-duration northeasterly wind commenced on February 10 (immediately after the field investigation ended) and continued for two weeks. From February 19 through 21, the steady northeasterlies became a full-blown storm with wind speeds of 30 to 35 kt (15 to 18 m/s). The storm was followed by light-to-moderate northeasterlies through March 6, moderate northwesterlies from March 8 through 12, light and variable winds from March 13 through 16, and moderate southeasterly winds on March 17 and 18. Moderate to strong northeasterly winds prevailed for the rest of March, except for a brief 20-kt (10-m/s) northerly on March 26.

As reported in Section 4.3, the multi-year ice north of the 73° parallel moved almost 300 nm (556 km) to the west during February and March. When the coastal flaw lead re-appeared in mid-February, the northeasterly winds drove the multi-year ice quickly to the southwest along the lead. A heavy concentration of multi-year ice estimated at 5 tenths moved south to 71°N, with an occasional tongue of significant multi-year ice as far south as 70°N, according to ice charts from the CIS and the NIC and based on RADARSAT mosaics compiled by the CIS at bi-weekly intervals.

A series of five AVHRR images acquired from February 23 through 26 shows a large multi-year floe with a diameter of 8 nm (15 km) moving from 13 nm (24 km) north of Point Barrow to 47 nm (87 km) west of Barrow, a total distance of 60 nm (111 km). The average

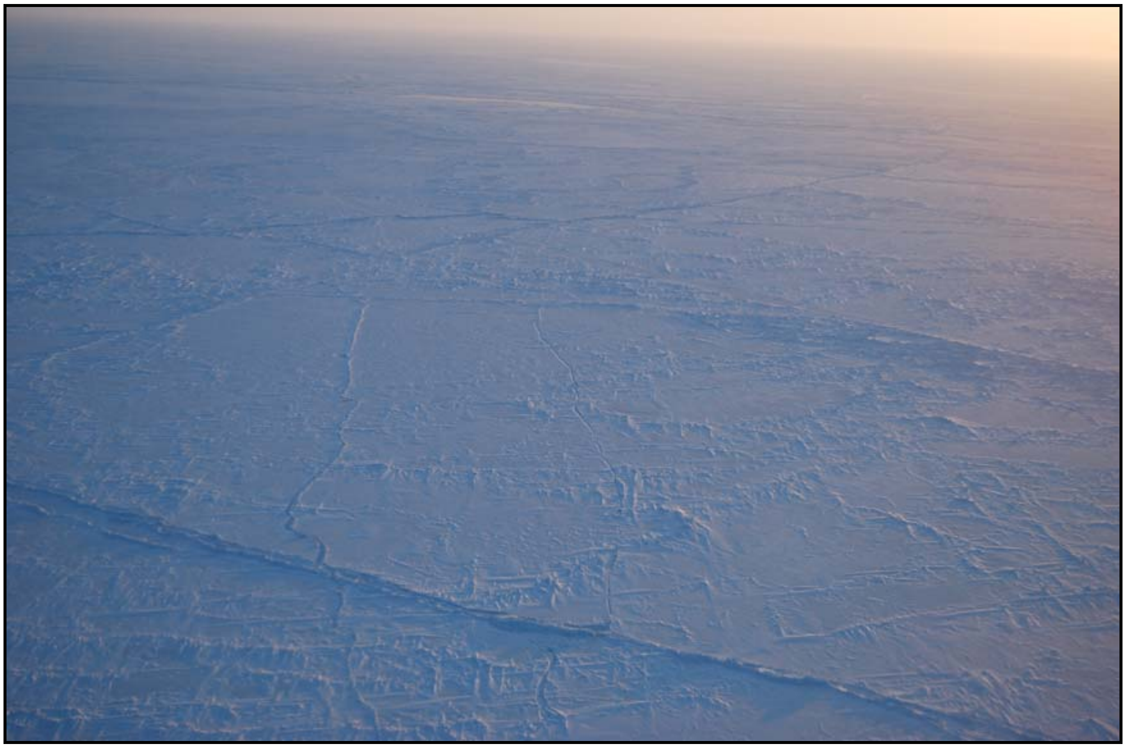


Plate 29. Vast, Flat First-Year Floes in Crackerjack Prospects.

Plate 30. Vast First-Year Pan with Finger Rafting in Burger Prospects.

ice movement rate was 0.8 kt (0.4 m/s), but the rate increased to 1.1 kt (0.6 m/s) over an 8-hour period on February 23. Although the northeasterly wind was moderate, at 10 to 15 kt (5 to 8 m/s), the floe was able to move freely as it left the Beaufort Sea and moved southwest into the open water of the coastal flaw lead.

By the end of February, the long-duration northeasterly had opened up the coastal flaw lead to a width of 15 nm (28 km) west of Barrow, 70 nm (130 km) west-northwest of Wainwright, and 50 nm (93 km) west of Point Lay.

Another series of seven daily AVHRR images acquired from March 22 through 28 shows a vast ice feature breaking away from the pack in the western Beaufort Sea and moving 54 nm (100 km) to the west southwest as the coastal flaw lead re-opens in response to a prolonged northeasterly. The average drift rate over the six-day period was 9 nm/day (17 km/day) or 0.4 kt (0.2 m/s). On March 25, the lead was 12 nm (22 km) wide at Barrow, 20 nm (37 km) wide at Wainwright, and 35 nm (65 km) wide at Point Lay.

As discussed in the previous section, there was no evidence of a grounded rubble pile at the historical location of Katie’s Floeberg (72°N, 162°W) during the reconnaissance flight on February 8. Subsequent AVHRR images indicate that the rubble pile developed between February 12 and 22, probably in response to the steady easterly winds that freshened to 30 kt (15 m/s) from February 19 to 21. Katie’s Floeberg remained prominent in the AVHRR imagery throughout March. In fact, on March 26, a 15-nm (28-km) open-water wake was evident on the lee side of the feature following a week-long period of 20-kt (10 m/s) northeasterly winds.

When Katie’s Floeberg was photographed during a Shell reconnaissance flight on March 30 (Spring, 2010), it was approximately 5 nm (9 km) long by 1 nm (2 km) wide and composed primarily of multi-year ice rubble (Plate 31). It was surrounded by a series of shear zones (Plate 32).

