

2013-14 Freeze-Up Study of the Alaskan Beaufort and Chukchi Seas

**Coastal Frontiers Corporation
Vaudrey & Associates, Inc.**



January 2015

Program Sponsors



Shell Oil Company



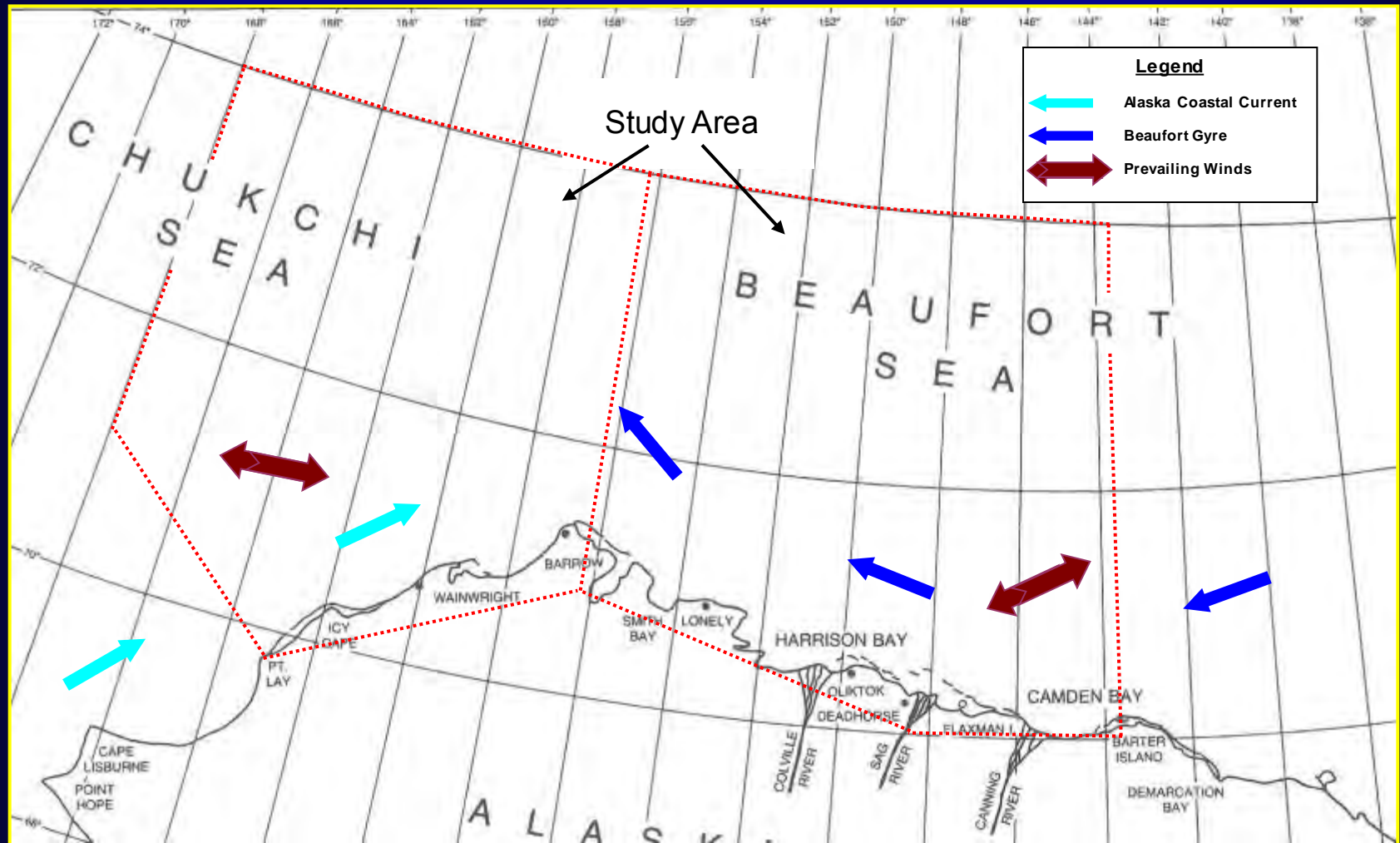
U.S. Department of the Interior
Bureau of Safety and Environmental
Enforcement

2013-14 Freeze-Up Study Wrap-Up Meeting

Agenda

1. Project Overview
2. Data Acquisition and Analysis
3. Beaufort Sea Freeze-Up
4. Chukchi Sea Freeze-Up
5. Freeze-Up: Recent Years vs. 1980s
6. Summary and Conclusions
7. Discussion

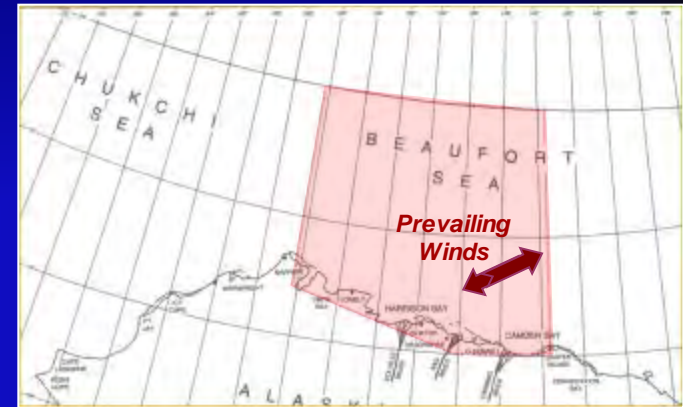
Study Area



Beaufort vs. Chukchi

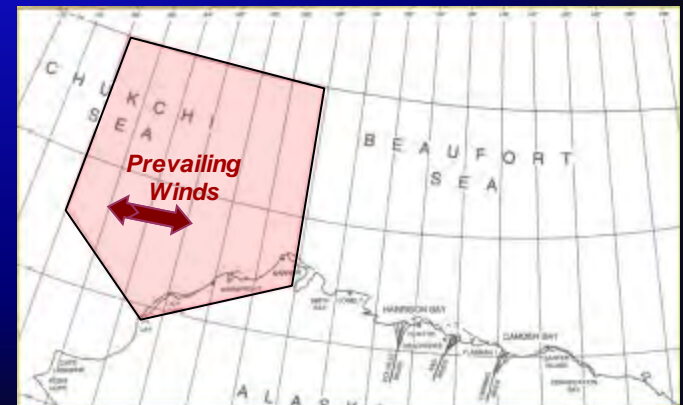
Alaskan Beaufort Sea

- ESE-WNW Coastline
- Coast-Parallel Winds
- Flat Nearshore Slopes
- Extensive Zone of Landfast Ice
- Small Leads and Polynyas



Chukchi Sea

- NE-SW Coastline
- Onshore-Offshore Winds
- Steep Nearshore Slopes
- Narrow Strip of Landfast Ice
- Coastal Flaw Lead



Freeze-Up Studies Prior to 2009-10

Vaudrey & Associates JIPs (1980-85)

- 1980-82: Central Beaufort Sea
- 1983-85: Beaufort and Chukchi Seas
- Data Source: Aerial Reconnaissance Missions at 2- to 3-Week Intervals

Remote Sensing (1987-Present)

- Investigators: Vaudrey & Assoc.; Eicken & Mahoney (UAF)
- Data Source: Satellite Imagery
- Scale: Synoptic

2013-14 Freeze-Up Study Objectives

1. Document Ice Conditions during Freeze-Up
2. Locate and Map Significant Features
 - Landfast Ice Zone
 - Ice Movement Lines, Rubble Fields, and Ridges
 - Leads and Polynyas
 - Multi-Year Ice
3. Locate and Characterize Ice Pile-Ups
4. Correlate Changes in Ice Canopy with Weather
5. Characterize Current Freeze-Up Processes and Compare with 1980s

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Data

- Meteorological Data
- Satellite Imagery
- Ice Charts
- Telemetry Buoys
- Reconnaissance Flights

Data

➤ Meteorological Data



➤ Satellite Imagery



➤ Ice Charts

➤ Telemetry Buoys

➤ Reconnaissance Flights



Meteorological Conditions

- Wind regime and storms
- FDD

Ice Conditions

- Landfast Ice Zone
- Multi-Year Ice Edge
- MYI Floe Movement
- Small-Scale Features
- Pile-Ups

Meteorological Data

➤ Sources

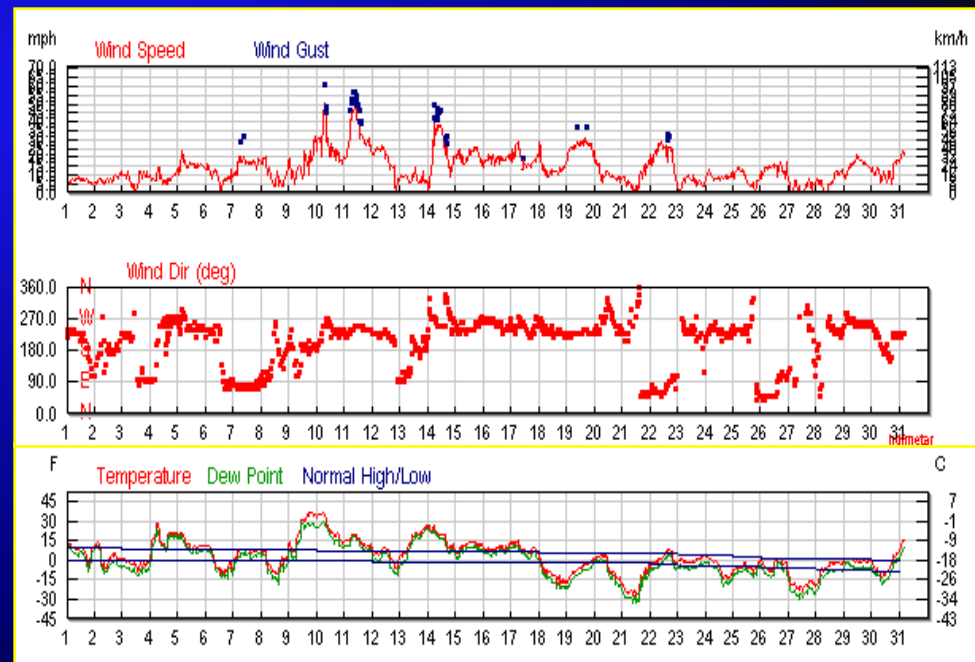
- Weather Underground
- National Ocean Service

➤ Sites

- Beaufort
 - Deadhorse Airport (WU)
 - West Dock STP (NOS)
- Chukchi
 - Barrow Airport (WU)

➤ Period

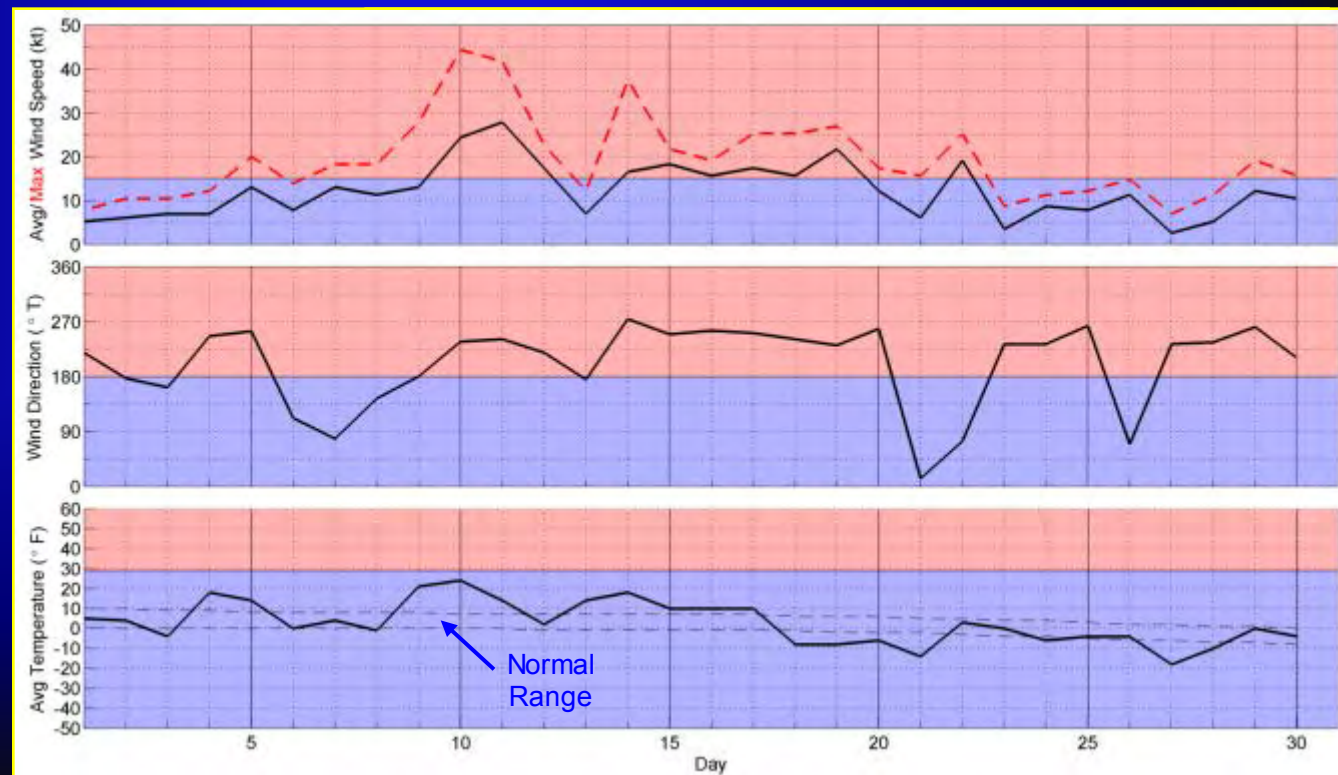
- September 2013 – March 2014



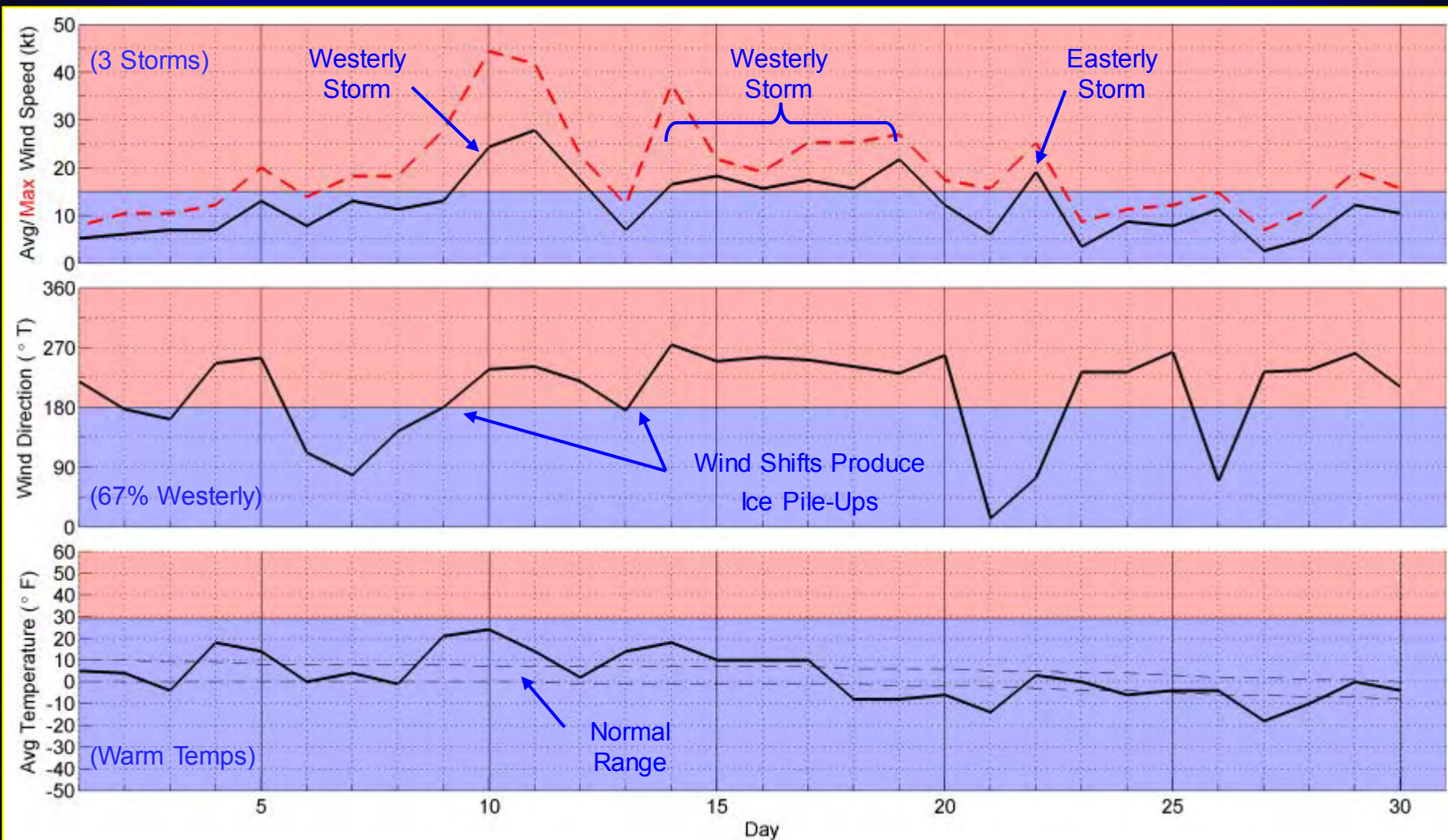
Meteorological Data

➤ Primary Parameters

- Wind: Daily Average Speed & Direction
- Air Temperature: Daily Average, Max & Min



Meteorological Data



Deadhorse Airport, November 2013

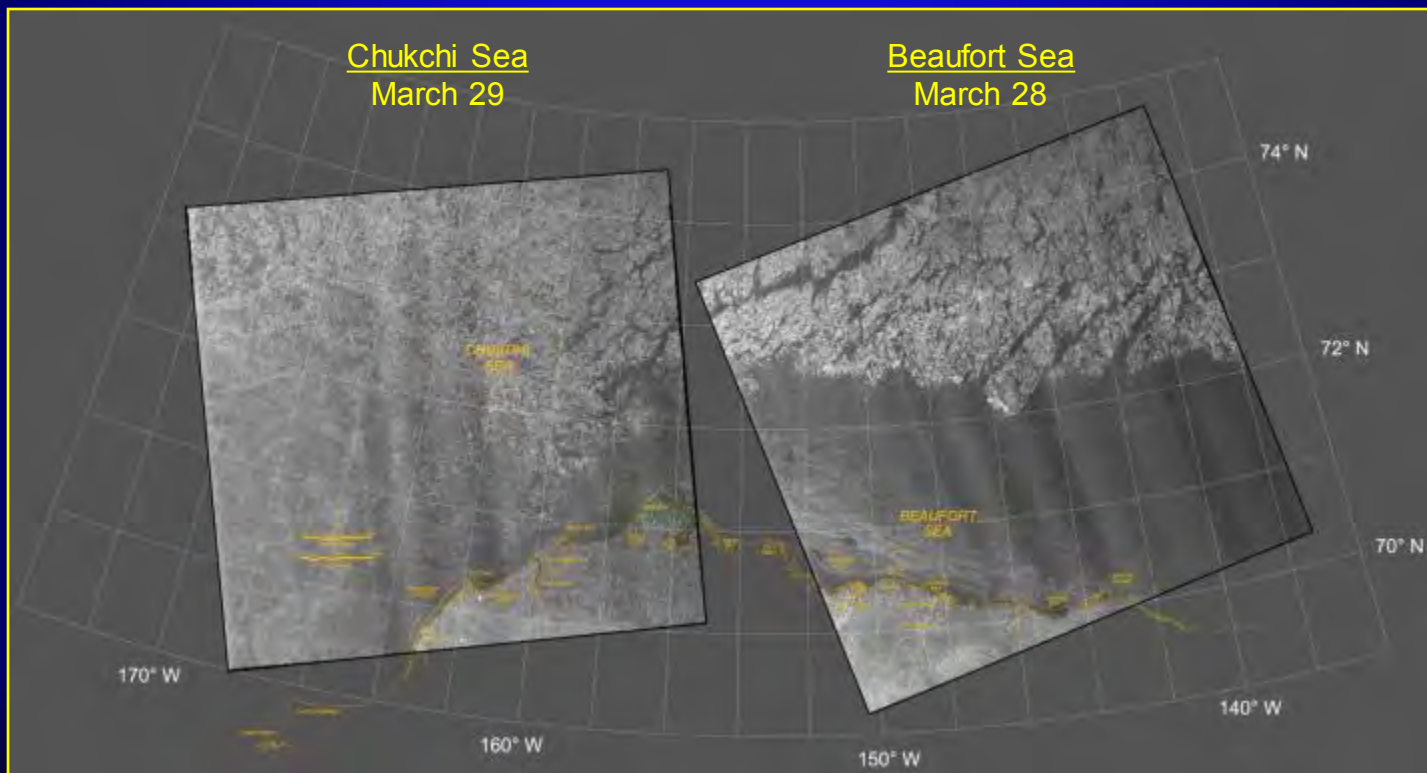
Cumulative Freezing-Degree Days, 2013-14