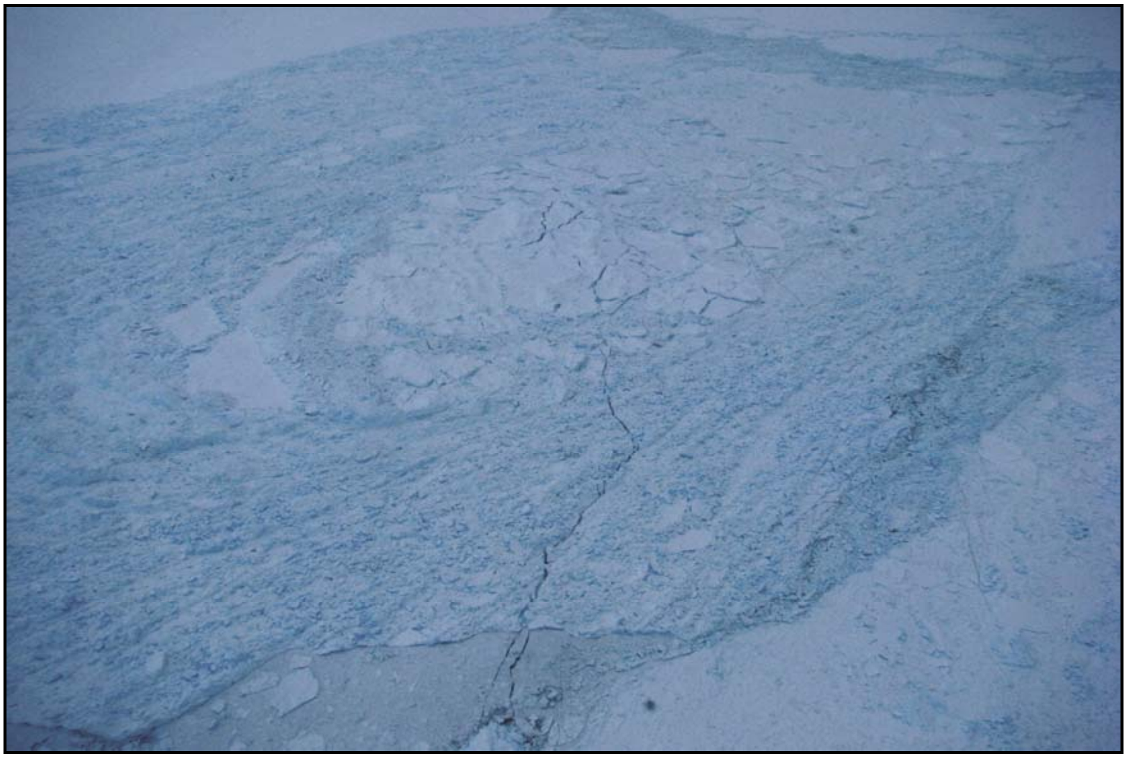


Plate 31. Katie's Floeberg on March 30, 2010 (Spring, 2010).

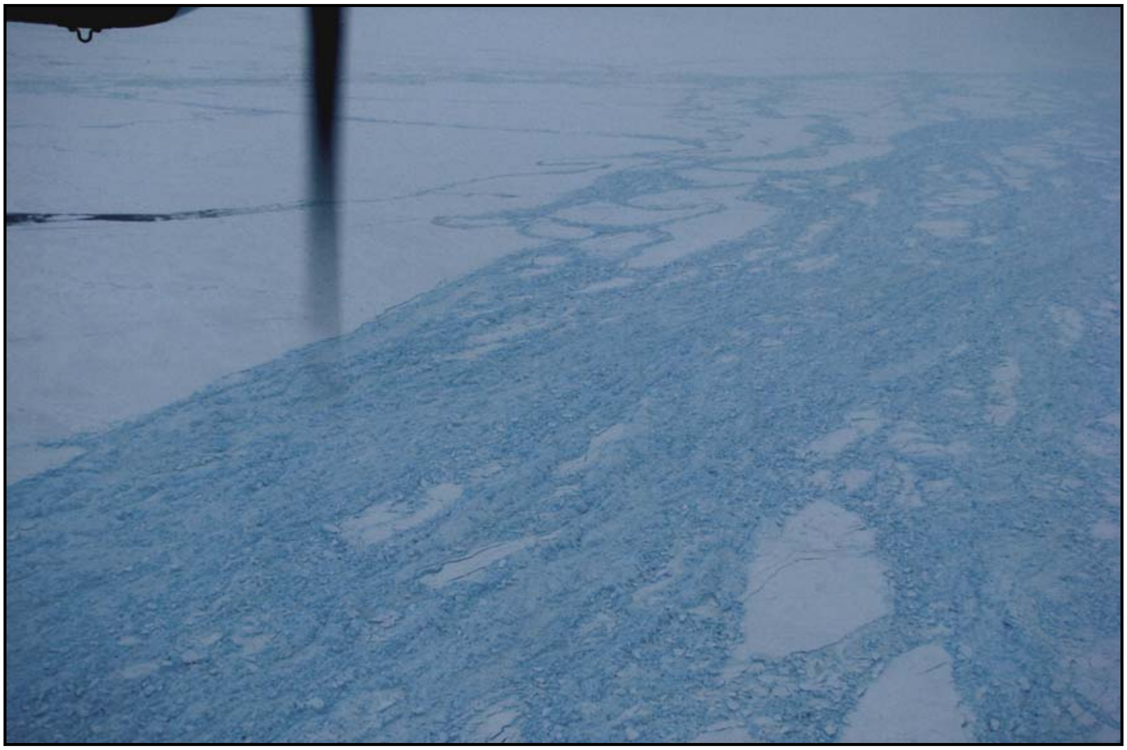


Plate 32. Shear Zones around Katie's Floeberg on March 30, 2010 (Spring, 2010).

6. COMPARISON OF FREEZE-UP IN THE 1980'S AND 2009

The primary objective of this section is to compare the ice conditions observed during the 2009-10 freeze-up and early winter seasons with those documented during the annual freeze-up studies conducted from 1980 through 1985.

The normal progression of the ice season in the Alaskan Beaufort Sea and northern Chukchi Sea begins with freeze-up in the fall and ends with open water in the summer. The ice cover typically persists for about nine months, but the duration can vary by as much as plus or minus one month depending on the location and year. Two of the most important parameters affecting the ice season in general and the freeze-up process in particular are the air temperature and wind characteristics. In consequence, air temperature data acquired at Barrow over the last 40 years were analyzed to investigate a perceived trend toward warmer conditions. Yearly storm counts were compiled from the Barrow wind data to determine if "storminess" has increased. Such an increase may make the sea ice more dynamic during freeze-up and midwinter.

Following the analysis of air temperatures and winds, seasonal variations are evaluated and compared for the following phenomena: the timing of freeze-up, multi-year ice invasions, ice growth and movement, shear zone development, landfast ice stability, and the formation, refreezing and reopening of leads. Based on comparisons between 2009-10 and the 1980's, trends in ice behavior are identified.

6.1 Air Temperatures

As discussed in Section 3.1, freezing-degree days were computed as the difference between the freezing point of seawater (29°F; -2°C) and the mean daily air temperature, and then accumulated by month. "Negative" freezing-degree days (>29°F; -2°C) were subtracted from the total.

Table 6 presents the cumulative freezing-degree days (FDD's) at Barrow computed monthly for each winter season from September 1970 through May 2010 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 20-year period from 1990-91 through 2009-10. The column on the right-hand side of Table 1 displays the rank of each winter over the entire 40-year database, with the highest ranking (No. 1) assigned to the warmest winter (fewest accumulated freezing-degree

Table 6. Annual Cumulative Freezing-Degree Days (<29°F) at Barrow, 1970-71 through 2009-10

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	40-yr Rank
1970-71	129	1013	2009	3224	4727	6270	7734	8738	9098	39
1971-72	7	466	1351	2603	4004	5402	6912	7914	8252	35
1972-73	30	275	1103	2092	3410	4591	6135	7086	7393	20
1973-74	9	307	958	2024	3255	4859	6381	7488	7826	30
1974-75	18	725	1823	3546	5263	6453	7579	8584	8891	38
1975-76	155	893	2102	3677	5162	6667	8043	8976	9342	40
1976-77	12	486	1281	2689	3836	5107	6694	7756	8066	33
1977-78	0	272	1309	2444	3529	4738	5963	6785	7176	13
1978-79	17	696	1404	2734	3710	5082	6496	7393	7684	24
1979-80	0	310	895	2166	3496	4636	5891	6875	7247	15
1980-81	117	566	1586	2969	3896	5148	6384	7221	7389	19
1981-82	105	564	1452	2602	3845	4839	6122	7022	7407	21
1982-83	32	723	1896	3084	4578	5821	7136	7925	8300	36
1983-84	153	835	1666	2546	3919	5717	7128	8316	8700	37
1984-85	0	366	1479	2799	3925	5218	6517	7585	7780	27
1985-86	60	635	1424	2537	3901	4959	6407	7508	7784	28
1986-87	13	404	1262	2359	3661	5033	6295	7306	7579	23
1987-88	51	240	1272	2447	3672	4931	6224	7052	7337	17
1988-89	49	886	2164	3351	4994	5546	6637	7327	7687	25
1989-90	0	363	1611	2805	4417	5878	7131	7776	7903	32
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**	**40-yr Rank**
1990-91	25	400	1477	2863	4177	5499	6947	7718	7748	26
1991-92	27	384	1494	2883	4358	5788	6972	7818	8076	34
1992-93	154	666	1569	2737	4027	5150	6439	7114	7300	16
1993-94	27	210	924	2074	3252	4313	5776	6649	6972	9
1994-95	60	699	1827	3222	4493	5758	7175	7817	7898	31
1995-96	0	326	1076	2343	3463	4776	5849	6719	6830	8
1996-97	87	816	1431	2469	3911	5120	6425	7184	7473	22
1997-98	5	293	830	2089	3441	4661	5644	6178	6339	2
1998-99	0	132	1023	2275	3681	4860	6243	7179	7375	18
1999-00	18	371	1251	2657	3979	5263	6493	7337	7792	29
2000-01	31	392	1251	2300	3510	4388	5764	6584	7137	12
2001-02	39	638	1507	2654	4070	5371	6315	7127	7273	14
2002-03	0	175	849	1811	3028	4269	5483	6104	6329	1
2003-04	0	167	945	2061	3210	4703	6063	6897	7065	11
2004-05	9	243	1045	2205	3341	4501	5636	6436	6648	7
2005-06	8	237	1143	2156	3421	4475	5930	6908	7059	10
2006-07	0	102	790	1769	3160	4258	5615	6232	6599	4
2007-08	0	170	616	1525	2922	4387	5792	6428	6648	6
2008-09	3	195	933	1809	3109	4103	5492	6297	6438	3
2009-10	6	125	981	1988	3391	4479	5687	6312	6608	5
Average	**25**	**337**	**1148**	**2295**	**3597**	**4806**	**6087**	**6852**	**7080**	
Std. Dev.	**38**	**212**	**316**	**437**	**461**	**519**	**516**	**548**	**532**	

days at the end of May) and the lowest ranking (No. 40) to the coldest (most accumulated freezing-degree days at the end of May).

The data in Table 6 show that each of the last eight winters, from 2002-03 through 2009-10, ranks among the eleven warmest in the past 40 years. Conversely, each winter during the 1970s and 1980s was colder than the average winter in the 1990's and 2000's. Based on decadal averages, the annual accumulation of freezing-degree days declined by 4% from the 1970's to the 1980's, 5% from the 1980's to the 1990's, and 8% from 1990's to the 2000's. The total decline from the 1970s to the 2000s was 16%. This trend toward warmer winter seasons is clearly evident in Figure 24, which presents a plot of the annual cumulative freezing-degree days at Barrow against time for the last 40 years along with a linear trend line.

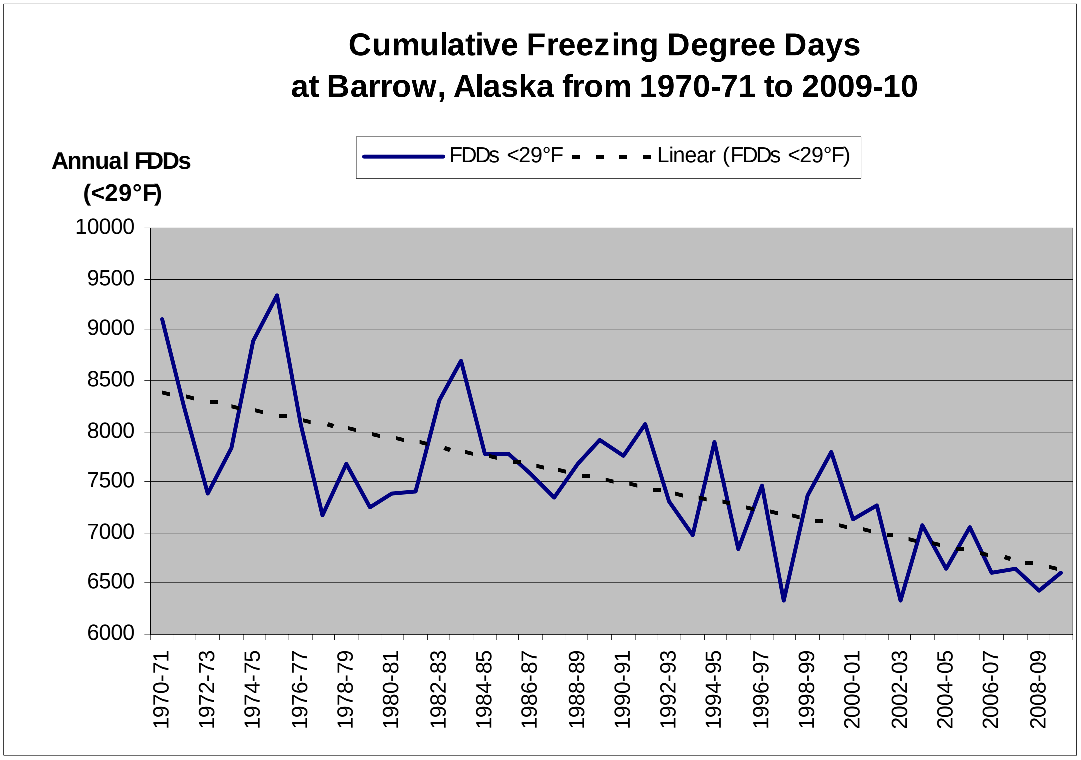


Figure 24. Annual Cumulative Freezing-Degree Days (<29°F) at Barrow, 1970-71 through 2009-10.

Melling and Riedel (2005) found a similar trend in the air temperatures at Tuktoyaktuk over the 30-year period from 1975 through 2004. They determined that the number of freezing-degree days decreased at a rate of 3.3% per decade, somewhat less than the 5% decadal rate computed for Barrow. The difference may be due to the warming influence of the flaw lead usually present offshore of the coast at Barrow during the winter.

Additional evidence of the dramatic increase in winter air temperatures can be seen in Figure 25, which displays the departure of the average monthly air temperature at Barrow in 2009-10 from the long-term average computed for the period 1971-2000. There is speculation that because warmer winters produce thinner sea ice, they may result in a more dynamic ice cover.