Definition: $FDD = \sum_{i=1}^{273} (29^{\circ} \text{ F} - \text{Daily Mean Air Temp}_i)$

Site	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Barrow	0	161	799	1,786	2,889	3,897	4,945	5,696	5,775 (Warmest in 44 yr)
		'14-'15: 235							
Dead-horse	27	239	1,025	2,089	3,254	4,450	5,637	6,390	6,425
		'14-'15: 210							

Satellite Imagery

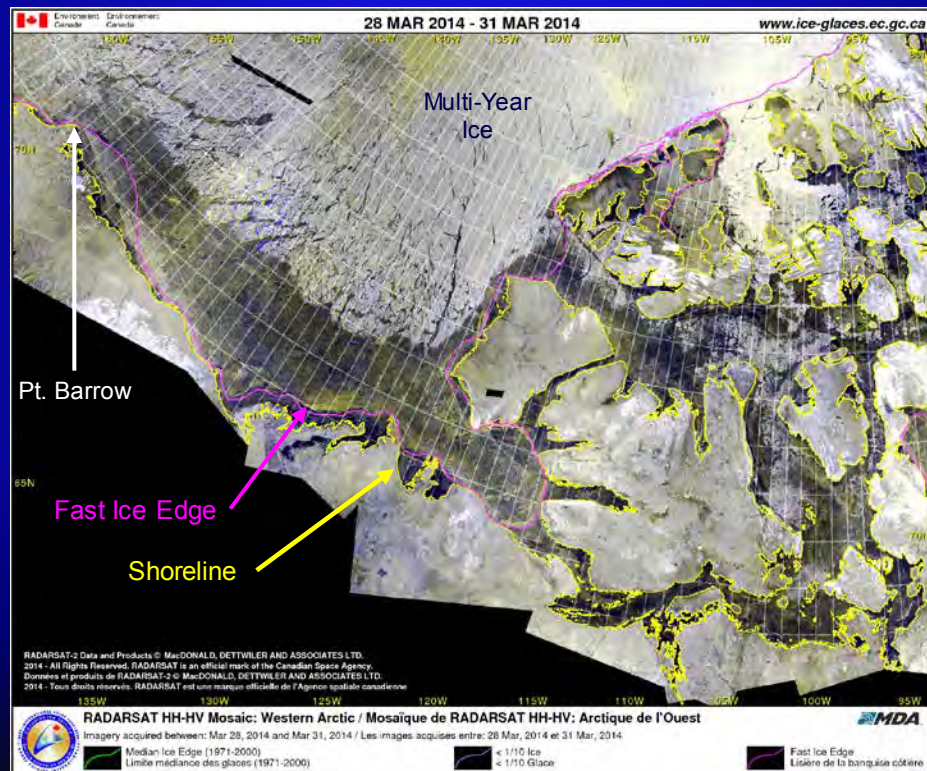
- High-Resolution Shell Images (Oct 2013 – Mar 2014)
 - RADARSAT-2
 - 20 images of Beaufort Sea, 20 images of Chukchi Sea



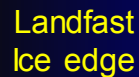
Satellite Imagery

➤ RADARSAT-2

- High-Resolution Shell Images (Oct 2013 – Mar 2014)
- Low-Resolution CIS Mosaics (Oct 2013 – Apr 2014)

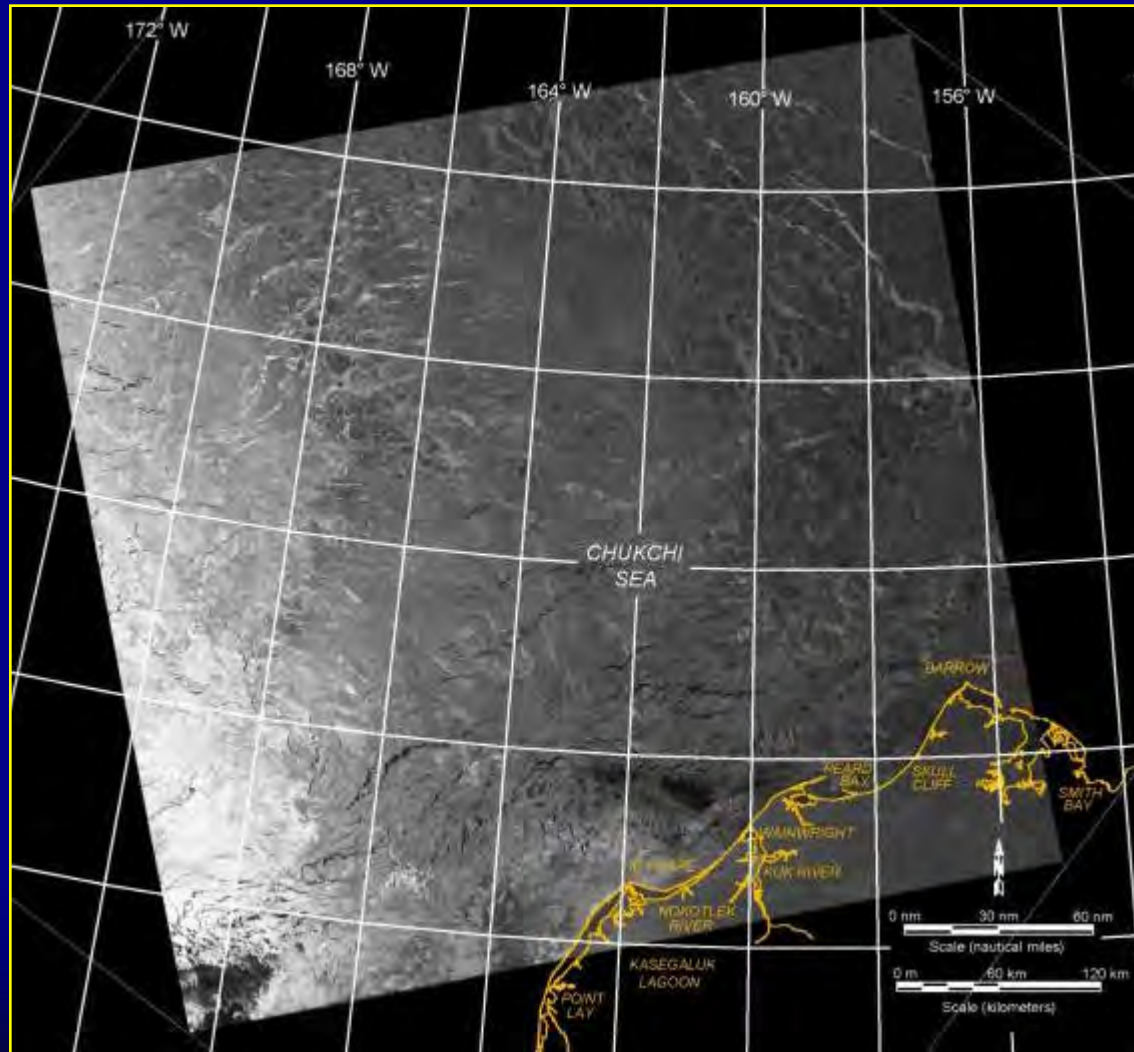


After: CIS, 2014



After: RADARSAT-2 Data and Products © MacDonald Dettweiler and Associates Ltd., 2014 – All Rights Reserved

RADARSAT-2 Image on November 29, 2013



After: RADARSAT-2 Data and Products © MacDonald Dettweiler and Associates Ltd., 2013 – All Rights Reserved

Satellite Imagery

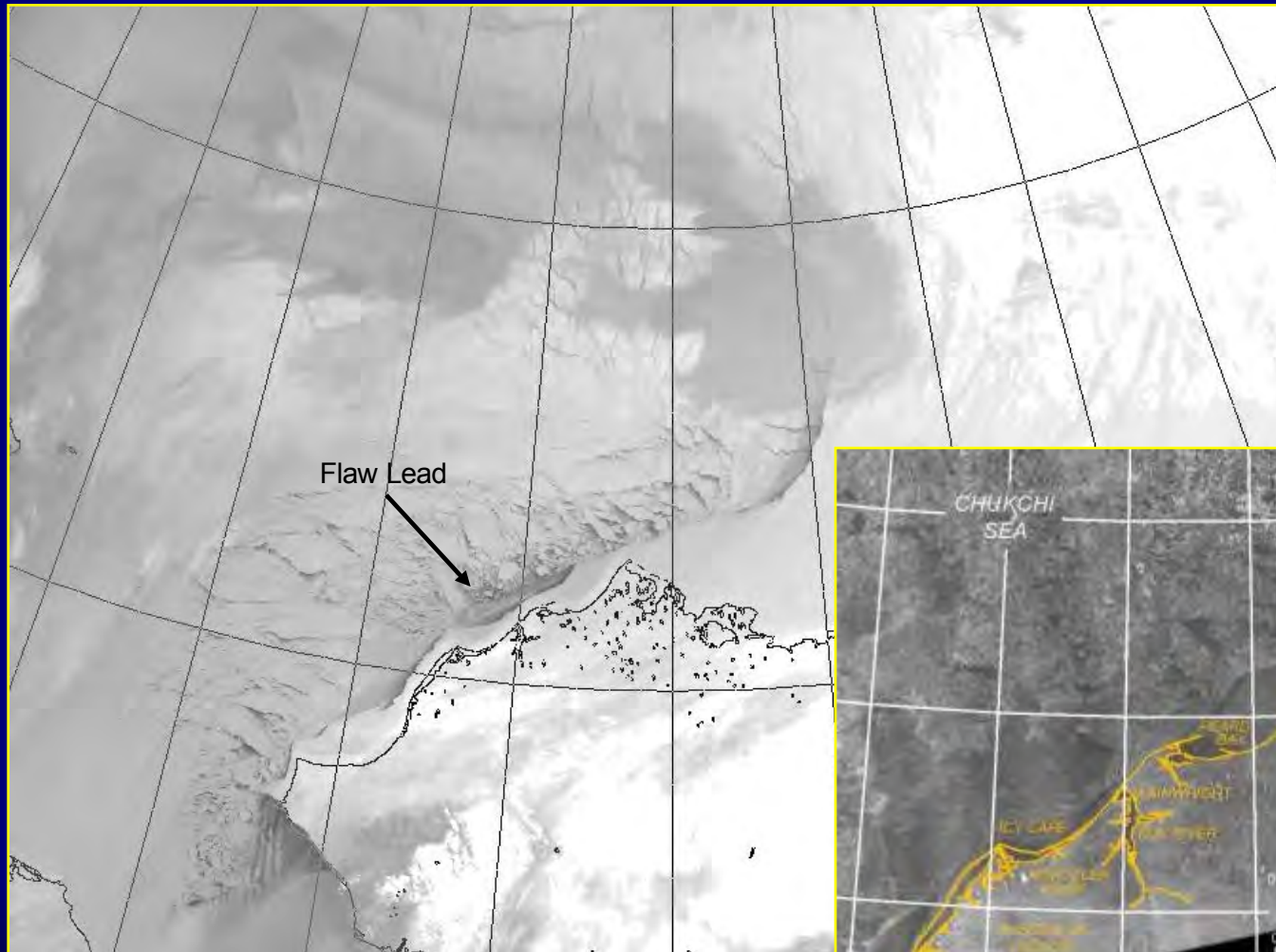
➤ AVHRR (Secondary Source)

- Oct 2013 – Mar 2014
- 1-km Resolution
- Inability to Penetrate Cloud Cover
- Multiple Images per Day

➤ MODIS (Limited Utility)

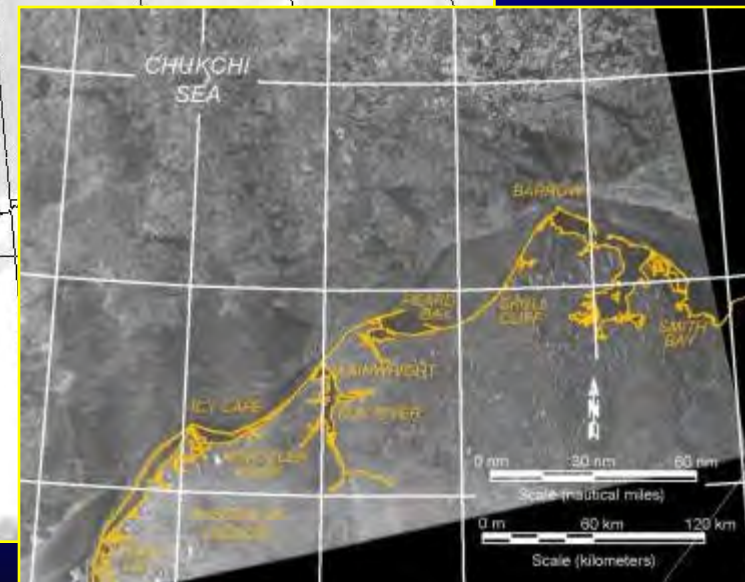
- Oct - Nov 2013 and Feb – Mar 2014
- 250-m Resolution
- Inability to Penetrate Cloud Cover, Darkness or above 72° N

AVHRR Image on February 16, 2014



February 16, 2014

After: National Weather Service, 2014



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MODIS Image on February 16, 2014



After: NASA, 2014

Ice Charts

➤ Sources

- Canadian Ice Service (CIS)
- National Ice Center (NIC)
- Shell Ice & Weather Advisory Center (SIWAC)

➤ Sites

- Beaufort Sea (CIS, NIC and SIWAC)
- Chukchi (NIC and SIWAC)

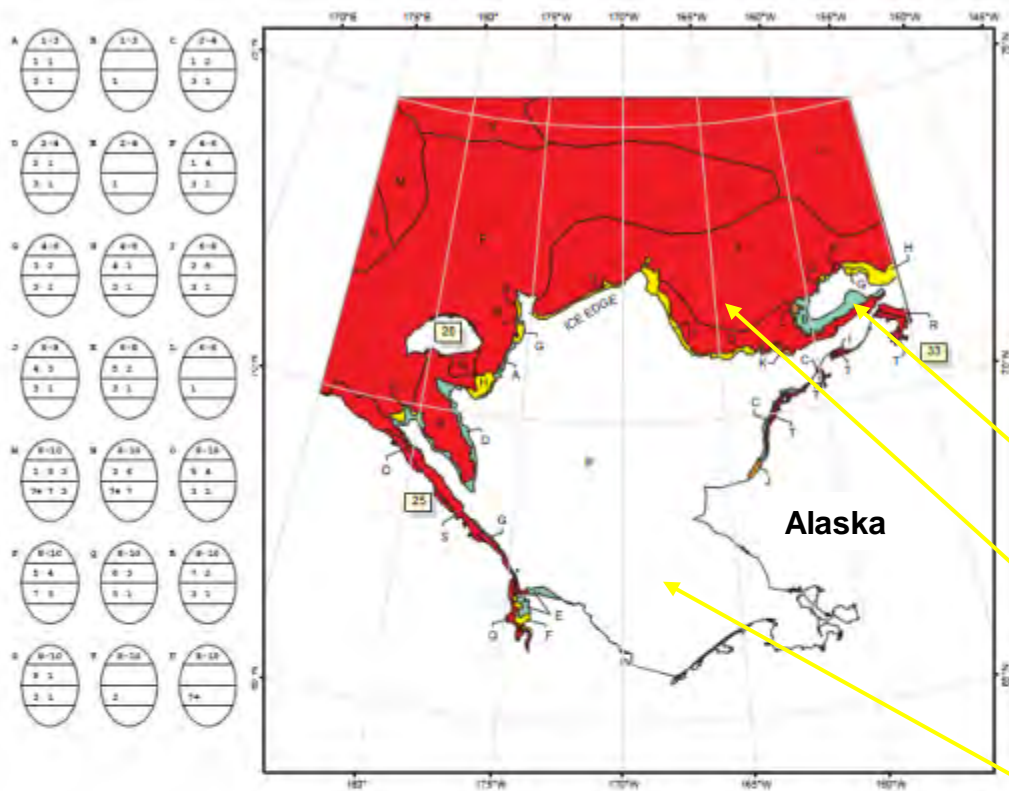
➤ Period

- Oct 2013 – March 2014

➤ Primary Applications

- Ice Coverage during Early Freeze-Up
- Large-Scale Processes
- Coastal Flaw Lead

NIC Ice Chart of Chukchi Sea for October 31, 2013



Alaska

1-3 Tenths

9-10 Tenths

Ice Free

CM = THEORETICAL ICE THICKNESS IN CENTIMETERS

IF = ICE FREE

COLOR CODES BASED ON TOTAL CONCENTRATION

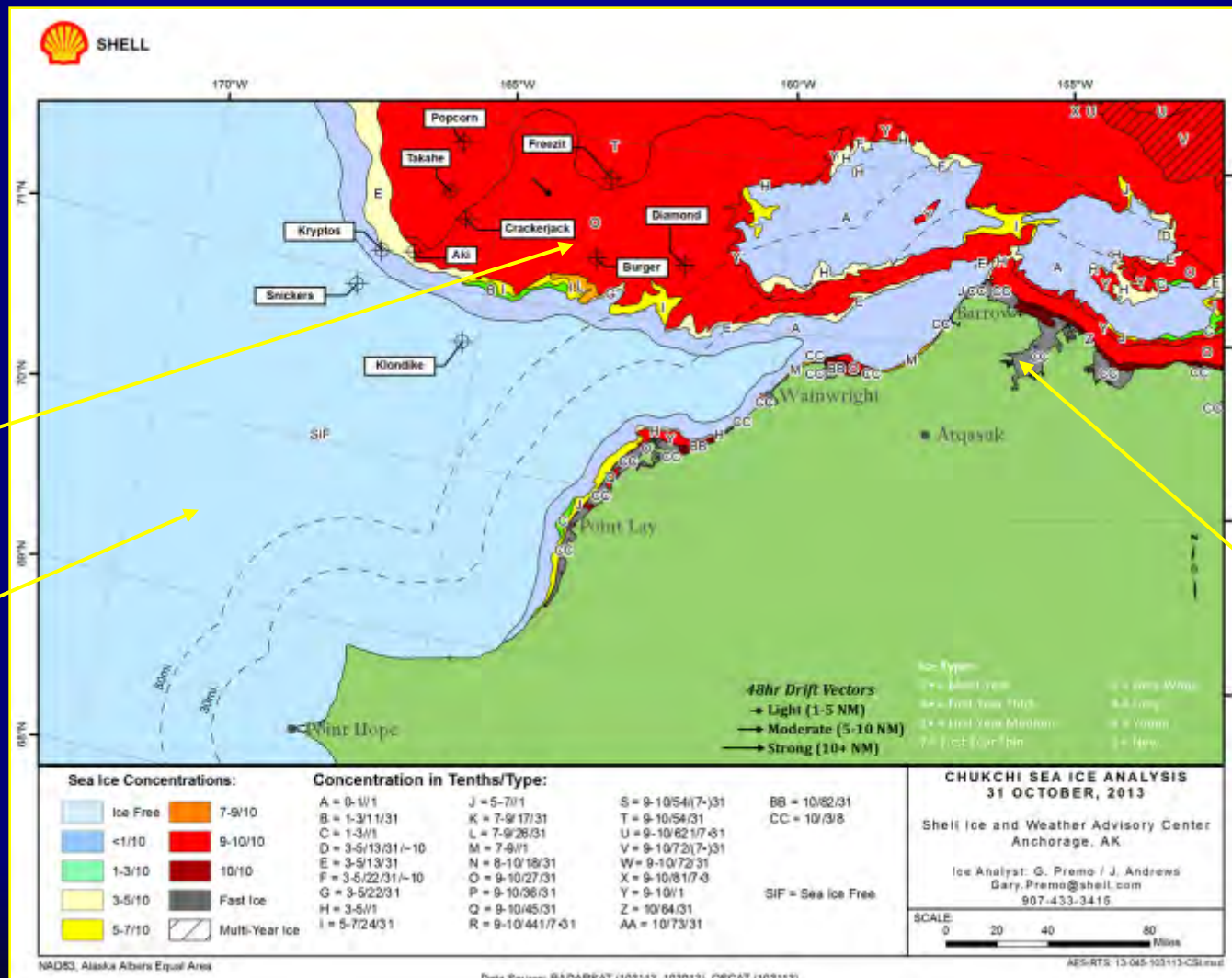
ICE FREE	4-6 TENTHS	PART ICE (20% TENTHS)
1-3 TENTHS	7-8 TENTHS	ICE BRFL
1-3 TENTHS	9-10 TENTHS	ICE BRFL
		ICE

ICE ANALYSIS
Chukchi Sea
NATIONAL/NAVAL ICE CENTER
Analysis Week 31 Oct 2013

Data Sources Date
RADARSAT.....30 - 31 Oct
MODIS.....31 Oct
Analyst: Christopher Szorc

UNCLASSIFIED

SIWAC Ice Chart of Chukchi Sea for October 31, 2013



9-10 Tenths

Ice Free

Landfast Ice

International Arctic Buoy Program

Telemetry Buoys

➤ Deployment

- 14 Buoys in the Beaufort Sea
- 7 Buoys in the Chukchi Sea

➤ Data

- Hourly Positions
- Temperature, Barometric Pressure

➤ Primary Applications

- Defining Landfast Ice Edge
- Correlating Ice Movements with Wind Events
- Computing Ice Movement Speeds

Beaufort Sea Telemetry Buoys



Data Source: Polar Science Center, 2014

- Camden Bay: 5 Buoys
- Harrison Bay: 4 Buoys
- Weller Bank: 2 Buoys
- Smith Bay: 1 Buoy
- Pt. Barrow: 2 Buoys

February 24 – March 31, 2014

Chukchi Sea Telemetry Buoys

- MYI Floes in Flaw Lead: 4 Buoys
- Peard Bay: 3 Buoys

February 28 – March 31, 2014



Data Source: Polar Science Center, 2014

Reconnaissance Flights

➤ Aircraft Freeze-Up (March 28 - 31)

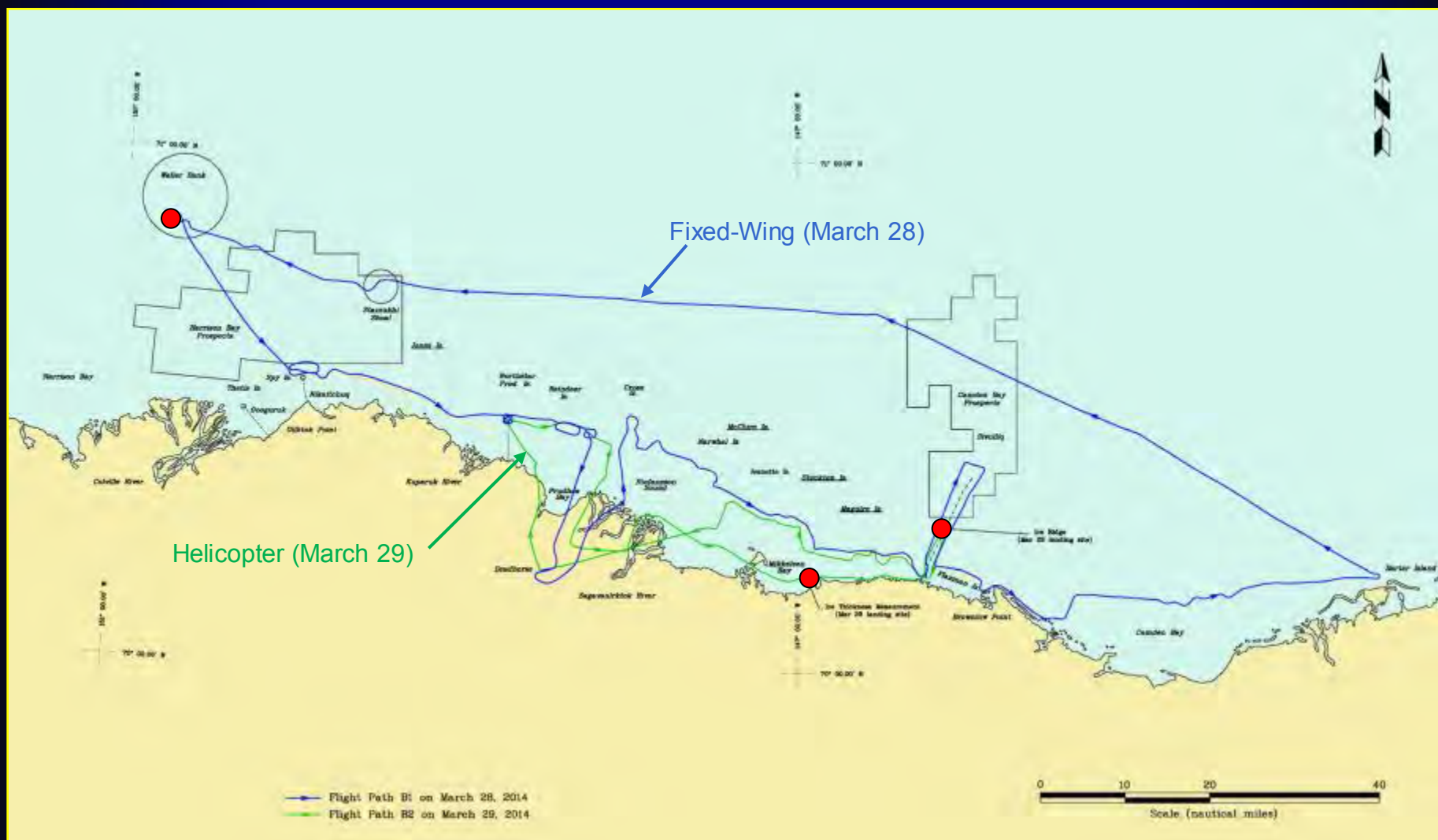
- Central Beaufort: Aero Commander 690 & 412
- Western Beaufort: Aero Commander 690
- CRB with Coal-Time Track Display: Aero Commander 690
- Northeast Chukchi: Aero Commander 690



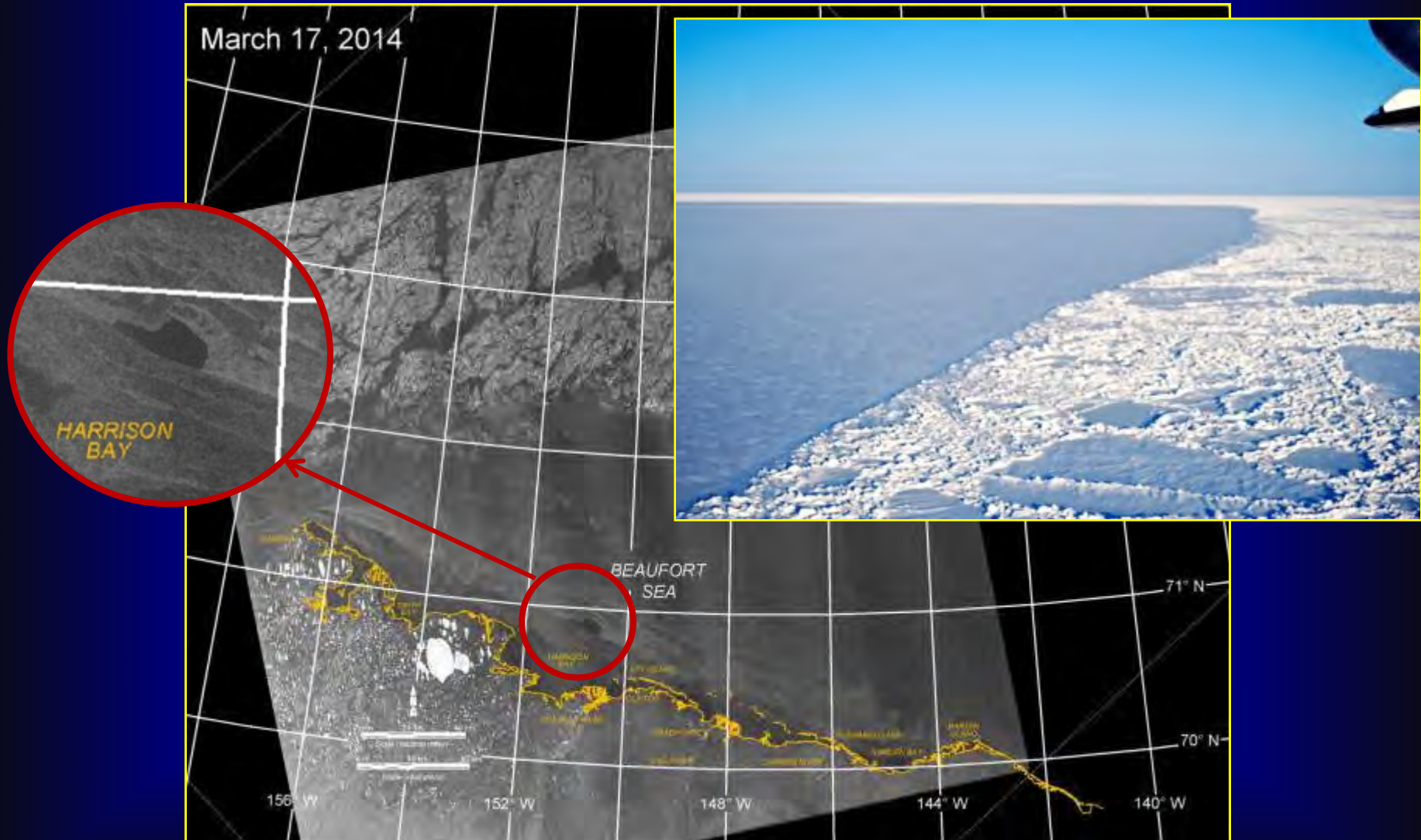
Aerial Reconnaissance Missions

➤ Objectives

- Obtain Ground-Truth Information for Satellite Imagery
- Investigate Large-Scale Ice Features Identified in Satellite Imagery (e.g., leads, landfast ice, major shear lines)
- Detect and Characterize Small-Scale Ice Features beneath Resolution of Satellite Imagery (e.g., ridges, rubble fields, shoreline pile-ups)



Aerial Reconnaissance Missions



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Ridge

March 29, 2014

March 29, 2014



Ice Thickness Measurements

March 29, 2014




Predicted: 140 cm

Measured: 135 & 142 cm (avg = 138.5 cm)


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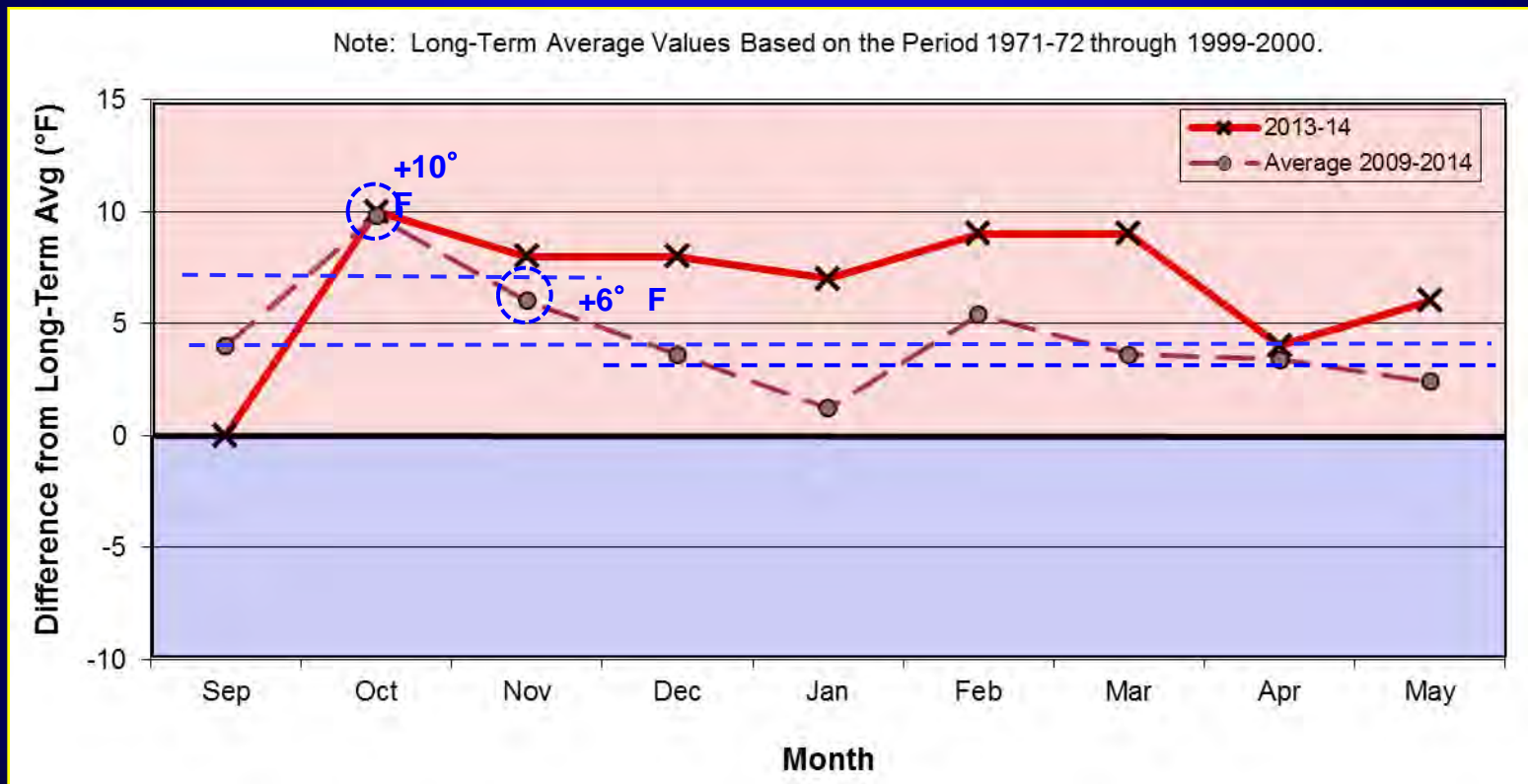
Freeze-Up: Recent Years vs. 1980s

- Air Temperatures
 - Winds
 - Timing of Freeze-Up
 - First-Year Ice Growth
 - Landfast Ice
 - Chukchi Sea Flaw Lead
 - Multi-Year Ice
 - Pack Ice Movement
- } Causes
- } Effects

Air Temperatures

➤ Monthly Average Values over Past 5 Years

- Average increase, Sep – May: $+4^{\circ}$ F ←
- Average increase, Sep – Nov: $+7^{\circ}$ F ←
- Average increase, Dec – May: $+3^{\circ}$ F ←



Differences from Long-Term Average Values at Barrow Airport

Air Temperatures

➤ Trends

- Air temperatures have increased substantially since 1970s
- Greatest increases in October and November (delaying onset of freeze-up)
- FDD have decreased at average rate of 44/yr (reducing first-year ice thickness)

Wind Directions: 2009-11 through 2012-13

Basin	Frequency (%)	
	Easterly	Westerly
Beaufort		
Minimum	40	50
Maximum	50	60
Average	45	55
Chukchi		
Minimum	61	29
Maximum	71	39
Average	67	33

Period of Record: October - March

Storm Events: 2009-11 through 2012-13

Beaufort Sea

Freeze-Up	Storm Events			Storm-Days		
	Easterly	Westerly	Total	Easterly	Westerly	Total
2009-10	10	5	15	24	13	37
2010-11	8	11	19	19	22	41
2011-12	8	6	14	16	18	34
2012-13	10	10	20	35	16	51
2013-14	9	11	20	23	20	43
Average	9	= 9	18	23	18	41

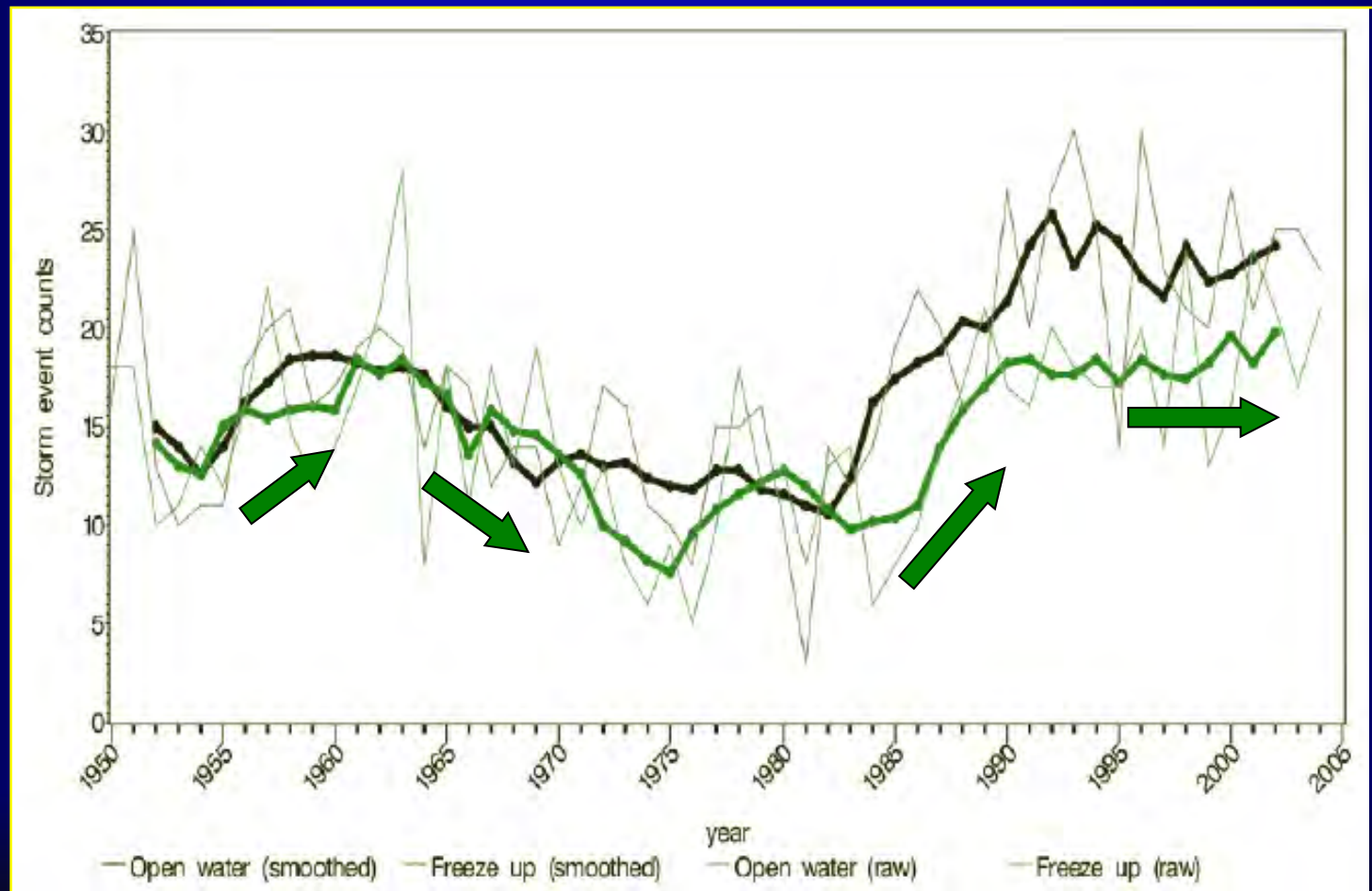
Chukchi Sea

Freeze-Up	Storm Events			Storm-Days		
	Easterly	Westerly	Total	Easterly	Westerly	Total
2009-10	14	3	17	37	4	41
2010-11	10	8	18	27	13	40
2011-12	8	3	11	21	6	27
2012-13	12	4	16	42	7	49
2013-14	12	7	19	29	13	42
Average	11	> 5	16	31	9	40