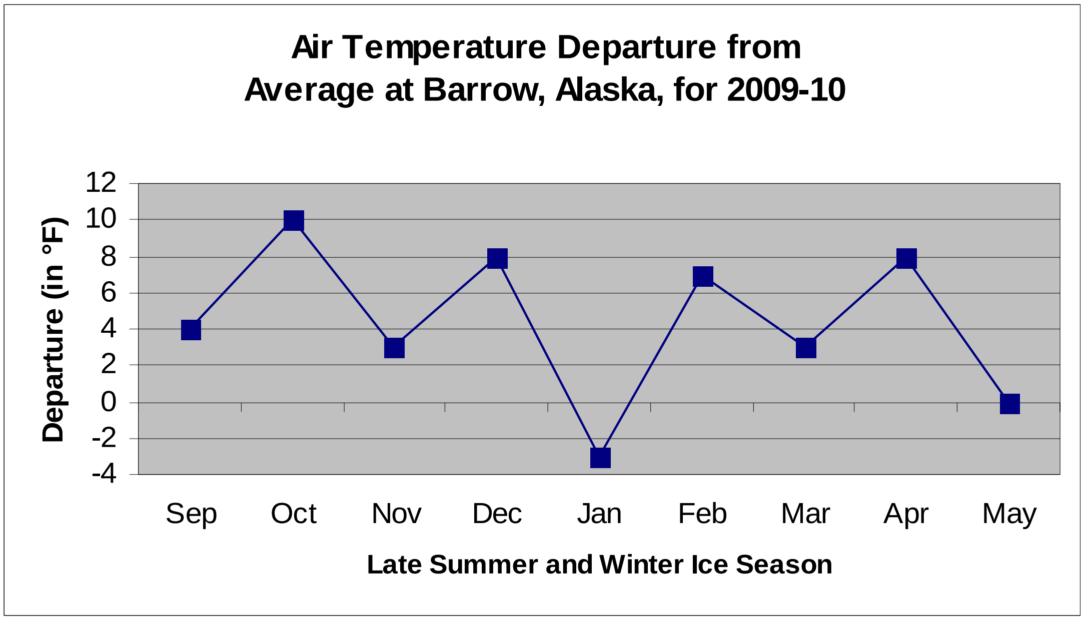


Figure 25. Monthly Air Temperature Departure from Average at Barrow for Late Summer and Winter Ice Season, 2009-10.

6.2 Winds

An indication of storm conditions in the 1980's 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 chosen from this database in order to compare the storminess that followed the 1980-85 freeze-up seasons with that which followed the 2009 freeze-up season.

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

A similar trend toward increased storm frequency was identified by Walsh and Eicken (2007), who tabulated the number of storm events during the open-water and freeze-up seasons at Barrow from 1950 through 2004. As illustrated in Figure 26, the annual storm count rose dramatically in the mid-1980's and early 1990's. The annual total increased from 10-15 storms per year in 1977-86 to 20-25 in 1990-2004. The criteria used to identify storms are unspecified, but the data nevertheless indicate that the jump in storm frequency which occurred during the 1980's and 1990's has been sustained since that time.

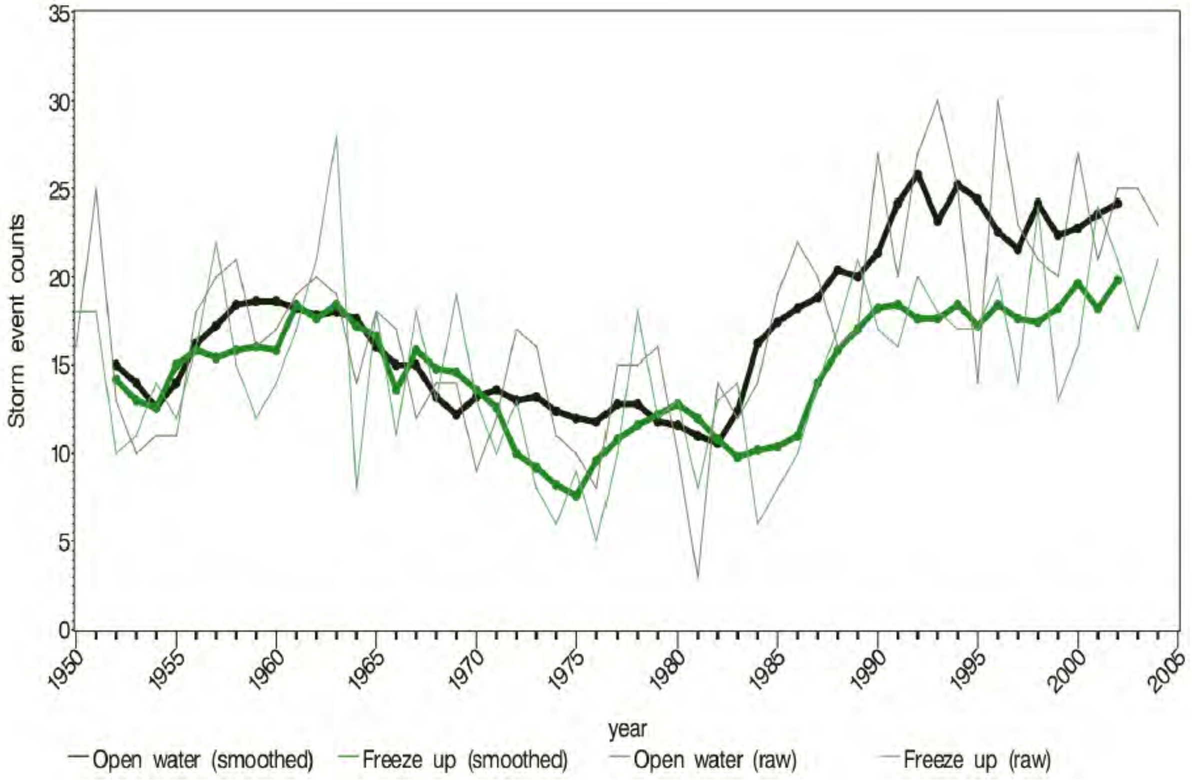


Figure 26. Yearly Storm Count at Barrow for Open-Water and Freeze-Up Seasons, 1950 -2004 (Walsh and Eicken, 2007).

6.3 Timing of Freeze-Up

During the last eight freeze-up seasons (2002-03 through 2009-10) every October has been extremely warm, averaging 8 to 12°F (4 to 7°C) above normal. This dramatic increase in air temperatures in October, combined with relatively warm Septembers over the same period, probably has been intensified by positive feedback from the absence of nearby ice and the presence of water warmed by longer exposure to solar radiation. The end result has been a delay in the onset of freeze-up in the nearshore waters of the Alaskan Beaufort and Chukchi Seas.

In 2009, the approximate date of freeze-up in the nearshore region of Beaufort Sea was October 22. This timing is comparable to the average date of October 20 computed for the five-year period from 2002 through 2006, but 18 days later than that determined from 11 years of on-site observations and satellite imagery acquired from 1980 through 1985 and 1987 through 1991 (Vaudrey, 1981; Vaudrey, 1982-86; Vaudrey, 1988-89; Vaudrey, 1990-92).

Even during the 1980's, when freeze-up in the Beaufort Sea typically occurred in early October, there were three years (1986, 1987, and 1989) when this event was delayed until mid-October due to a combination of warm air temperatures and an ice edge located well offshore. It thus appears that the timing of freeze-up at the end of warm summers in the 1980's was very similar to that in recent years that include 2009-10.

In recent years, freeze-up in the nearshore region of the Chukchi Sea has tended to occur during the first week in November (about two to three weeks later than in the Beaufort). Mahoney, *et al*. (2007), concluded that this timing is about one month later than in the mid-1970s. A significant delay in the occurrence of freeze-up also is implied by the research of Rodrigues (2009), who found that the length of the ice-free season off the coast between Point Barrow and Point Lay increased from approximately 30 days in the late 1970's to 125 days at present.