Period of Record: October – March
 Storm Event: Daily Average Wind Speed > 15 kt

Storm Winds: 1980s - Present

Walsh and Eicken (2007): sharp rise in storm frequency during open water & freeze-up seasons from mid-1970s through early 1990s



Storm Winds: 1980s - Present

➤ 1981 through 1986 (Dickins & Vaudrey, 1994)

- Storm Event: wind > 15 kt
- Period: January - April
- Average Frequency: 8.5 storms/yr

➤ 2010 - 2013

- 2010: 10 storms
 - 2011: 10
 - 2012: 7
 - 2013: 9
 - 2014: 7
-
- Average Frequency: 8.6 storms/yr

Storm Winds

➤ Trends

- Storm frequency during freeze-up has increased by more than 50% since 1970s
- Storm frequency in mid-winter is nearly identical to that in the 1980s

Timing of Freeze-Up in Nearshore Region

➤ Beaufort Sea

- 1980-85, 1987-91: Oct 4 (Vaudrey, 1982-86; 1988-92)
- 2009: Oct 22
- 2010: Oct 11
- 2011: Oct 26
- 2012: Nov 5
- 2013: Oct 26
- Recent Average: Oct 24

➤ Chukchi Sea

- Mid-1970s: early October (Mahoney, *et al.*, 2007)
- 2009: Nov 16
- 2010: Nov 4
- 2011: Nov 20
- 2012 : Nov 15
- 2013: Nov 26
- Recent Average: Nov 16

Timing of Freeze-Up in Nearshore Region

➤ Trends

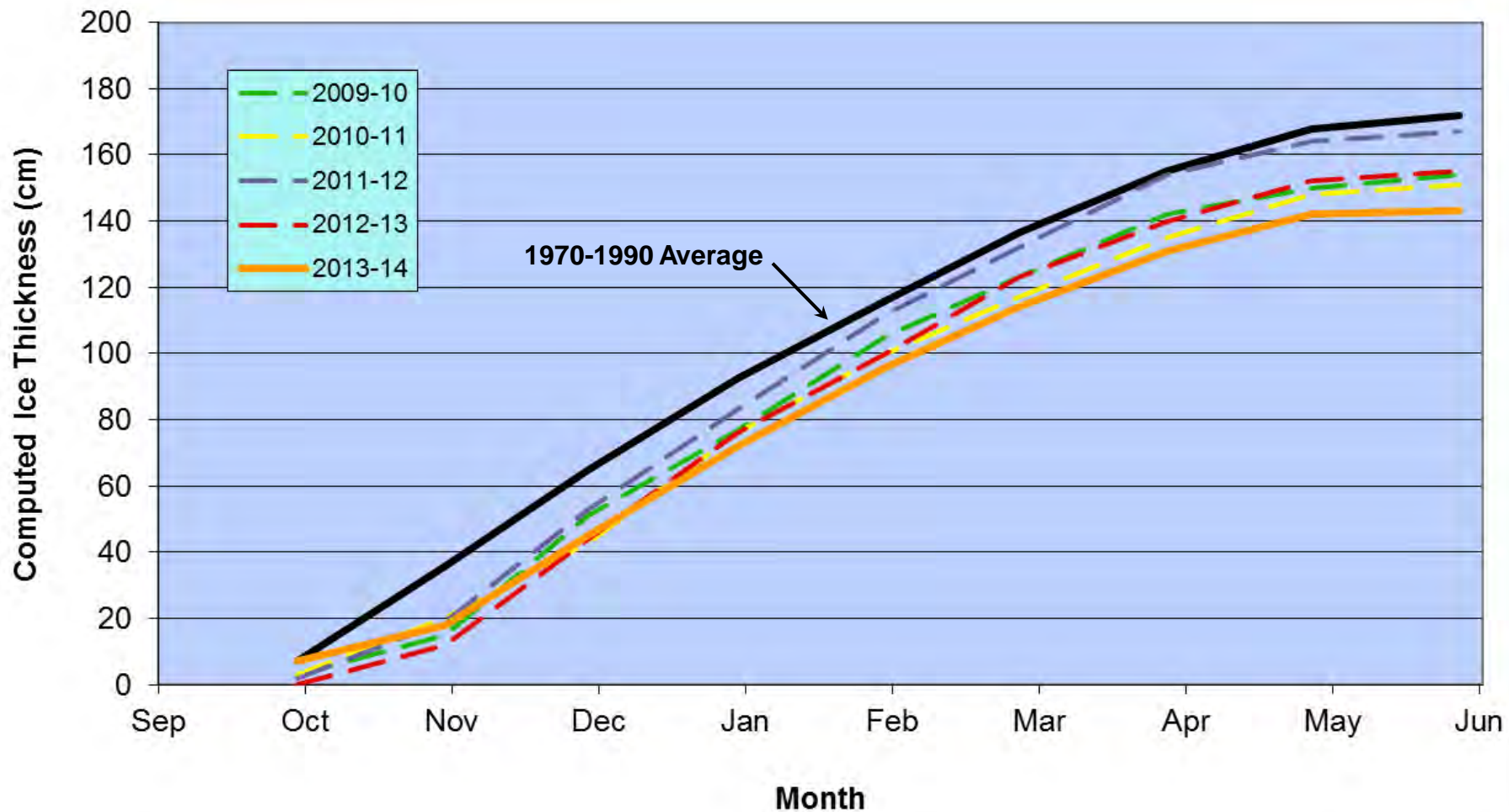
- Beaufort Sea Freeze-Up:
 - Currently occurs during fourth week in October
 - About 3 weeks later than in 1980s
- Chukchi Sea Freeze-Up:
 - Currently occurs during third week in November
 - About 1 month later than in 1970s

First-Year Ice Growth (Barrow)

➤ Computed Ice Thickness

- 1980-81 through '85-86: 171 cm
- 2009-10: 154
- 2010-11: 151
- 2011-12: 167
- 2012-13: 155
- 2013-14 143 ← lowest in 44 yr
- Recent Average: 154 cm
- Net Change: -17 cm

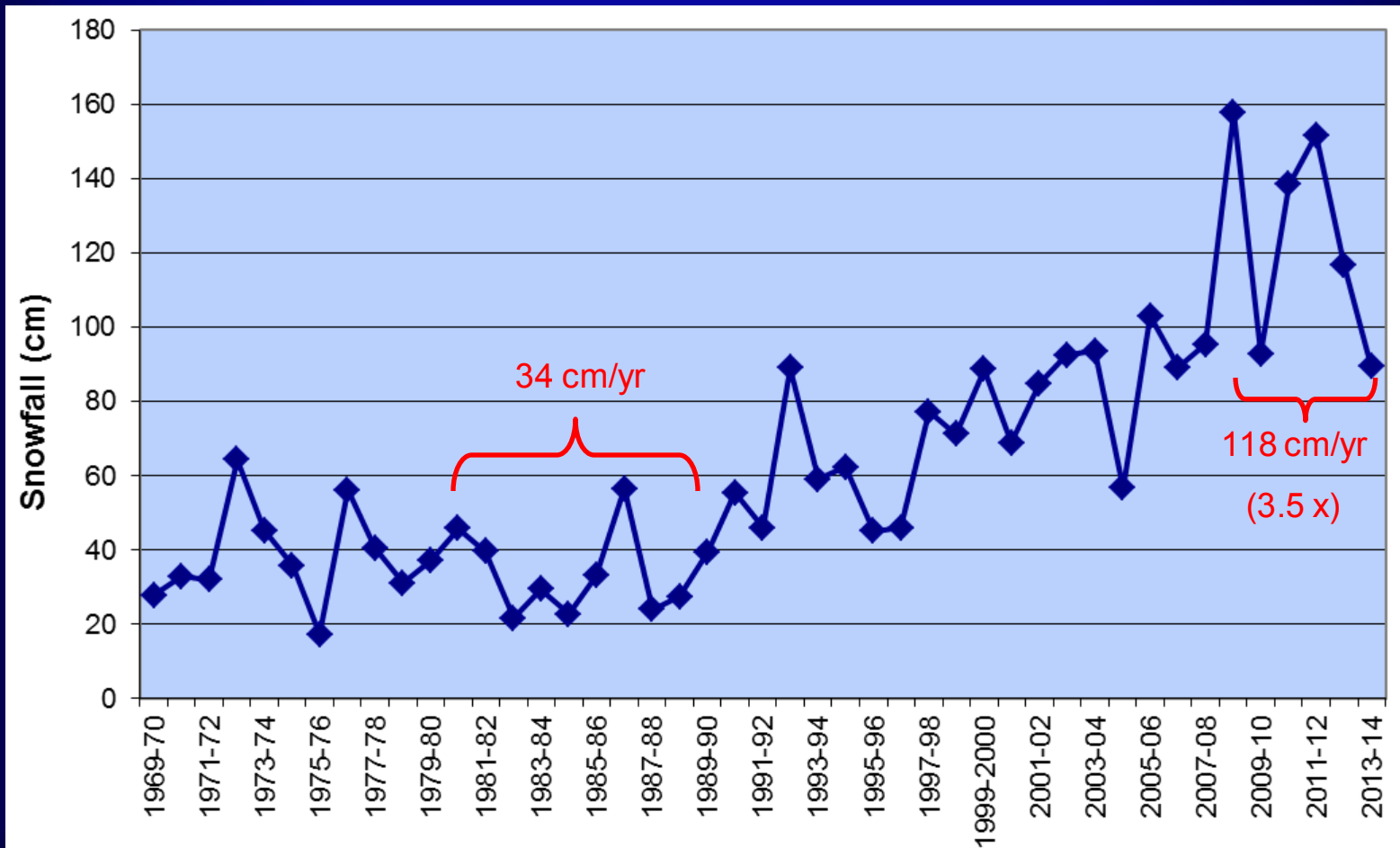
First-Year Ice Growth



Barrow Airport

First-Year Ice Growth

Brown & Cote (1992): insulating effect of increased snowfall outweighs warmer air temperatures in reducing ice thickness



Snowfall at Barrow: October - March

First-Year Ice Growth (Barrow)

➤ Trends

- Based on temperature alone, ice thickness has decreased by nearly 10% (17 cm) since early to mid-1980s
- Increased snowfall may be causing an even greater reduction in thickness due to its insulating effects
- Other temperature-related effects including reduced ice production in leads, decreased consolidation of ridges, & reduced ice strength probably exert greater influences on ice dynamics

Landfast Ice: Beaufort Sea

➤ 1980s

- Stable LFI anchored by grounded shear zone developed inside 20-m isobath by end of November

➤ Recent Years

- West of Prudhoe Bay, comparable LFI zone developed by end of January in 4 of past 5 years
- East of Prudhoe Bay, ice tended to remain poorly-grounded and unstable through mid-winter in 3 of past 5 years

➤ Trends

- West of Prudhoe Bay: LFI zone is similar to that in 1980s, but develops more slowly
- East of Prudhoe Bay: Stable, well-grounded shear zone is less likely to develop than in 1980s

Landfast Ice: Chukchi Sea

➤ 1980s

- Narrow strip of LFI anchored by grounded rubble
- Seaward limit typically located within 5 nm of coast
- Breakout events triggered by easterly storms prevented progressive expansion during freeze-up season

➤ Recent Years

- Comparable strip of LFI subject to breakout events in each of past five years

➤ Trend

- Narrow, ephemeral LFI zone noted in 1980s continues to prevail today

Chukchi Flaw Lead

➤ Mechanics

- Opens when ice is driven offshore by easterly winds
- Closes when ice is driven onshore by westerly winds or when cold temps & light winds promote refreezing
- Often extends NE of Point Barrow (“EFL”), providing a gateway for MYI invasions (“MYG”)

➤ 1980s

- Vaudrey observed widths less than 20 nm (aerial observations)

➤ Recent Years

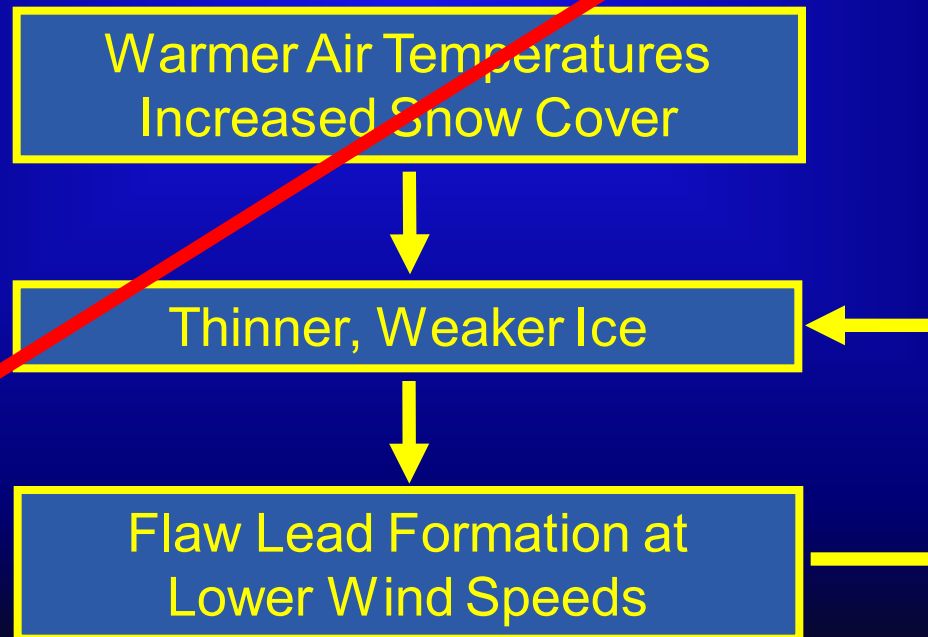
- 2009-10: up to 50 nm wide
- 2010-11: up to 60 nm wide
- 2011-12: up to 60 nm wide
- 2012-12: up to 150 nm wide (ice fracture event)
- 2013-14: up to 100 nm wide

Chukchi Flaw Lead

➤ Trends

- May attains greater widths than in 1980s
- Extends north of Point Barrow more frequently than in 1980s (EFL)

Feedback Loop



Coastal Flaw Lead

➤ Frequency of Occurrence

Feature	1993-94 to 2002-03	2003-04 to 2013-14
Flaw Lead	51%	49%
EFL	35%	37%

➤ Trends

- Frequencies with which flaw lead and EFL occur have remained constant since 1990s
- Width of lead may have increased since 1980s

Multi-Year Ice: Beaufort Sea

➤ 1980s

- Large MYI floes in 3 of 6 years
- MYI Fragments in remaining 3 years

➤ 2000-01 through 2008-09

- Sole MYI invasion in 2001-02

➤ Recent Years

- 2009-10: High concentration of large MYI floes
- 2010-11: Small MYI fragments on barrier islands
- 2011-12: None
- 2012-13: None
- 2013-14: None

Multi-Year Ice: Beaufort Sea

➤ Trends

- Probability of large MYI floes invading nearshore region has decreased substantially (2 invasions in last 14 yr)
- Causes:
 - Amount of MYI has decreased
 - Ice edge has retreated farther north
 - Open-water season has become warmer & stormier

Multi-Year Ice: Chukchi Sea

➤ 1980s

- Large MYI floes in all 3 years

➤ 2000-01 through 2008-09

- MYI floes in 5 of 9 years

➤ Recent Years

- 2009-10: High concentration of large MYI floes
- 2010-11: Large MYI floes present in Nov-Dec ← New Finding
- 2011-12: High concentration of large MYI floes
- 2012-13: None
- 2013-14: High concentration of large MYI floes

Multi-Year Ice: Chukchi Sea

➤ Trends

- Probability of large MY floes invading nearshore region has decreased, but to lesser extent than in Beaufort (9 invasions in last 14 yr)
- Impacts of less MYI, ice edge retreat, warmer temperatures & increased storminess have been partially offset by ability of EFL to divert MYI to southwest
- Nearly all invasions occur through MYG. (Sole exception occurred in Nov 2010, when MYI ice edge moved south before first-year ice canopy developed)

Long-Term Pack Ice Movement

➤ Constraints

- Period: Nov & Dec (data suitable for comparison)
- Region: Alaskan Beaufort Sea (Beaufort Gyre)

➤ 1980s

- Range: 4.9 – 6.3 nm/day

➤ Recent Years

Year	Monthly Drift Rate (nm/day)		
	Max	Min	Average
2010	9.9	5.5	7.3
2011	8.3	4.9	6.3
2013	3.4	1.2	1.9
Average			5.2

Long-Term Pack Ice Movement

➤ Trend

- Average drift rate in Alaskan Beaufort Sea (Nov-Dec):
~5 nm/day
- Similar to that in 1980s

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Summary & Conclusions

- Entire Study Area
- Beaufort Sea
- Chukchi Sea

Entire Study Area

1. Air Temperatures

- 2013-14: warmest winter in past 44 years

2. First-Year Ice Growth

- Computed thickness: 152 cm in Beaufort; 143 cm in Chukchi
- 5-yr average: 163 cm in Beaufort; 154 cm in Chukchi
- Long-Term: Nearly 10% less than in early 1980s

3. Freeze-Up

- Date of freeze-up cannot be predicted on the basis of FDD alone

Beaufort Sea

1. Late Summer

- Minimum extent of pack ice (Sep 13, 2013) was 50% larger than in 2012, but 6th lowest since 1979

2. Freeze-Up

- First Ice: Sep 24 ← earliest in 5 yr
- Nearshore Freeze-Up: Oct 26
- Complete Freeze-Up: Nov 20 ← latest in 5 yr
- Five-Year Averages
 - First Ice: Oct 5
 - Nearshore: Oct 24
 - Complete: Nov 9

Findings for Beaufort Sea

(continued)

3. Wind Regime (Oct – Mar)

- Westerlies predominated: 57% frequency
- Easterly predominance: January
- 20 storms (>15 kt): 9 easterly & 11 westerly
- 5-yr Averages: 9 easterly & 9 westerly

4. Landfast Ice

- Narrow & poorly-developed through Dec (westerly winds)
- Rapid expansion past 18-m isobath in Jan (sustained easterly winds & 2 prolonged easterly storms)
- Waxed and waned in Feb and Mar but retreated no farther than 18-m isobath

Findings for Beaufort Sea

(continued)

5. Pile-Ups

- 46 pile-ups caused by wind shifts in Nov & Dec
- 39 on barrier islands; 4 on man-made facilities; 3 on mainland
- Heights: 1 – 8 m
- Lengths: 50 – 2,600 m
- Encroachment Distances: 0 – 20 m

Findings for Beaufort Sea

(continued)

6. Multi-Year Ice

- Offshore: Present throughout freeze-up
- Nearshore: Absent except at Point Barrow
- Current invasion probability: < 15% (2 of past 14 freeze-up seasons)

7. Pack Ice Movement

- ~5 nm/day in Nov & Dec
- Unchanged from 1980s

Findings for Chukchi Sea

1. Freeze-Up

- First Ice: Oct 2 ← earliest in 5 yr
- Nearshore Freeze-Up: Nov 26
- Complete Freeze-Up: Dec 14 } latest in 5 yr
- Five-Year Averages
 - First Ice: Oct 7
 - Nearshore: Nov 16
 - Complete: Dec 4

2. Flash Freeze Event

- Nov 12
- 130 nm west of Icy Cape
- Much smaller than 2013 flash freeze patch
- 2nd documented occurrence in past five years

Findings for Chukchi Sea

(continued)

3. Wind Regime (Oct – Mar)

- Easterlies predominated: 61% frequency (all 6 months)
- 19 storms (>15 kt): 12 easterly & 7 westerly
- 5-yr Averages: 11 easterly & 5 westerly

4. Landfast Ice

- Narrow strip through Dec, except Blossom Shoals
- Mid-January: prolonged easterly storm dislodged virtually all LFI north of Nokotlek River mouth
- Feb & Mar: Width ranged from negligible to 20 nm
- End of Mar: Seaward edge located inside 11-m isobath in most areas

Findings for Chukchi Sea

(continued)

5. Flaw Lead

- Frequency of occurrence:
 - December: ~50%
 - January: ~70% (easterly winds & 3 easterly storms)
 - February: ~60%
 - March: ~50%
 - Entire Period: 57%
- Maximum width: 100 nm (Burger & Crackerjack plus parts of Hanna Shoal & West Prospects)
- Maximum length: Cape Lisburne to Point Barrow
- Maximum persistence: 15 days

Findings for Chukchi Sea

(continued)

6. Nearshore vs. Offshore Ice

- Transition ~50 nm offshore
- Nearshore: greater deformation indicative of collisions (loss of confinement associated with flaw lead)
- Offshore: less deformation indicative of rigid body motion
- Similar transition noted in past freeze-up studies, except location varies in accordance with width of flaw lead prior to flights

Findings for Chukchi Sea

(continued)

7. Pile-Ups

- 22 pile-ups caused by wind shifts in Nov & Dec
- Highest concentration on barrier islands east of Icy Cape
- Heights: 1 – 3 m ← Smallest in 5 yr
- Lengths: 100 – 7,800 m
- Encroachment Distances: 5 – 20 m

Findings for Chukchi Sea

(continued)

8. Multi-Year Ice

- MYI remained north of Point Barrow until mid-Dec
- 4 invasions from mid-Dec through mid-Jan via EFL
- Invasion in mid-Jan produced significant southerly displacement of MYI edge
- MYI continued to advance south through mid-March, when it reached vicinity of Icy Cape
- Current invasion probability: ~65% (9 of past 14 freeze-up seasons)

2013-14 Freeze-Up Study Wrap-Up Meeting

Agenda

1. Project Overview
2. Data Acquisition and Analysis
3. Beaufort Sea Freeze-Up
4. Chukchi Sea Freeze-Up
5. Freeze-Up: Recent Years vs. 1980s
6. Summary and Conclusions
7. Discussion



Discussion



2013-14 Chukchi Sea Freeze-Up

- Meteorological Overview
- Early Freeze-Up
 - Late Summer
 - October
 - November
- Late Freeze-Up
 - December
 - January
- Mid-Winter
 - February
 - March
 - Late March Reconnaissance Flights

2013-14 Meteorological Overview

➤ Air Temperatures

- Temperatures: normal to well above normal
- Especially warm in Oct, Feb, & Mar

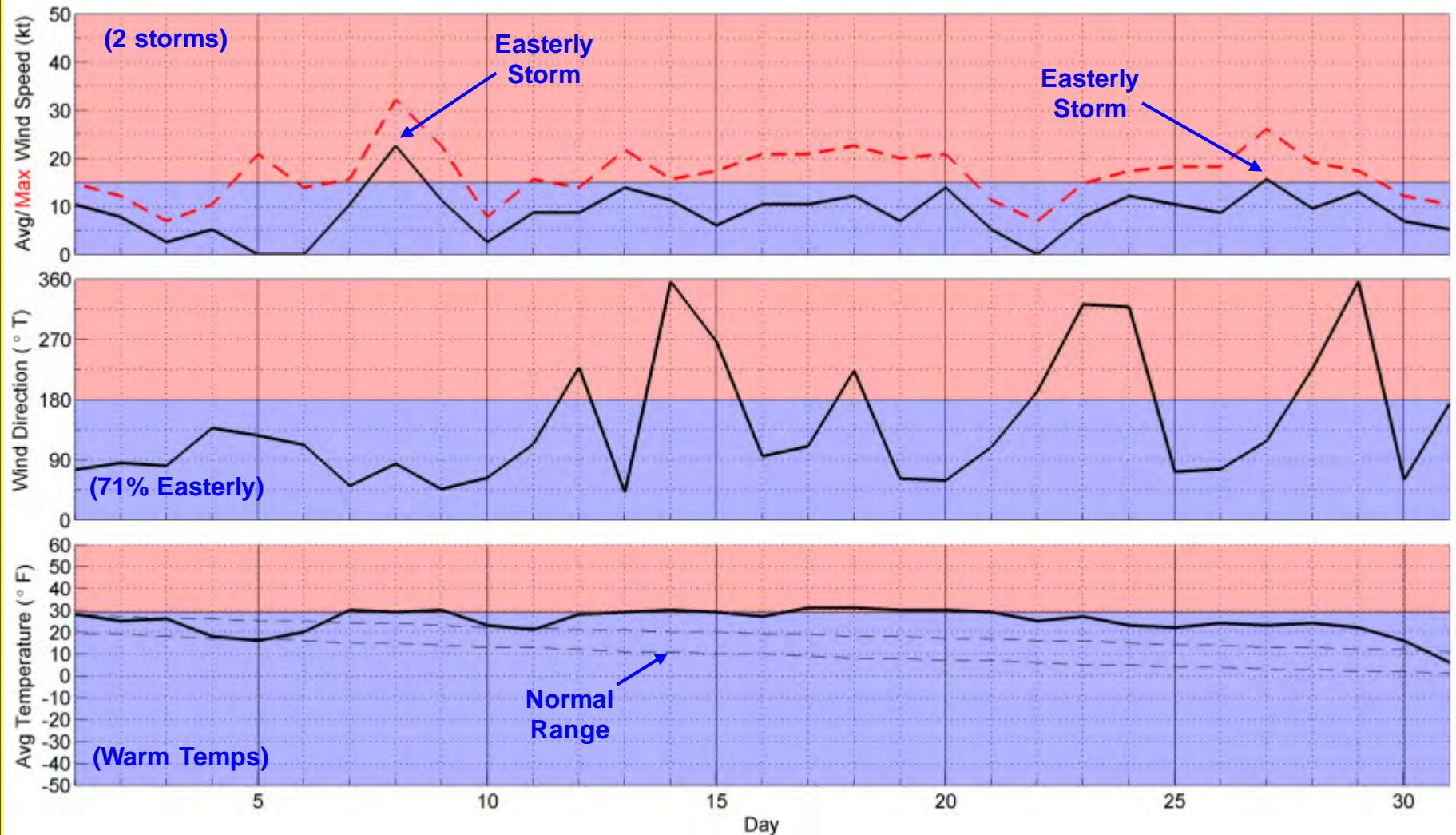
➤ Winds

- Easterlies prevailed 61% of the time
- Average monthly speed
 - Highest in November and January (14 kt)
 - Lowest in March (8 kt)

➤ Storms

- 19 storms (>15 kt)
- 12 easterlies + 7 westerlies

October Meteorological Conditions



Barrow Airport

October Overview

Ice Cover

- 1st Week: Ice began to form in Kasegaluk Lagoon, Kuk River Inlet & Peard Bay
- Freeze-up proceeded slowly due to unseasonably warm air temperatures
- Coastal waters remained ice-free at month-end

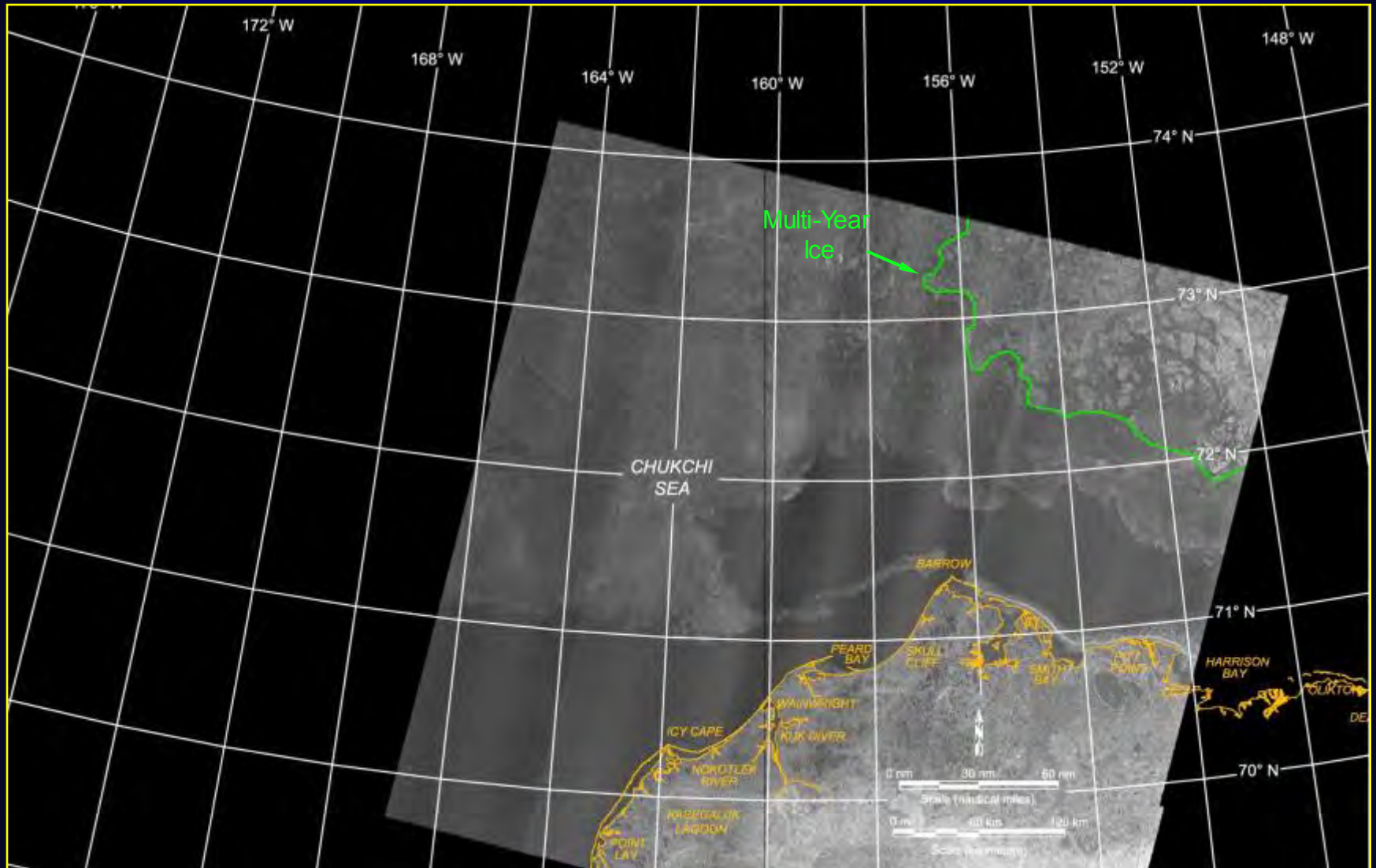
Computed Ice Thickness

- 18 cm for undisturbed ice at month-end

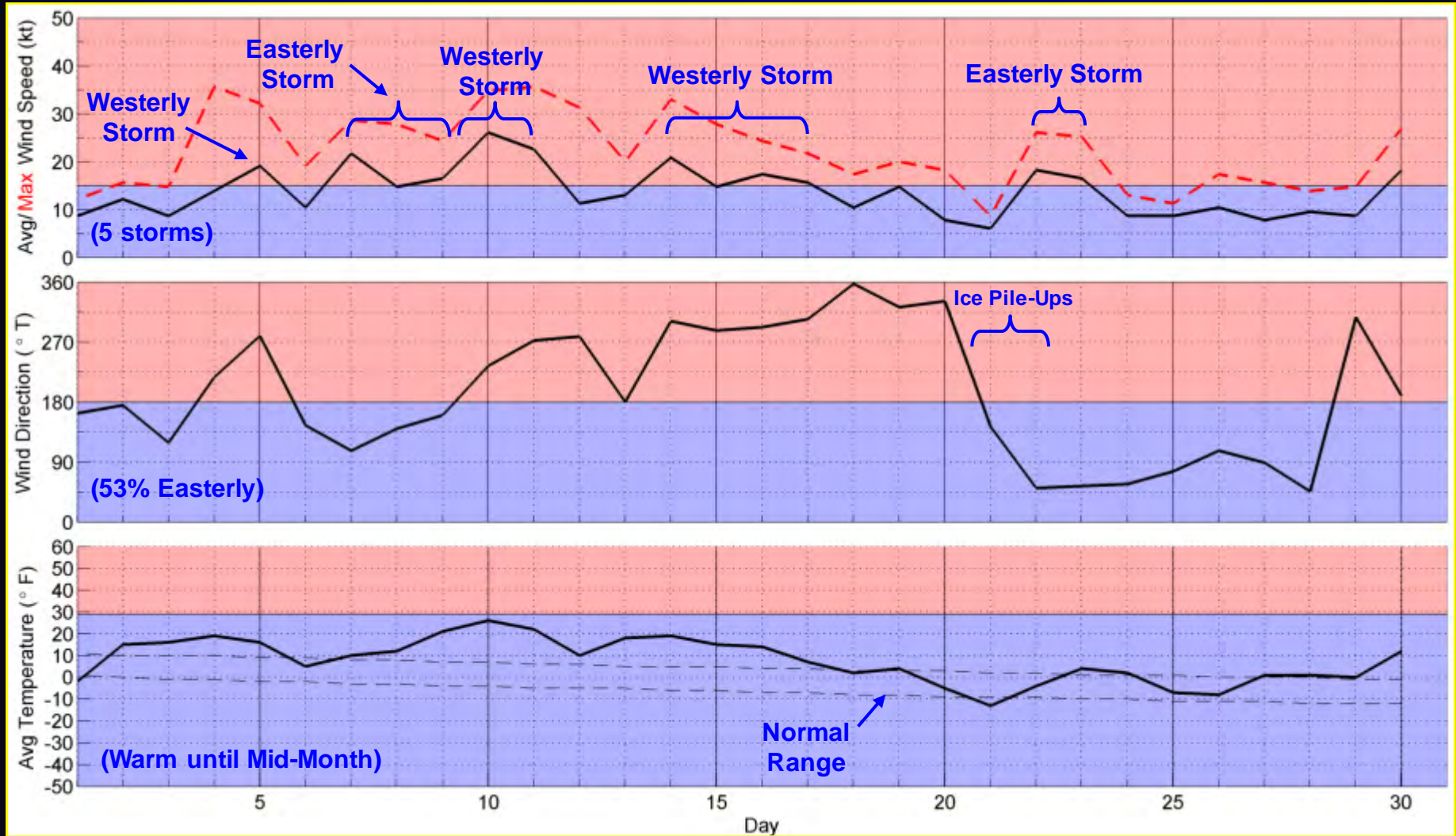
Multi-Year Ice

- North of Point Barrow

RADARSAT-2 Image on Oct 30, 2013



November Meteorological Conditions



Barrow Airport

November Overview

Ice Cover

- 1st Half: Ice edge retreated slightly to north
- Nov 12: Flash freeze 130 nm west of Icy Cape
- Nearshore Freeze-Up: Nov 26

Date	Ice Cover in Shell Prospects (%)			
	Hanna Shoal	Burger	Crackerjack	West
Oct 22	0	0	0	0
Oct 26	30	30	0	0
Oct 30	10	90	25	0
Nov 2	90	20	0	0
Nov 7	100	50	0	0
Nov 15	70	0	0	0
Nov 21	100	100	100	100

November Overview

Computed Ice Thickness

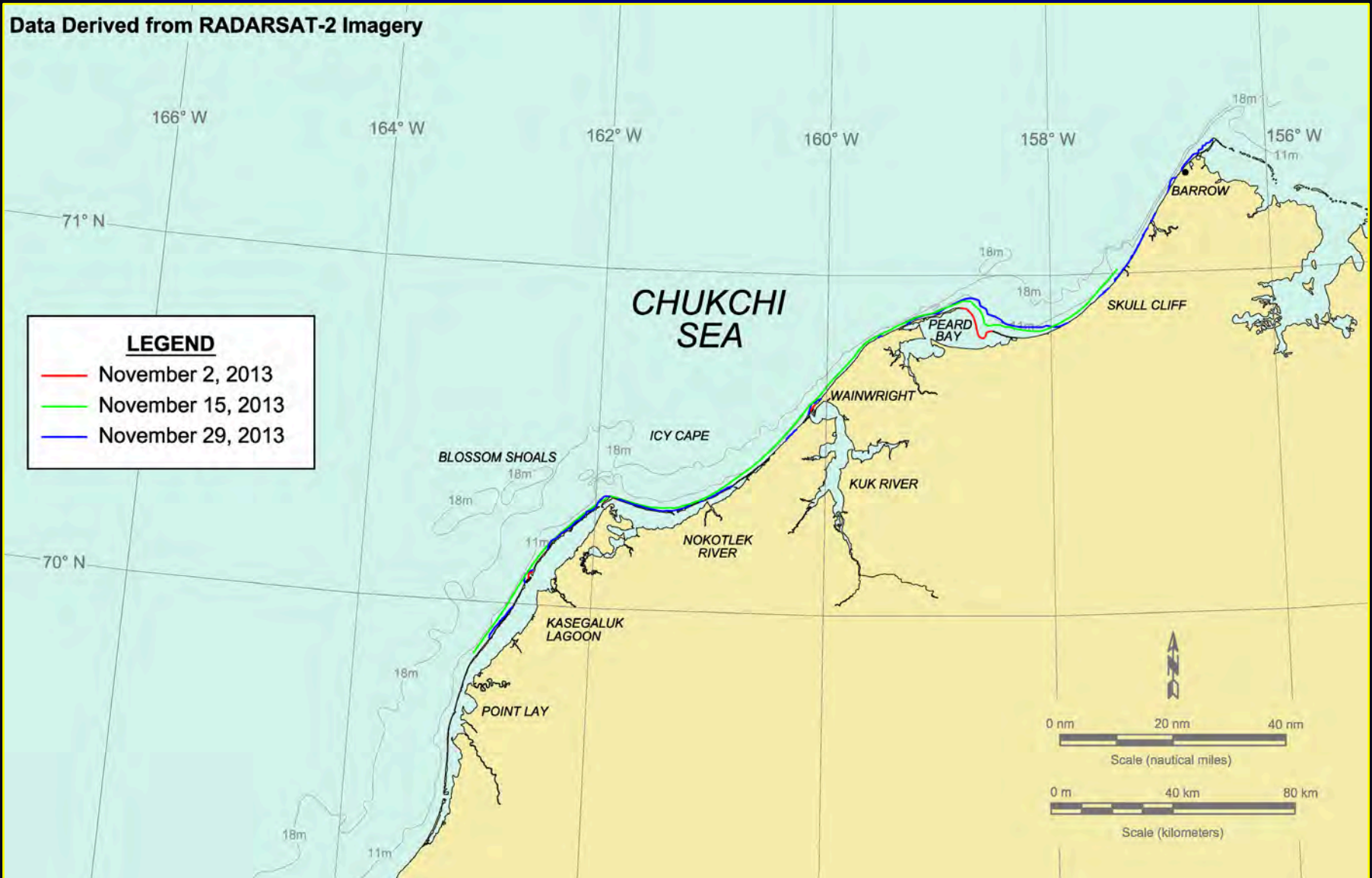
➤ 18 cm → 45 cm (+27 cm)

Landfast Ice

- Began to form in early Nov in semi-protected waters of Peard Bay, Kuk River Inlet & Utukok River Inlet
- At month-end:
 - Narrow, discontinuous strip from Barrow to Peard Bay
 - Narrow strip from Wainwright to Point Lay