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

6.4 First-Year Ice Growth

Typically, ice growth during the winter is predicted using accumulated freezing-degree days. During eight of the nine months from September 2009 through May 2010, monthly air temperatures at Barrow were normal or above normal (Figure 25). The abnormally-warm temperatures produced 6,608 accumulated freezing-degree days for the 2009-10 ice season, a 16% decrease relative to the average of 7,893 for the six seasons when the original freeze-up studies were conducted (1980-81 through 1985-86; Table 6). Since seasonal ice grows roughly in proportion to the square root of accumulated freezing-degree days, the warmer winter temperatures account for a modest 15 cm decrease in the first-year sheet ice thickness at the end of the ice season (from 170 cm in the 1980's to 155 cm in 2009-10).

Brown and Cote (1992) used a physical one-dimensional heat transfer model of fast ice growth to investigate the interannual variability of the maximum ice thickness at four sites in the Canadian High Arctic between 1950 and 1989. The depth of the snow cover was found to be the most important factor, explaining 30% to 60% of the variance in the maximum landfast ice thickness due to its insulating effect on the ice. Density fluctuations in the snow cover were estimated to explain an additional 15% to 30% of the variance. In contrast, annual variations in air temperatures accounted for less than 4% of the variance in the maximum first-year ice thickness.

The predicted reduction in ice thickness attributable to warmer temperatures may be exacerbated by an increase in the depth of the snow cover. The average annual snowfall at Barrow has increased dramatically, from 58 cm in the early-to-mid 1980’s to 93 cm in the 1990’s (Figure 27). The total snowfall at Barrow during the nine-month ice season (September through May) in 2009-10 was 85 cm, significantly greater than the average value in the 1980’s.

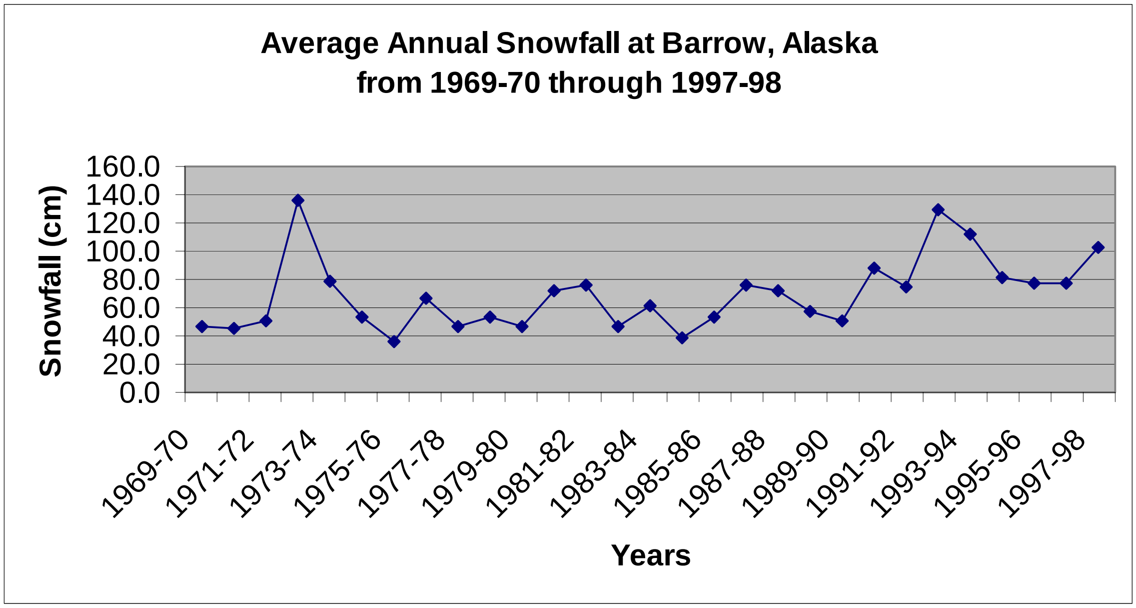


Figure 27. Average Annual Snowfall at Barrow.

In addition to reducing ice thickness, higher air temperatures keep leads open longer and retard new ice production. Furthermore, higher temperatures and heavier snowfall decrease the consolidation within ice ridges and rubble fields and reduce the overall ice strength.

<u>Trend</u>: Based on air temperature alone, the first-year ice thickness attained during an average winter has decreased by 8 to 10% relative to that attained in the early to mid-1980’s.

However, increased snowfall may be causing a greater reduction in the ice thickness. Other temperature-related factors, including reduced ice production in leads and decreased consolidation of ridges, probably exert a greater impact on ice behavior than a thinner ice cover.

6.5 Multi-Year Ice Invasions

The multi-year ice invasion that took place in the Alaskan Beaufort and Chukchi Seas during the winter of 2009-10 was the first such occurrence since 2001, when northerly and northeasterly winds drove a low-level concentration of multi-year floes into the nearshore region of the western Beaufort and the northern Chukchi during the initial stages of freeze-up. In contrast, multi-year ice was present in the nearshore zone of the Beaufort Sea at freeze-up during each of the six years when freeze-up studies were conducted in the 1980's (Vaudrey, 1981-86). Similarly, multi-year ice was present in the northern Chukchi Sea during each of the three freeze-up seasons from 1983-84 through 1985-86 (Vaudrey, 1984-86) and during the midwinter season of 1987 (Vaudrey, 1987).

A multi-year ice invasion in the Beaufort and Chukchi Seas can contain two types of "old" or "multi-year" ice: (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 lack of easterly winds or preponderance of northerly or westerly winds. Second-year floes are fragments of first-year rubble fields or remnants of the shear zone that develops throughout the winter in water depths of 10 to 30 m off the coast of the Beaufort Sea and Canadian archipelago. Such floes can be distinguished from pack floes by their more jagged appearance, with many embedded ridges, and by greater thicknesses (6 to 9 m for "nearshore floes" versus 3 to 5 m for pack floes).

During the 2000's, no first-year ice survived in the nearshore region of the Beaufort Sea to become second-year (nearshore) floes. By comparison, second-year ice was plentiful during the late summer and freeze-up seasons in the early to mid-1980s.

Beaufort Sea: During freeze-up in 1981 and 1982, the multi-year ice in the nearshore region was composed primarily of fragments of second-year ice that were grounded along the coast and the shoreline of the barrier islands. In 1983, most of the invading multi-year ice consisted of second-year floes that had survived a very cold summer and remained near the coast due to a lack of strong, sustained winds.

The multi-year ice invasion that occurred in 2009 resembled that of 1980 (Vaudrey, 1981) in terms of concentration, floe size, and surface appearance. Both invasions included a large number of massive floes with embedded ridges. A representative floe from each year is shown in Plates 33 and 34, as seen from the air during late March 1981 (Vaudrey, 1981a) and early February 2010.

Despite the similarities, there were two major differences between the two invasions: (1) the multi-year ice invasion in late September 1980 contained many second-year floes, suggesting that the multi-year pack floes observed in February 2010 may have been, in aggregate, thinner but more consolidated; (2) the multi-year ice invasion of 1980 came close to shore and eventually became trapped in the landfast ice, evenly distributed over the central Beaufort Sea in a band 10-20 nm (19-37 km) wide. The band was located 5 nm (9 km) off of Cape Halkett and 2 nm (4 km) off the barrier islands from Thetis Island to Flaxman Island. In contrast, the invasion of 2009-10 remained 10 to 20 nm (19 to 37 km) offshore and stayed in the pack ice, which migrated to the west under the influence of the Beaufort Gyre. By February 2010, the invading floes were confined to the region west of Prudhoe Bay.