November Landfast Ice Edge

Data Derived from RADARSAT-2 Imagery



November Overview

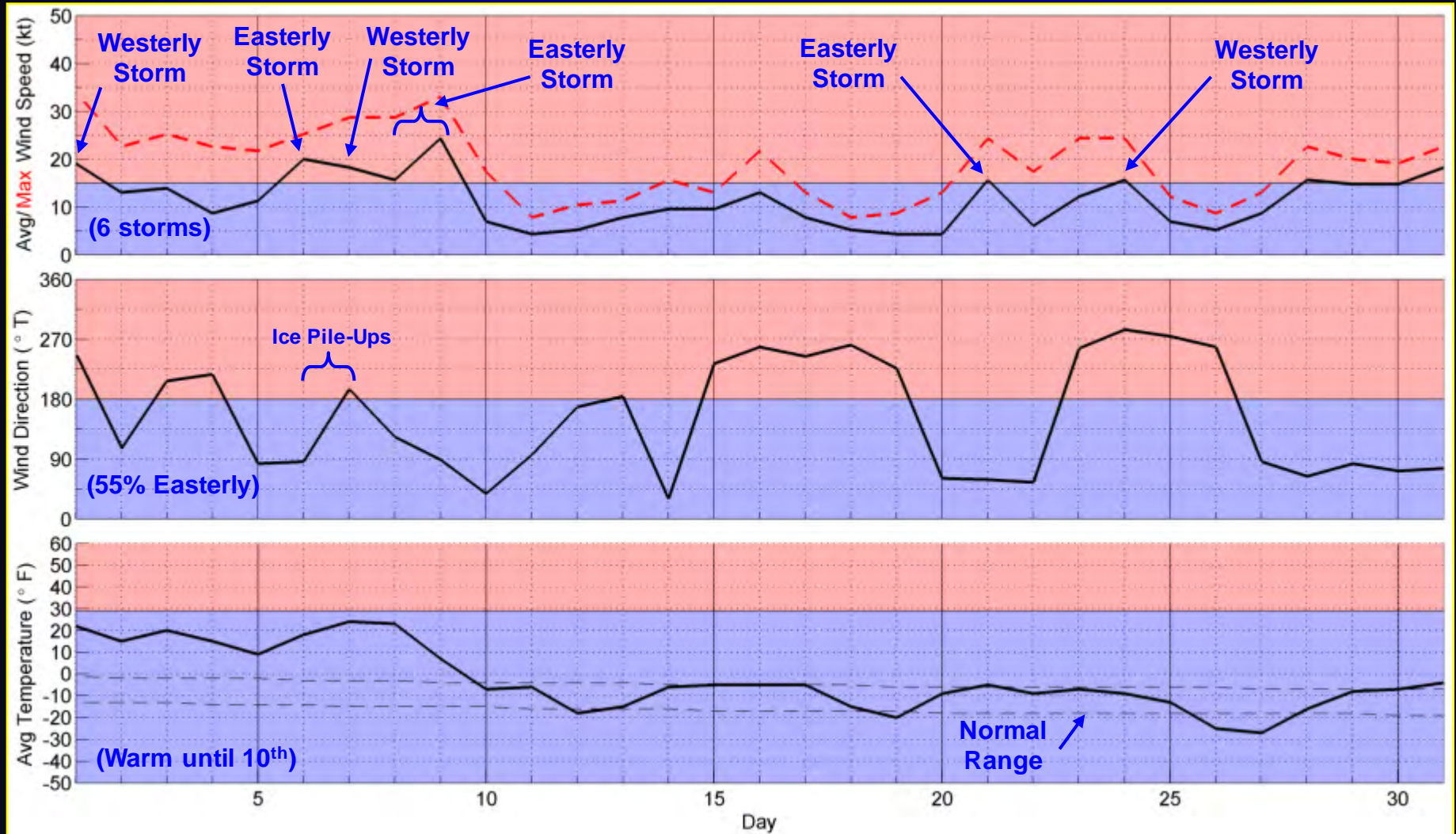
Ice Pile-Ups

- Nov 21-22: 3 pile-ups formed on NE-facing beaches when winds backed from S to NE

Multi-Year Ice

- Remained north of Point Barrow

December Meteorological Conditions



Barrow Airport

December Overview

Computed Ice Thickness

- 45 cm → 72 cm (+27 cm)

Landfast Ice

- LFI zone remained narrow and poorly-developed due to frequent wind shifts
- Width on Dec 30:
 - 0.9 nm off Pt. Barrow
 - 0.9 nm off Pt. Belcher
 - 0.7 nm off Wainwright
 - 7.8 nm E of Icy Cape (Blossom Shoals)

Ice Pile-Ups

- Dec 7: 19 pile-ups formed on NW-facing beaches when winds veered from E to W

December Overview

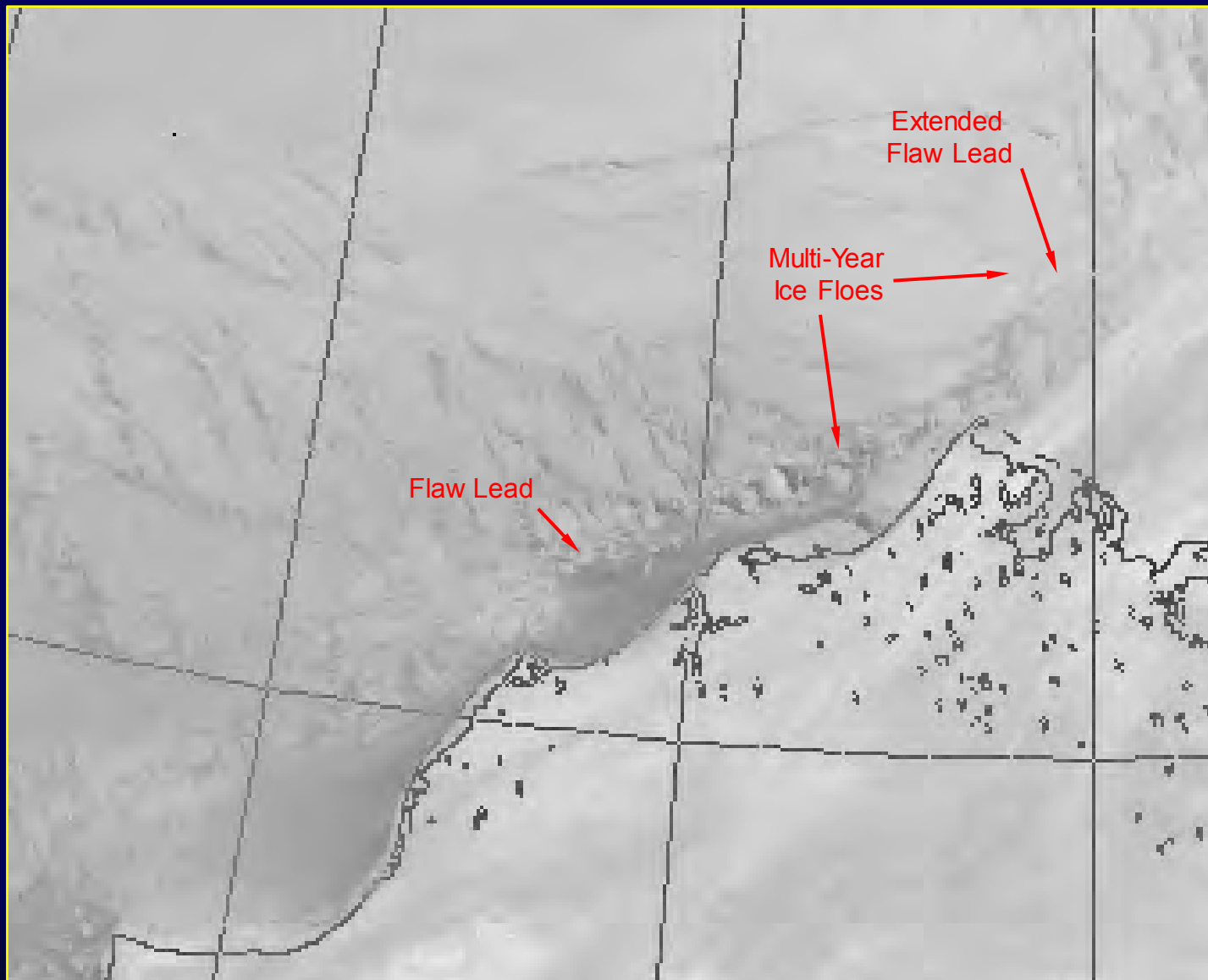
Flaw Lead

- Open 48% of the time due to easterly winds & 3 easterly storms
- Length: 50 to 220 nm
- Width: 12 to 60 nm

Multi-Year Ice

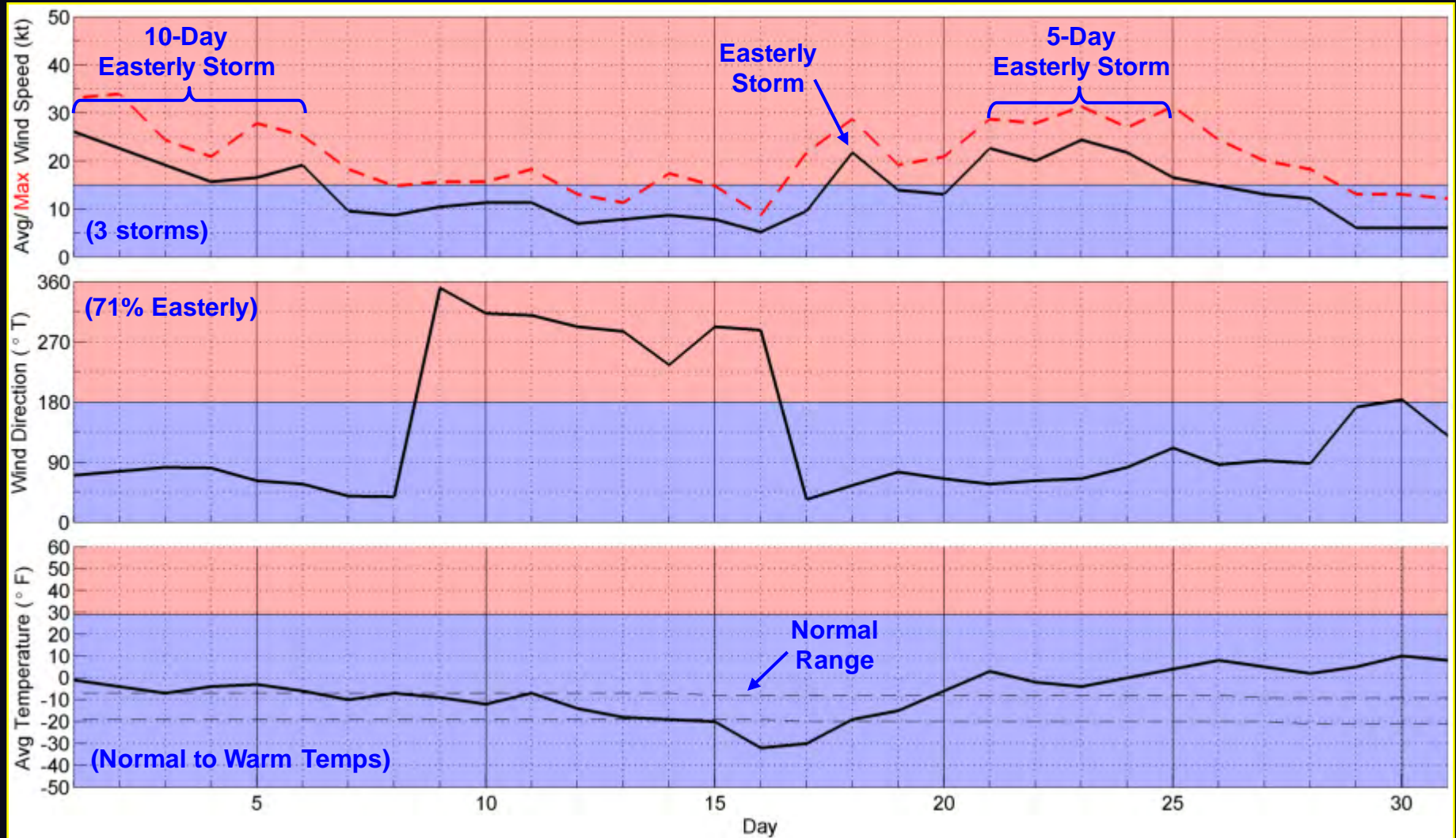
- North of Point Barrow until Dec 23
- MYI invasions occurred on Dec 23 and Dec 30-Jan 3 when flaw lead extended north of Pt. Barrow (“Extended Flaw Lead” or “EFL”) to intersect S boundary of MYI (“Multi-Year Gateway”)

Multi-Year Gateway on Dec 23, 2013



After: National Weather Service, 2014

January Meteorological Conditions



Barrow Airport

January Overview

Computed Ice Thickness

- 72 cm → 96 cm (+24 cm)

Landfast Ice

- Narrowed in response to first easterly storm
- Rebounded modestly in response to light westerly winds
- Disappeared completely north of Nokotlek River in response to second easterly storm ●

Flaw Lead

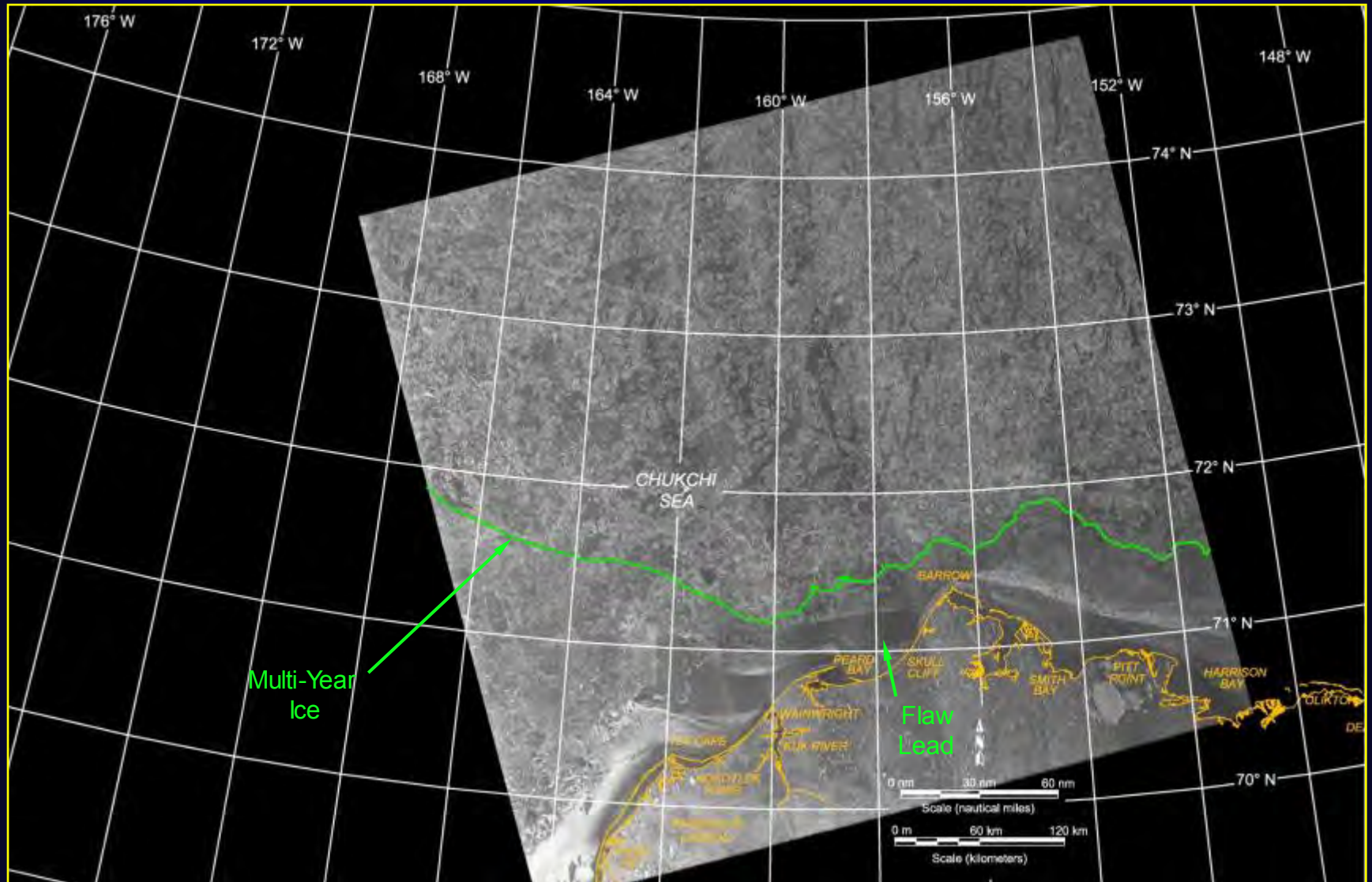
- Open 69% of the time due to easterly winds & 3 easterly storms
- Length: 190 to 210 nm
- Width: 50 to 60 nm

January Overview

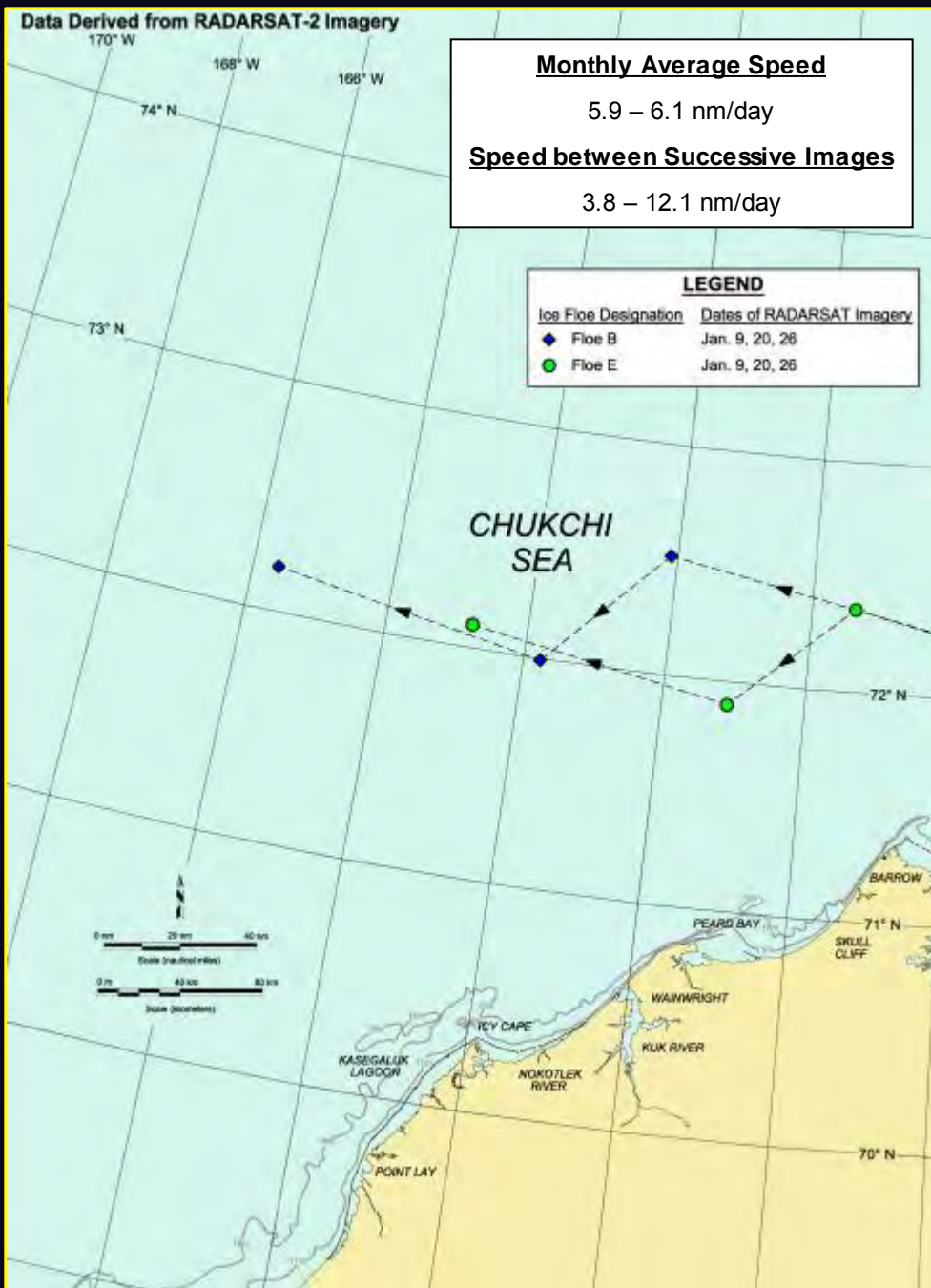
Multi-Year Ice

- MYI invasions via EFL:
 - Dec 30 – Jan 3
 - Jan 7 – 10
 - Jan 18 – 28
- Invasion that began Jan 18 introduced substantial quantity of MYI into region south and west of Pt. Barrow
- MYI remained in this region through end of study period (end of March)