Chukchi Sea: Multi-year ice coverage in the Chukchi Sea in 2009-10 was similar to that noted during the 1983-84, 1984-85, and 1985-86 freeze-up seasons and the midwinter invasion in 1987. Specifically, the concentrations were similar and all of the invasions attained a southerly limit between 70.5° and 71°N. However, the typical floe size appeared to be much larger in 2009-10.

Trend: Despite the significant invasion of multi-year pack ice that occurred in 2009-10, the probability of such an invasion occurring in any given year is less than in the 1980's. This conclusion follows in part from the location of the ice edge, which has retreated farther to the north in recent summers (Section 4.1), and in part from warmer air temperatures and increased storminess, which have reduced the likelihood that remnants of the Beaufort Sea shear zone will survive the summer melt season to become second-year floes. Nevertheless, as demonstrated in 2009-10, the possibility of multi-year ice encounters cannot be ruled out for developments in either the Beaufort or Chukchi Sea.

6.6 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 during the course of the winter. Factors that contribute to the recurring patterns include the seasonal cycle of weather and

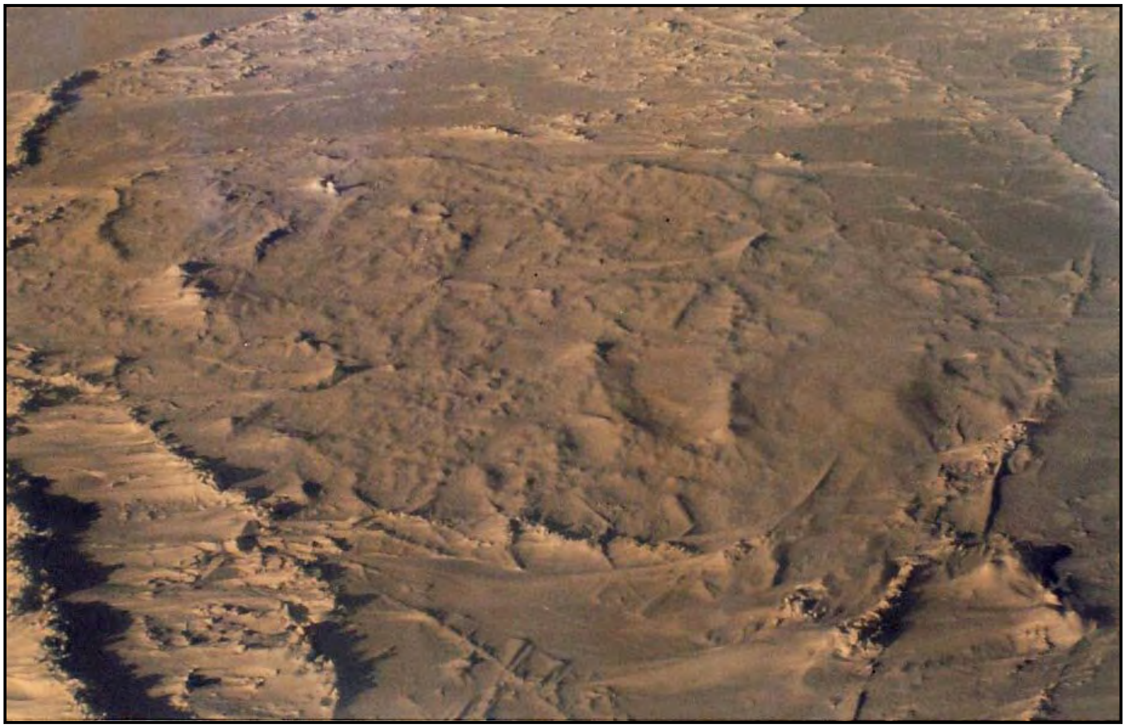


Plate 33. Multi-Year Floe Located 5 nm North of Narwhal Island, March 1981.

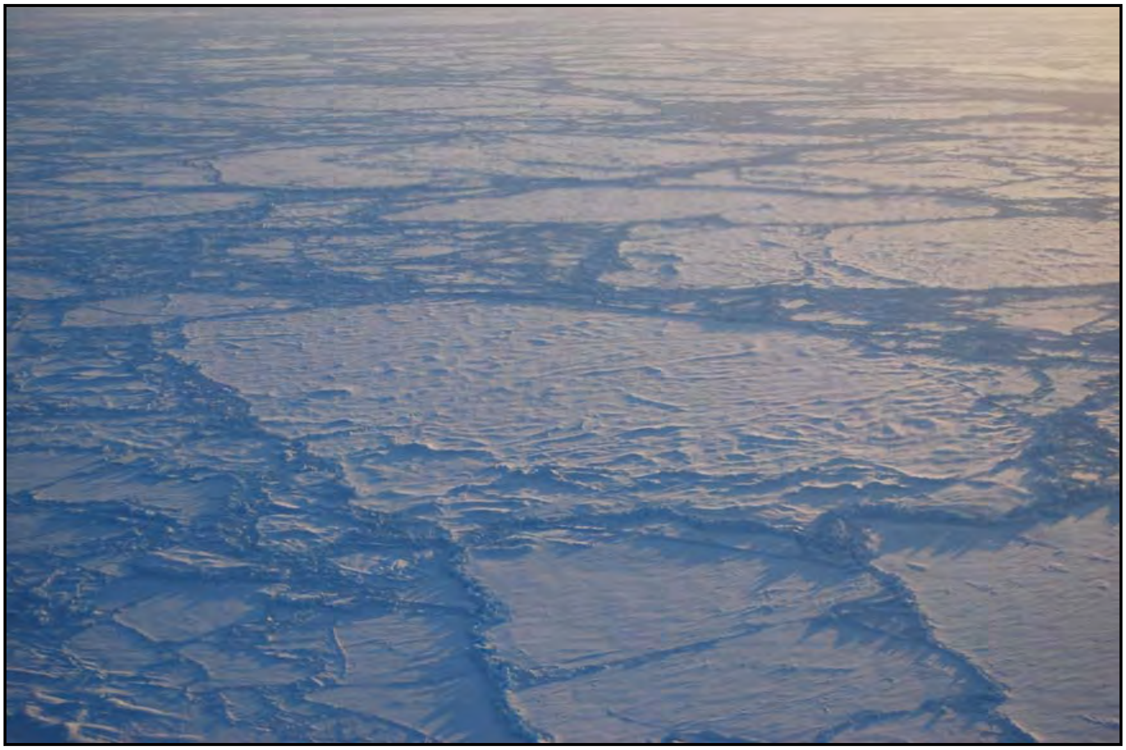


Plate 34. Multi-Year Floe Located 25 nm Offshore in Western Beaufort Sea, February 2010.

oceanographic conditions, the geometry and orientation of the shoreline and bathymetric contours, and the presence of shoals.

Beaufort Sea: Winds constitute the dominant driving force for ice movement in the Alaskan Beaufort Sea. The prevailing easterlies produce ice motion roughly parallel to the shoreline, creating a stable landfast ice zone out to the 18-m isobath. The western Beaufort between Point Barrow and Prudhoe Bay contains numerous shoals that are located as much as 10 to 20 nm (19 to 37 km) offshore. The most prominent is Weller Bank, which is located in northeastern Harrison Bay. The large rubble piles of first-year ice that typically form on this shoal produce a significant seaward extension of the landfast ice. By contrast, water depths in the eastern Beaufort Sea increase more rapidly offshore of the barrier islands from Cross to Flaxman and north of coast in the vicinity of Barter Island. Along these stretches of the coastline, the landfast ice zone is 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.