RADARSAT-2 Image on Jan 20, 2014



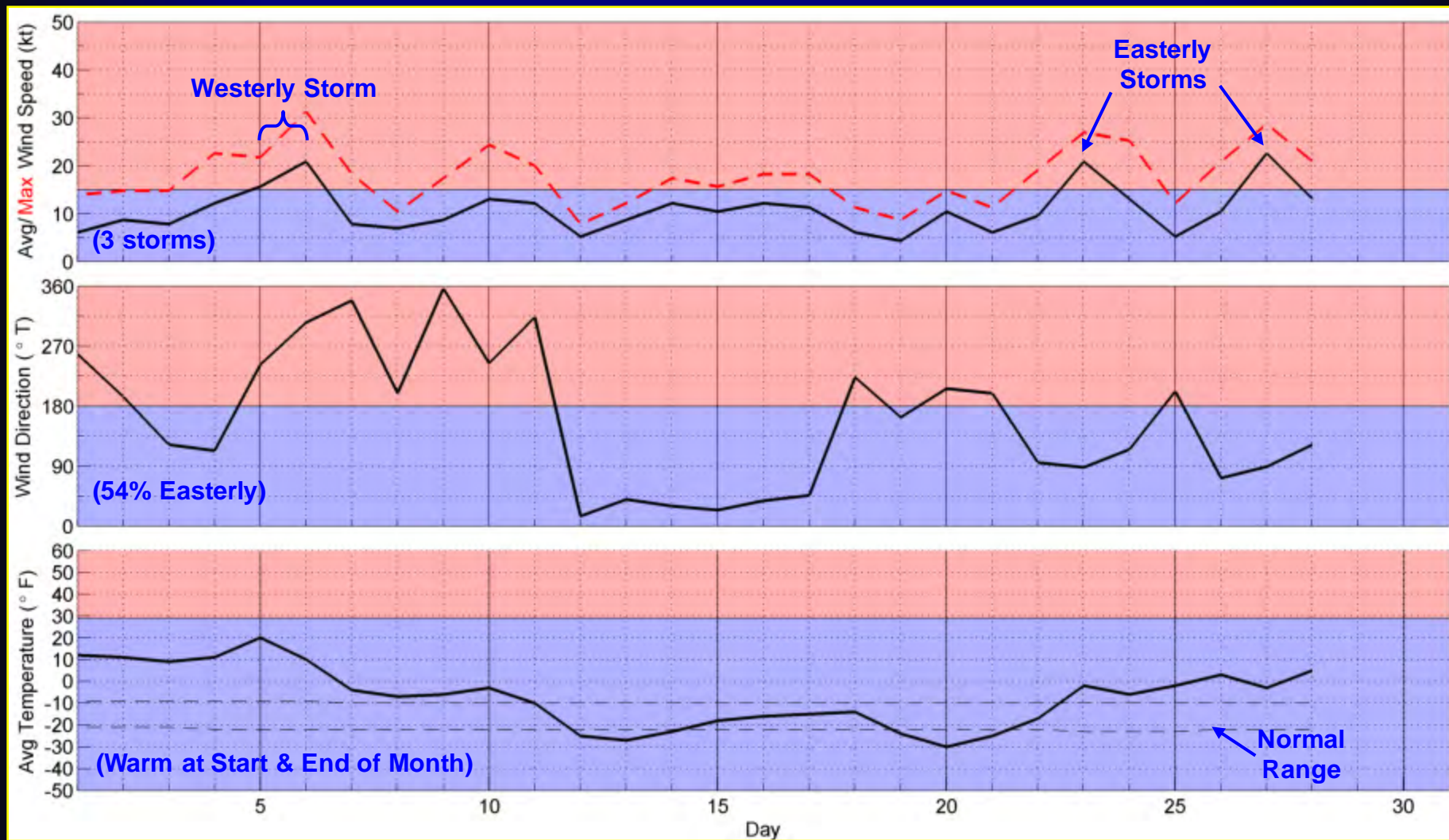
After: RADARSAT-2 Data and Products © MacDonald Dettweiler and Associates Ltd., 2014 – All Rights Reserved



January Multi-Year Ice Floe Movement

- Rapid westerly movement driven by easterly storms

February Meteorological Conditions



Barrow Airport

February Overview

Computed Ice Thickness

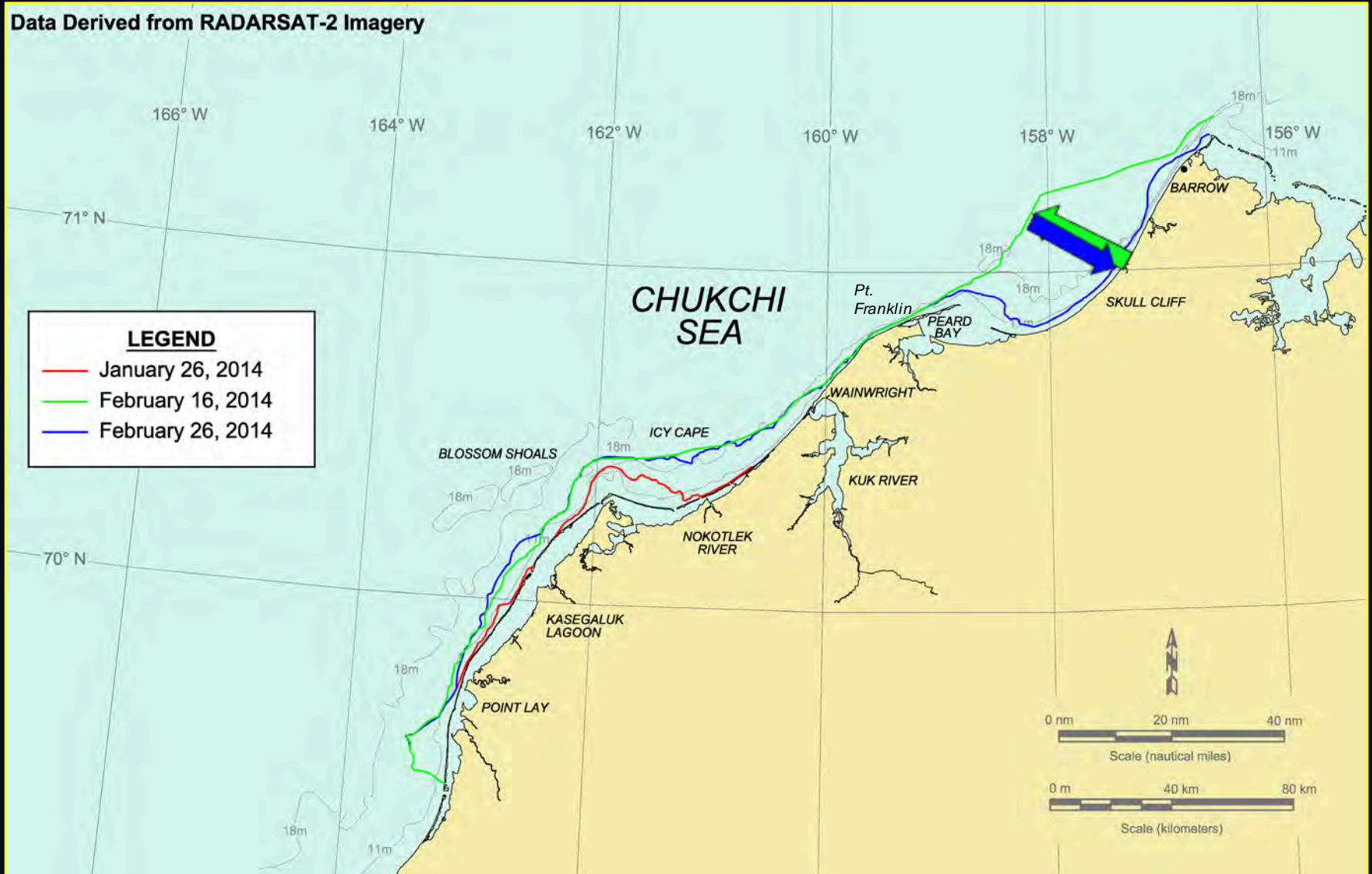
➤ 96 cm → 114 cm (+18 cm)

Landfast Ice

- First half of month: continuous band re-established from Pt. Barrow to Pt. Lay by westerly winds & westerly storm
- Second half of month:
 - North of Pt. Franklin: losses resulted from easterly winds & easterly storm
 - South of Pt. Franklin: sufficiently well-grounded to remain stable

February Landfast Ice Edge

Data Derived from RADARSAT-2 Imagery



February Overview

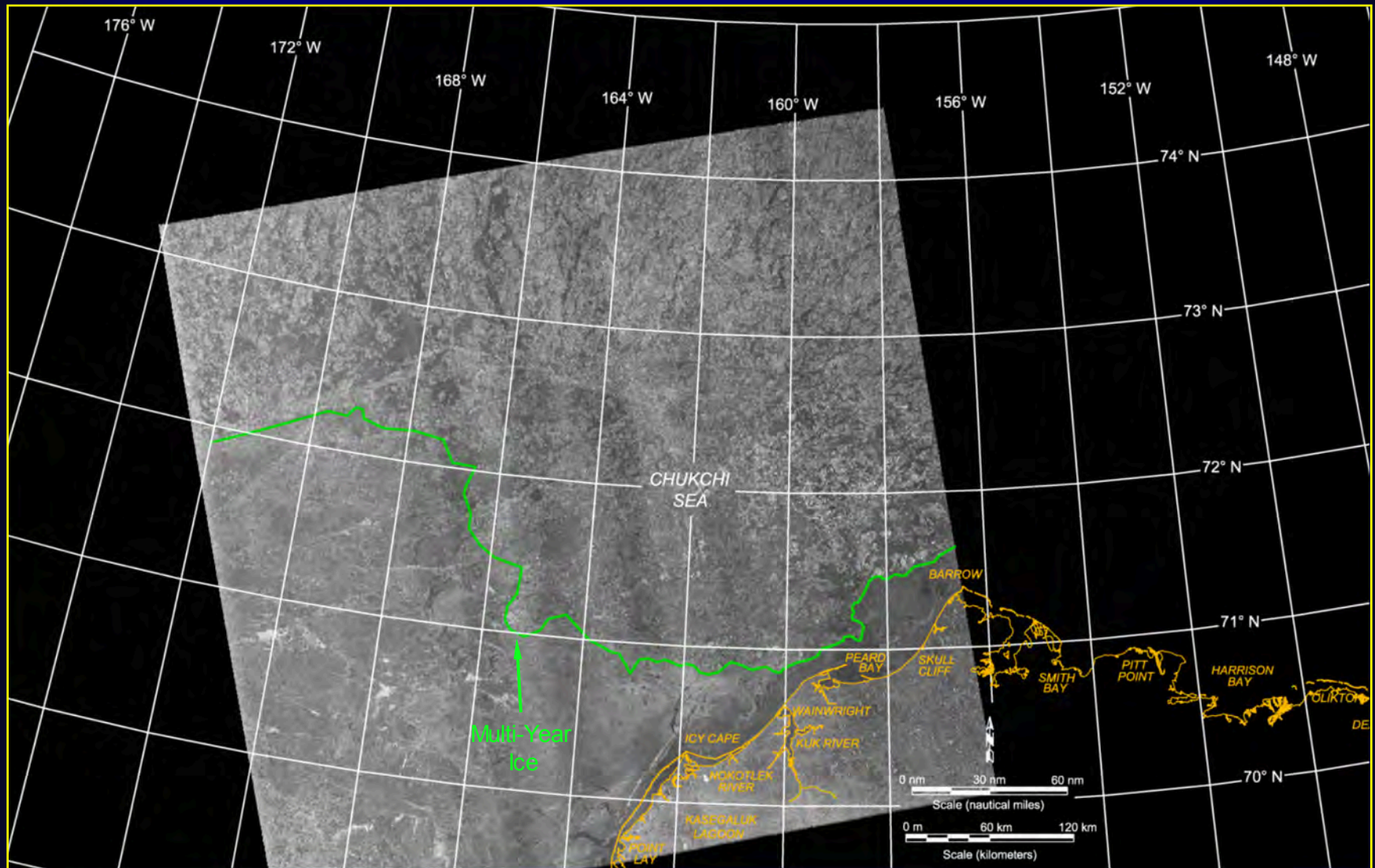
Coastal Flaw Lead

- Open 62% of the time
- Length: 190 to 250 nm
- Width: 9 to 100 nm
- 100-nm width encompassed all of Burger & Crackerjack plus parts of Hanna Shoal & West Prospects

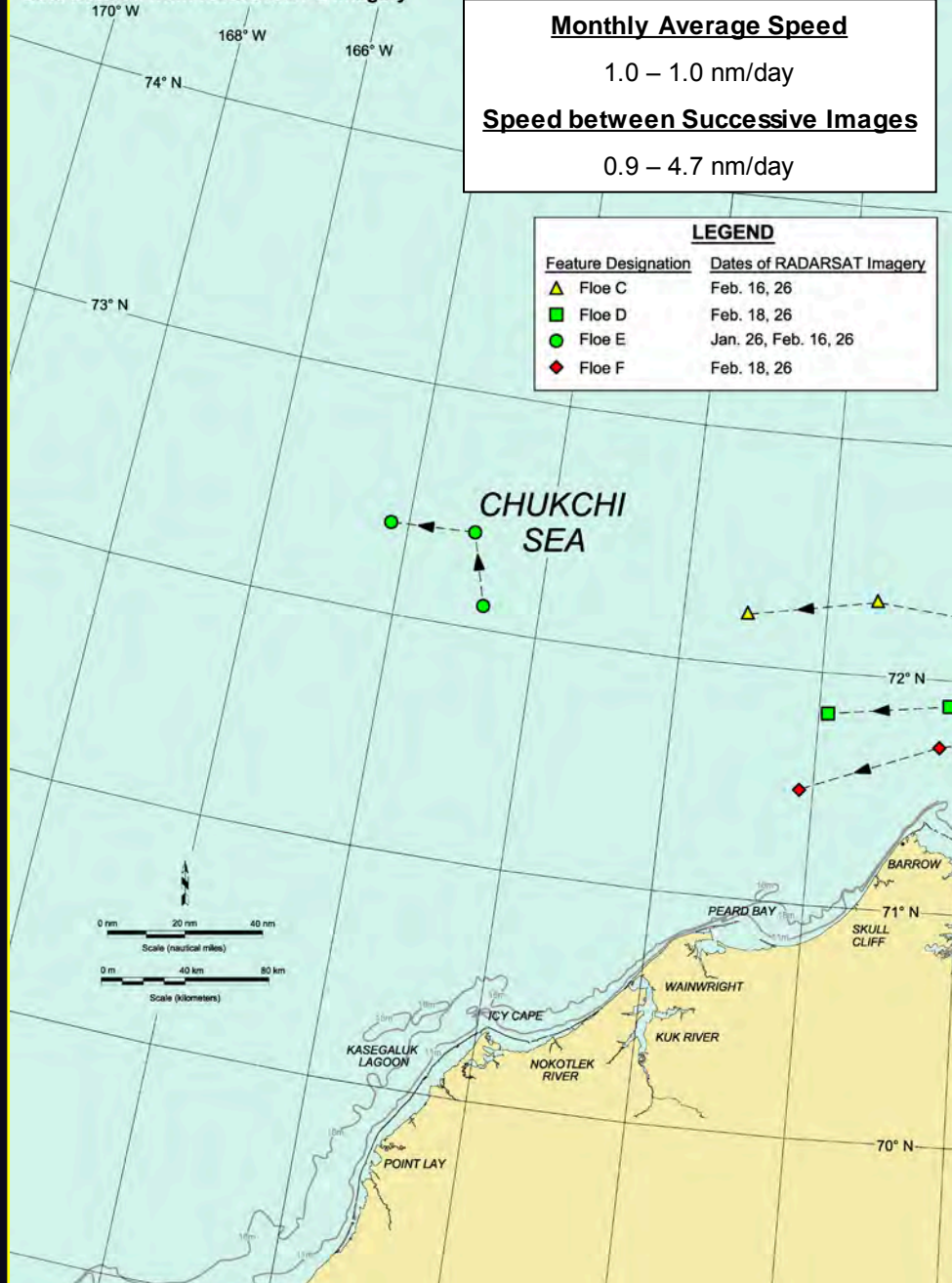
Multi-Year Ice

- MYI edge advanced farther south and closer to shore as month progressed

Radarsat-2 Image on Feb 26, 2014



Data Derived from RADARSAT-2 Imagery



February Multi-Year Ice Movement

- Jan 26 – Feb 16: Small northerly displacement from mixed winds
- Feb 16 – 26: Westerly displacement from easterly winds & easterly storm