After freeze-up commenced in late October 2009, warm air temperatures and a lack of sustained easterly winds produced an unusually narrow landfast ice zone that persisted through November and most of December. An intense easterly in late December created a grounded shear zone and a typical offshore boundary for the landfast ice west of Prudhoe Bay that remained intact through midwinter. However, westerly winds in early to mid-January 2010 removed most of the landfast ice offshore of the barrier islands to the east of Prudhoe Bay, and the ice remained very dynamic through mid-February. This instability is consistent with the finding of Vaudrey (2009), who estimated the probability of midwinter ice movement along the Sivulliq pipeline route offshore of the 9-m isobath at 50% based on observations that showed movement in 16 of 32 years during the 36-year period from 1973 through 2008.

The landfast ice edge that developed in the western Beaufort Sea in 2009-10 was comparable to that observed during the six freeze-up studies in the early and mid-1980’s in terms of location and stability, but it formed about one month later. The contrast was significantly greater to the east of Prudhoe Bay, where a well-established, firmly-grounded shear zone developed off the barrier islands during all but one of the freeze-up periods monitored in the 1980’s (Plate 35). The sole exception occurred 1983-84, when a relatively calm stretch from October until late December was followed by a strong southwesterly that removed virtually all of the landfast ice between Cross and Flaxman 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

Plate 35. 5-m High Grounded Shear Wall in 30-m Water Depth off Flaxman Island (created during easterly storm in mid-November 1984).

narrow strip between the shoreline and grounded shear rubble located in water depths of 15 to 25 m. The offshore edge typically lies between several hundred meters and several nautical miles off the coast, and the ice often experiences severe deformation except for a narrow ice foot adjacent to the shoreline. Local increases in the width of the landfast ice occur in protected locations that include the embayments east of Point Franklin and Icy Cape.

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

As examples of the variability in flaw lead width, Vaudrey (1984, 1985, and 1986) reported widths of 1, 5, and 15 nm (2, 9, and 28 km) at the end of January 1984, 1985, and 1986, respectively. During midwinter in the 2000’s, however, both the width and persistence of the lead appeared to increase. The winter of 2009-10 was no exception, with sustained easterlies producing a 40- to 50-nm (74- to 93-km) wide feature that remained open for the 25-day period from February 10 through March 6, and again for the 10-day period from March 20 though 29.

Trend: The locations and shapes of the landfast ice zones and their associated leads and polynyas tended to follow the same general patterns in 2009-10 as noted in previous decades, but the landfast ice zone developed more slowly while the lead widths and polynya sizes both appeared to have increased. An additional difference in the Beaufort Sea was the absence of a stable, grounded shear zone between Cross Island and Camden Bay in 2009-10.

As observed in 2009-10, the coastal flaw lead in the Chukchi Sea seems to attain greater widths and persist longer during the middle of winter. One possibility is that a winter feedback loop has been established wherein warmer air temperatures make the ice weaker and more susceptible to wind stress, ice motion commences at lower wind speeds, and the new ice that forms between wind events is thinner and more prone to subsequent displacement.

6.7 Pack Ice Movement

Pack ice motion in the Beaufort 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 2009-10 and those in the 1980's. In consequence, the remainder of this section addresses long-term ice movements.

Long-term pack ice motion, often referred to as "ice flux" or "ice drift", usually is expressed in nautical miles per day. It 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 through 1985, a separate, site-specific buoy measurement program was undertaken in 1985-86 to complement the 1985 freeze-up study (Vaudrey, 1987a). The median ice flux during the 1985-86 freeze-up period was found to be 5 to 7 nm (9 to 13 km) per day. Similar results were obtained from a number of other Beaufort Sea ice buoy programs conducted in the 1980's (Vaudrey, 1988a, 1989a, 1989b).

In the present study, an analysis of sequential satellite images encompassing 14 separate events in the Beaufort Sea during November and December 2009 yielded an average ice drift rate of 6 nm (11 km) per day, with a range of 1 to 13 nm (2 to 24 km) per day. In the Chukchi, where the westward set of the Beaufort Gyre is greatly diminished south of Point Barrow, an average ice flux of 4 nm (7 km) per day day was obtained for ten long-term movement events in November, December, and January. The daily ice drift ranged from 1 to 8.5 nm (2 to 16 km) per day.

Trend: The average drift rate measured for Beaufort Sea pack ice during the 2009-10 freeze-up season is comparable to the values obtained in the 1980's, suggesting that the drift rate has remained unchanged. This finding contrasts with that of Walsh and Eicken (2007), who suggested that thinner sea ice in the winter may lead to increased ice movement.

7. SUMMARY AND CONCLUSIONS

Study Methods

1. ***Satellite Imagery:*** Geo-referenced RADARSAT-2 images with a nominal resolution of 100 m can be used to investigate individual ice features as well as regional ice conditions. Weekly images are ideal for correlating changes in the ice cover with meteorological events. Images obtained at longer intervals, although less suitable for tracking individual ice features, nevertheless provide useful information. In contrast, the low-resolution RADARSAT mosaics compiled by the Canadian Ice Service (CIS) are unsuitable for the analysis of individual features.

2. ***Aerial Reconnaissance Missions:*** Reconnaissance flights provide invaluable opportunities to confirm and refine the findings derived from satellite imagery, and to expand upon those findings with respect to small-scale features and processes. If budgetary constraints permit, two sets of aerial reconnaissance missions are recommended:

   Late November/Early December: Flights in the Beaufort Sea to enhance the interpretation of satellite imagery obtained early in the freeze-up process;

   Late January/Early February: Flights in the Beaufort and Chukchi Seas (analogous to those undertaken in 2010) to document the ice conditions at the end of the freeze-up process and investigate features identified in the satellite imagery.

3. ***Reconnaissance Aircraft***: In the Beaufort Sea, where distances offshore are comparatively small, the use of an intermediate-size helicopter to augment the missions conducted with a fixed-wing aircraft is warranted by the helicopter's ability to land at features of interest. In the Chukchi, where the distances offshore tend to be large, the cost of a long-range helicopter capable of visiting sites of interest (other than those along the coast) likely would be prohibitive.

Findings for Entire Study Area

1. ***Ice Regimes***: The ice regimes in the Beaufort and Chukchi Seas differ markedly due to factors that include geography, meteorology, and oceanography. In 2009-10, as in prior years, the easterly winds that prevailed in both regions tended to push the ice along the Beaufort Sea coast and away from the Chukchi coast. In the western Beaufort, the alongshore ice movement produced an extensive zone of landfast ice contained within a well-established shear zone. In the Chukchi, the offshore ice

movement produced a recurring coastal flaw lead that repeatedly removed all but a narrow strip of landfast ice. These patterns are consistent with those noted in the past.

2. ***Air Temperatures***: The daily mean air temperatures from September 2009 through May 2010 were the fifth warmest out of the last 40 years, based on freezing-degree days accumulated at Barrow. The total of 6,608 freezing-degree days was 16% less than the average value obtained for the six winters from 1980-81 through 1985-86.
3. ***First-Year Ice Growth***: The computed ice thickness at the end of the 2009-10 winter season was 155 cm, based on the freezing-degree days accumulated at Barrow. This value is about 10% less than the average from 1980-81 through 1985-86.
4. ***Multi-Year Ice***: Significant numbers of multi-year ice floes invaded both the Beaufort and Chukchi Seas during the 2009-10 freeze-up and early winter seasons. The floes consisted primarily of multi-year ice from the polar pack rather than second-year ice formed in the nearshore zone. Many were of large diameter and contained embedded ridges. The invasion constituted the first such occurrence since 2001.

Findings for Beaufort Sea

1. ***Late Summer:*** The total area covered by the pack ice at its minimum extent in mid-September 2009 was the third lowest since 1979. In late September, the ice edge was located about 60 nm (111 km) north of the central and eastern Beaufort Sea coast, close to its median location for this time of year during the period from 1979 through 2000.
2. ***Freeze-Up***: In 2009, the approximate date of freeze-up in the nearshore region of Beaufort Sea was October 22. This timing is comparable to the average date for the five-year period from 2002 through 2006, but 18 days later than the average computed for the 11 years from 1980 through 1985, and 1987 through 1991.
3. ***Landfast Ice:*** Warm air temperatures and a lack of sustained easterly winds produced an unusually narrow landfast ice zone that persisted from the initiation of freeze-up through most of December 2009. An intense easterly storm in late December created a grounded shear zone and a typical offshore boundary for the landfast ice west of Prudhoe Bay that remained intact through midwinter. However, westerly winds in early to mid-January 2010 removed most of the landfast ice offshore of the barrier islands east of Prudhoe Bay, and the ice remained very dynamic through mid-February. This instability is consistent with the finding of a prior study that the probability of midwinter ice movement on the Sivulliq pipeline route is 50%.

4. ***Multi-Year Ice:*** The multi-year floes that invaded the Beaufort Sea in 2009-10 remained 10 to 20 nm (19 to 37 km) offshore as they migrated to the west under the influence of the Beaufort Gyre. The highest concentrations, 7 to 8 tenths, were noted between Smith Bay and Point Barrow. Typical diameters ranged from hundreds of meters to several nautical miles.

5. ***Ice Pile-Ups:*** Ice pile-ups were observed on or adjacent to six natural barrier islands and Northstar Production Island during the aerial reconnaissance flights conducted in early February. The estimated pile-up heights ranged from 1-2 m on Flaxman Island to 16 m on a shoal west of Narwhal Island, while the ice blocks comprising the piles ranged from 25 to 75 cm thick. The pile-up off Narwhal Island was unique in that it consisted of a grounded ridge rather than an assemblage of individual ice blocks, and resulted from ice movement inside rather than outside the barrier islands. Also noteworthy was the fact that it exceeded 1 nm (2 km) in length.

Findings for Chukchi Sea

1. ***Freeze-Up***: A combination of unseasonably warm air temperatures and persistent easterly winds delayed the onset of ice growth in most regions of the Chukchi Sea until the first week in November. Freeze-up proceeded more slowly than in the Beaufort, with the ice edge advancing to the south and west through late November. By the end of November, the entire Chukchi Sea was ice-covered north of Cape Lisburne and east of 169°W.

2. ***Landfast Ice:*** With the exception of Peard Bay, Kasegaluk Lagoon, and protected areas east of Point Franklin and Icy Cape, the early-season ice off the coast between Barrow and Point Lay never had an opportunity to stabilize before it was dislodged by a series of easterly winds that caused freeze-up to start anew. At times, westerly winds drove the young ice against the shoreline and created pile-ups or offshore rubble fields. When a coastal reconnaissance flight was conducted on February 9, the edge of the fast ice zone was located only 1 to 2 nm (2 to 4 km) off Barrow, 0.5 to 1 nm (1 to 2 km) off Point Belcher, 2 to 3 nm (4 to 6 km) off Wainwright, and 3 to 4 nm (6 to 7 km) off Point Lay. Most of the coast lacked a shear zone with sufficient grounding to stabilize the offshore boundary of the fast ice. As a result, the ice was susceptible to removal during subsequent easterly storms.

3. ***Coastal Flaw Lead:*** Seaward of the landfast ice, a coastal flaw lead opened and closed repeatedly in response to easterly (offshore) and westerly (onshore) winds. Whenever it was open, the lead generated new ice as it refroze. 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. Because the coastal flaw lead reduces confinement, it leaves the ice in the nearshore zone susceptible to rapid movement and substantial deformation.

4. ***Nearshore vs. Offshore Ice Cover:*** The ice cover in the nearshore and offshore regions differed markedly at the time of the aerial reconnaissance missions in early February 2010. The former consisted primarily of heavily-deformed ice with small, undisturbed first-year pans between ridges. The latter was smoother, with fewer and smaller ridges, and was composed of vast first-year pans with diameters as large as several nautical miles. These contrasting characteristics indicate that the differential motion between floes was substantially smaller in the offshore zone, where the influence of the coastal flaw lead was minimal.

5. ***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 into Shell's Crackerjack and West Prospects to the west of the 165°W meridian, and (2) a southern or coastal branch that extended southwest from Barrow to the vicinity of the 70°N parallel. Concentrations as high as 4 to 5 tenths were observed in the northern branch between 72°N and 73°N, and as high as 7 tenths in the southern branch off Barrow. As in the case of the Beaufort Sea, the diameters typically ranged from hundreds of meters to several nautical miles, and many of the floes contained embedded ridges.

6. ***Ice Pile-Ups:*** Sixteen ice pile-ups and three ice ride-ups were observed on the Chukchi Sea coast during the February 9 reconnaissance mission, with thirteen of these located in the exposed stretch between Point Franklin and Icy Cape. 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, while the ice blocks comprising the piles ranged from 20 to 45 cm thick. The three ride-ups all encroached 5 to 6 m onto the beach in the vicinity of Point Belcher.

Comparison of Freeze-Up in the 1980's and 2009

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

2. ***First-Year Ice Growth:*** Based on air temperatures alone, the first-year ice thickness attained during an average winter has decreased by about 10% since the early to mid-

1980's. However, increased snowfall accompanied by greater snow accumulation on the landfast ice sheet may be causing a more significant reduction in ice thickness. Other temperature-related factors, including reduced ice production in leads and decreased consolidation of ridges, probably exert a greater impact on the ice dynamics than a thinner ice cover.

3. ***Landfast Ice Development and Stability*****:** The locations and shapes of the landfast ice zones and their associated leads and polynyas tended to follow the same general patterns in 2009-10 as noted in previous decades, but the landfast ice zone developed more slowly while the lead widths and polynya areas tended to increase. An additional difference in the Beaufort Sea in 2009-10 was the absence of a stable, grounded shear zone between Cross Island and Camden Bay.

4. ***Multi-Year Ice:*** Despite the invasion of multi-year pack ice that occurred in 2009-10, the probability of such an invasion in any given year is less than in the 1980's. This conclusion follows in part from the location of the ice edge, which has retreated farther to the north in recent summers, and in part from warmer air temperatures and increased storminess, which have reduced the likelihood that remnants of the Beaufort Sea shear zone will survive the summer melt season to become second-year floes. Nevertheless, as demonstrated in 2009-10, the possibility of encountering multi-year ice floes and ice gouges inflicted by such floes cannot be ruled out for developments in either the Beaufort or Chukchi Sea.

5. ***Pack Ice Movement:*** The average drift rate measured for pack ice during the 2009-10 freeze-up season was 6 nm (11 km) per day. This value is comparable to that obtained in the 1980's, suggesting that the drift rate has remained unchanged.

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