February Landfast Ice Edge and Telemetry Buoy Tracks



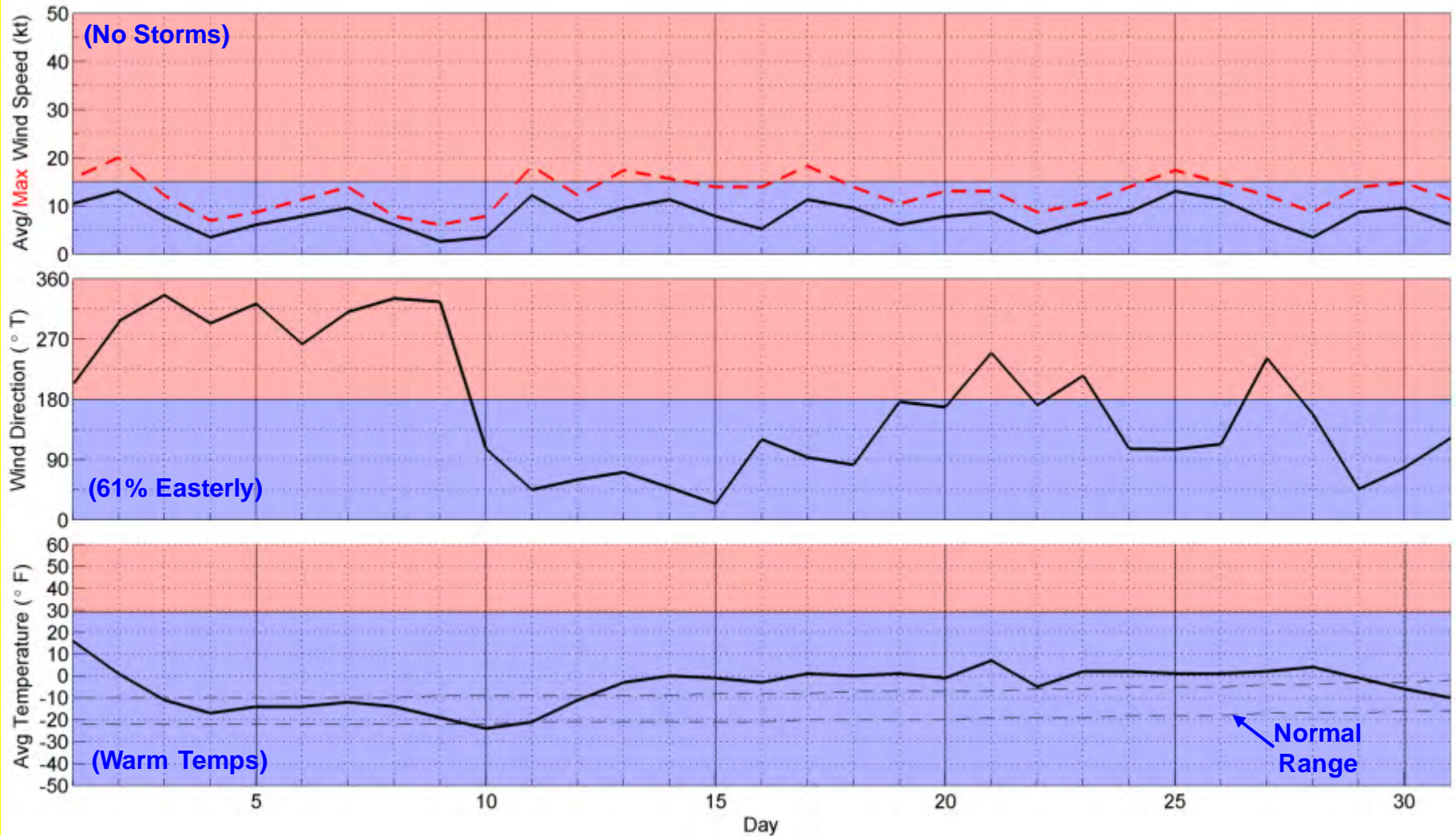
➤ Feb 27

Winds 23 kt

Buoys 0.72 kt

Wind Factor 3.1%

March Meteorological Conditions



Barrow Airport

March Overview

Computed Ice Thickness

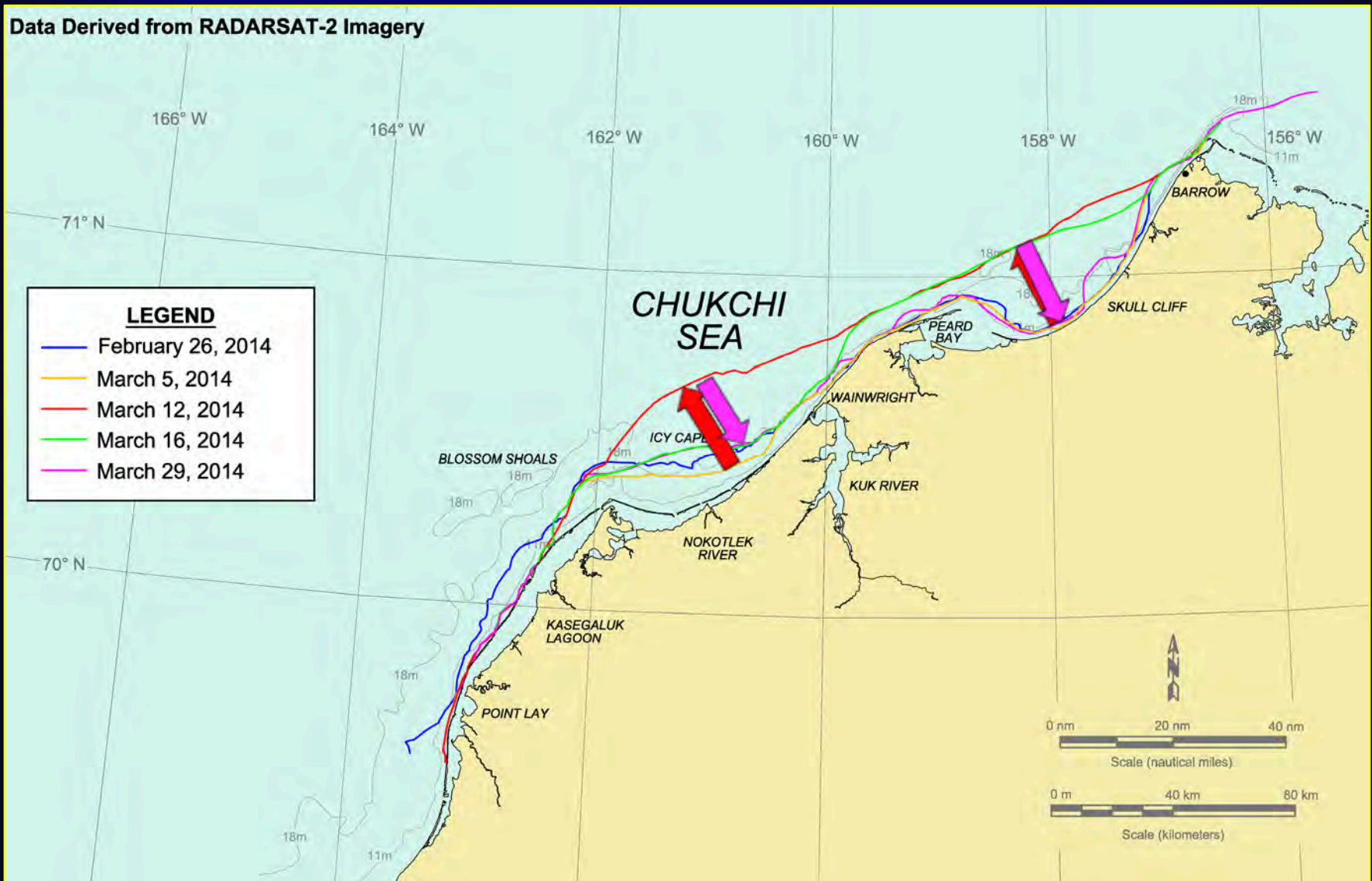
- 114 cm → 131 cm (141 cm in Beaufort)

Landfast Ice

- Mar 5 – 12: Light westerly winds produced substantial advance (up to 18 nm)
- Mar 12 – 29: Light easterly winds reversed advance
- Month-end:
 - Continuous but narrow strip
 - Max width (10 nm) E of Icy Cape

March Landfast Ice Edge

Data Derived from RADARSAT-2 Imagery



March Overview

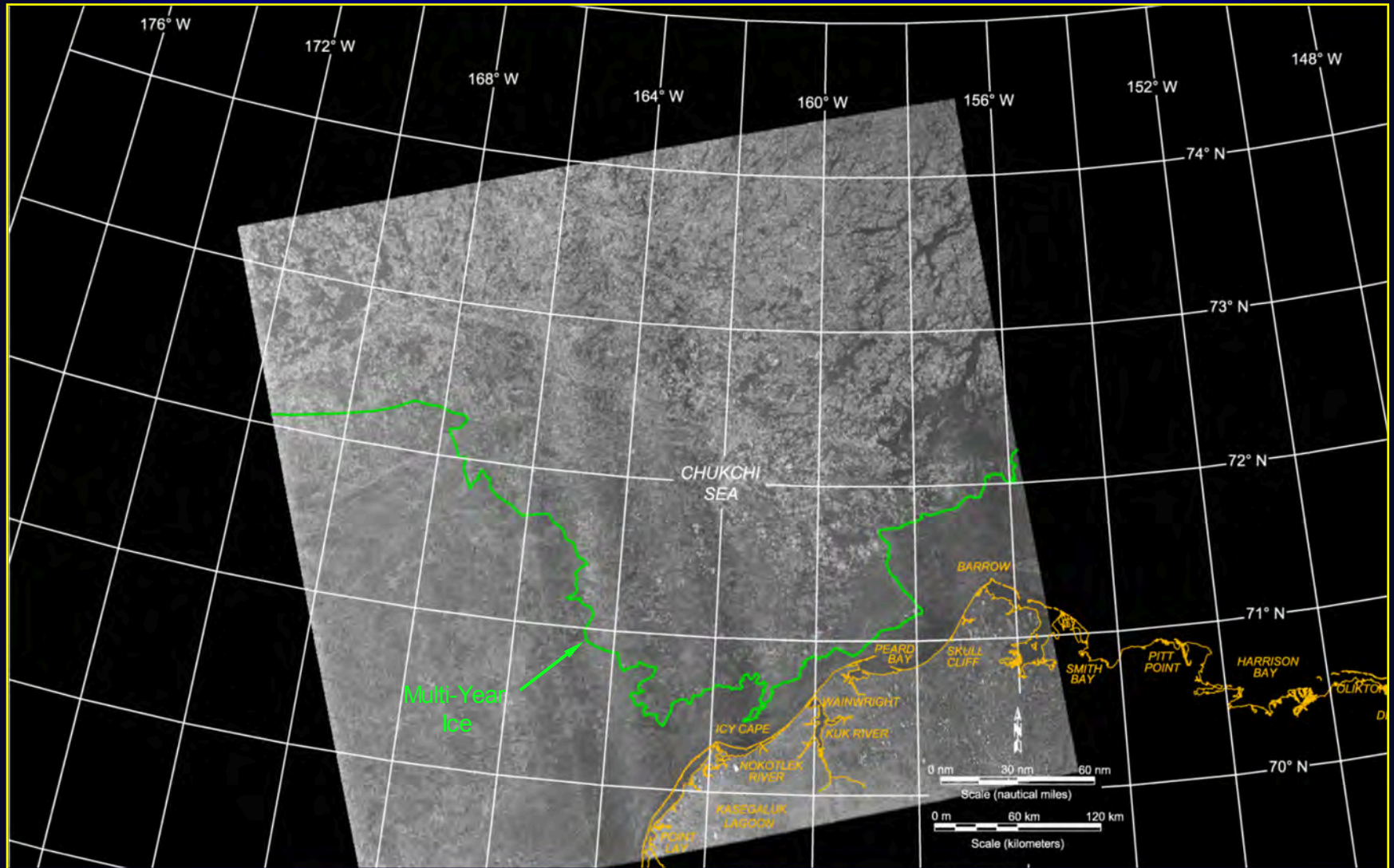
Coastal Flaw Lead

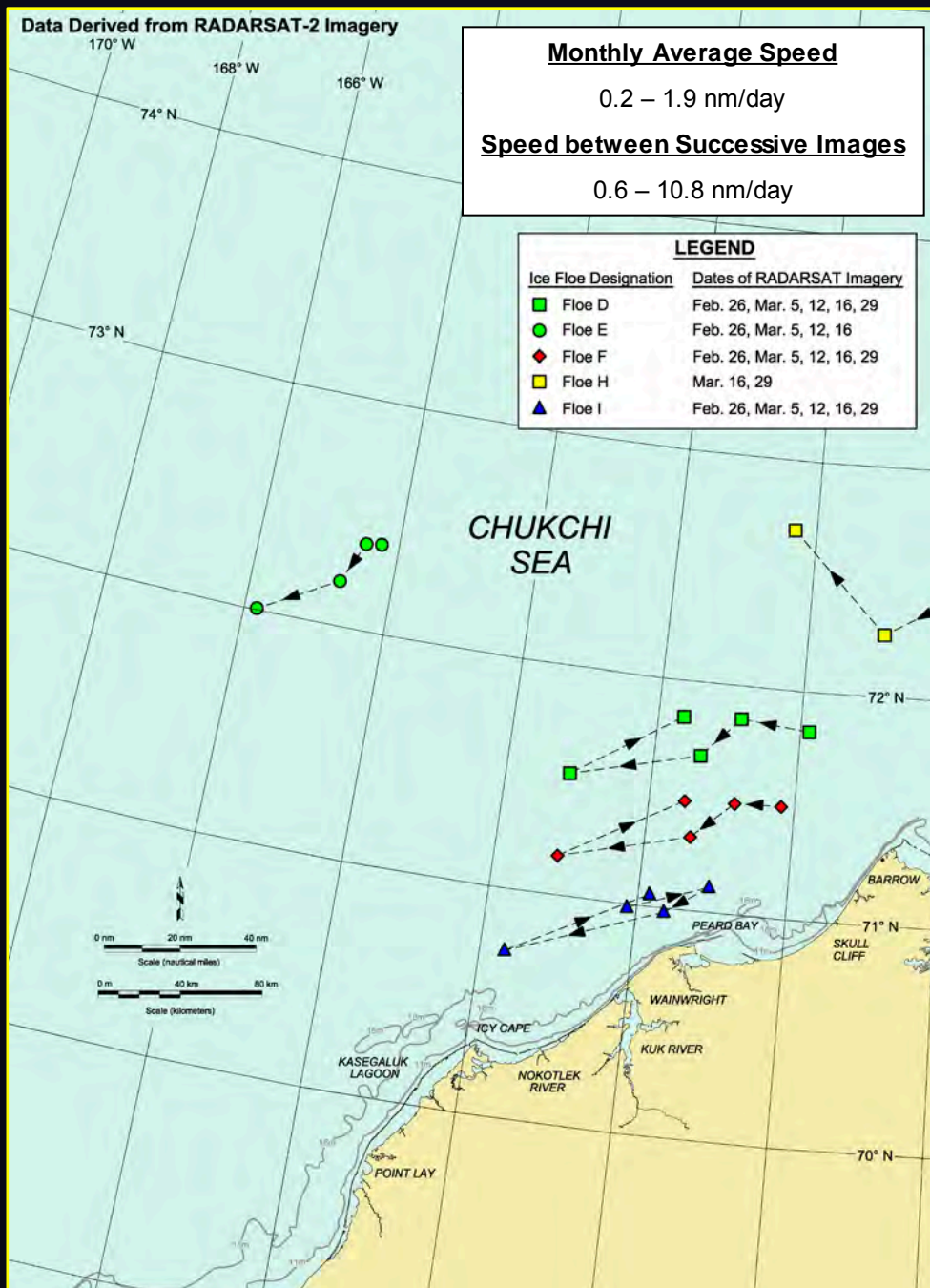
- Open 48% of the time
- Length: 250 nm (all 3 occasions)
- Width: 15 to 30 nm

Multi-Year Ice

- EFL occurred on multiple occasions but never developed into MYG
- MYI edge drifted farther south, reaching Icy Cape at month-end

Radarsat-2 Image on Mar 29, 2014





March Multi-Year Ice Movement

- Low average speeds reflecting wind reversals
- Influence of flaw lead
 - SW – NE trajectories
 - High speeds



March Landfast Ice Edge and Telemetry Buoy Tracks

- 3 buoys at entrance to Peard Bay remained stationary (landfast ice)
- 4 buoys on MYI floes moved SW – NE at relatively high speeds due to loss of confinement (max daily average = 0.67 kt)

Reconnaissance Flights: March 30 & 31

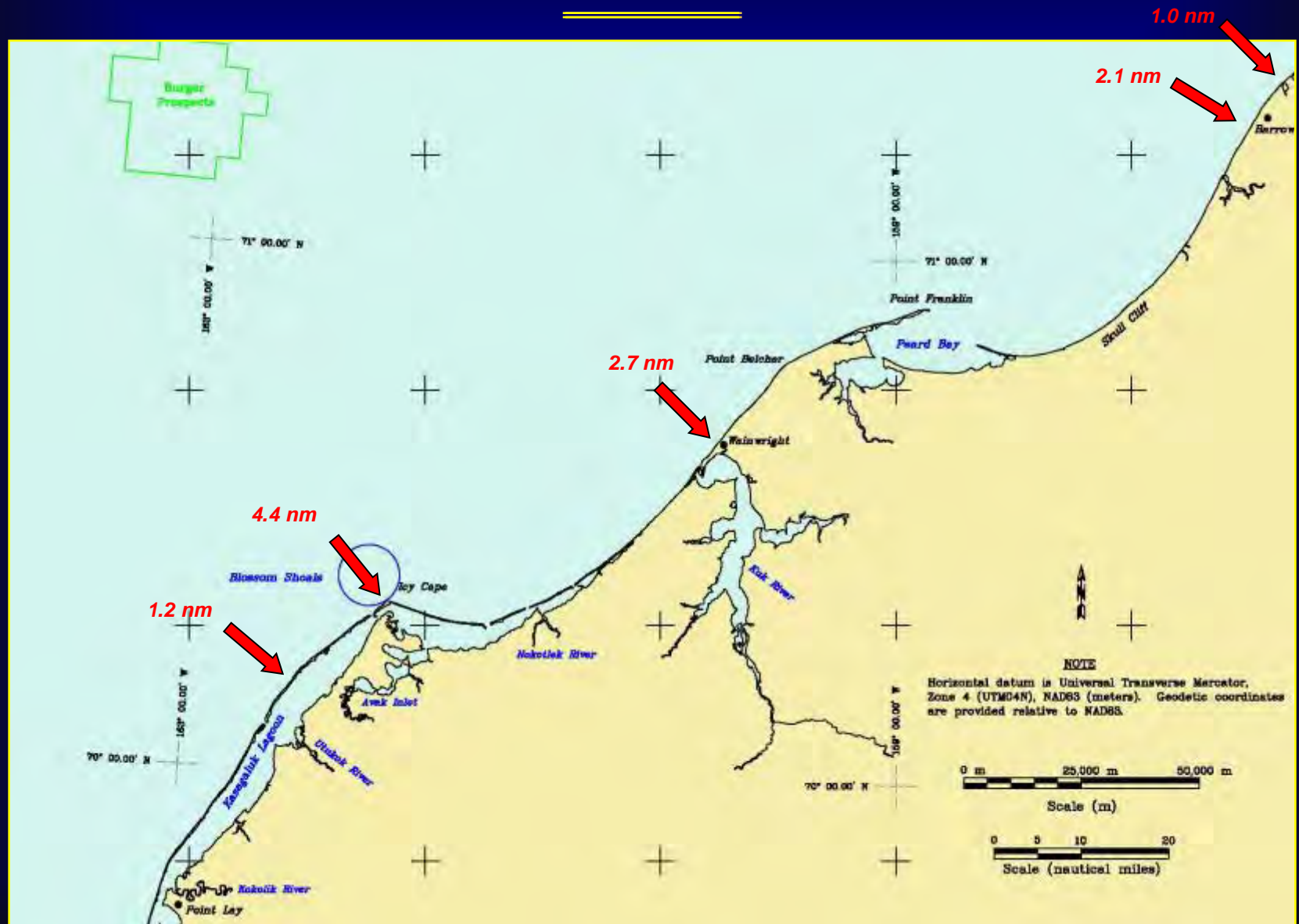
Lagoon Ice

- Flat and undeformed (as in each of past 4 yr)

Landfast Ice

- Narrow, continuous strip from Pt. Barrow to Pt. Lay
- Mixture of flat & deformed ice
- Ridge & rubble heights to 5 m, with largest accumulation on Blossom Shoals

Landfast Ice Zone



Reconnaissance Flights: March 30 & 31

Coastal Flaw Lead

- Modest lead reflecting light easterly winds preceding the flights
- 5 nm wide off Barrow; 15 nm wide off Point Lay
- Mixture of open water, nilas, and young ice

Offshore Ice

- From flaw lead to Burger Prospects: ridge & rubble heights relatively constant at 2 to 3 m
- More extensive deformation within 50 nm of coast reflecting influence of flaw lead (loss of confinement)
- Less deformation farther offshore (greater confinement)

Reconnaissance Flights: March 30 & 31

Ice Pile-Ups

- 22 pile-ups observed between Barrow and Point Lay
- Probable causes: wind shifts on Nov 21-22 and Dec 7
- Highest concentration: barrier islands east of Icy Cape
- Dimensions:
 - Heights 1 – 3 m
 - Lengths 100 – 7,800 m
 - Encroachment Distances 5 – 20 m
 - Block Thickness 30 – 40 cm

Reconnaissance Flights: March 30 & 31

Multi-Year Ice

- Numerous floes north of Icy Cape
- Diameters: <100 m – 5 km
- Concentrations: 10 – 60%
- Embedded Ridges: up to 5 m
- Some contained recent cracks
- Small floes embedded in landfast ice off Barrow

Katie's Floeberg

- Rubble accumulation on Hanna Shoal
- 4 x 8 km with major axis oriented NE-SW
- Rubble heights to 8 m
- 20% MYI

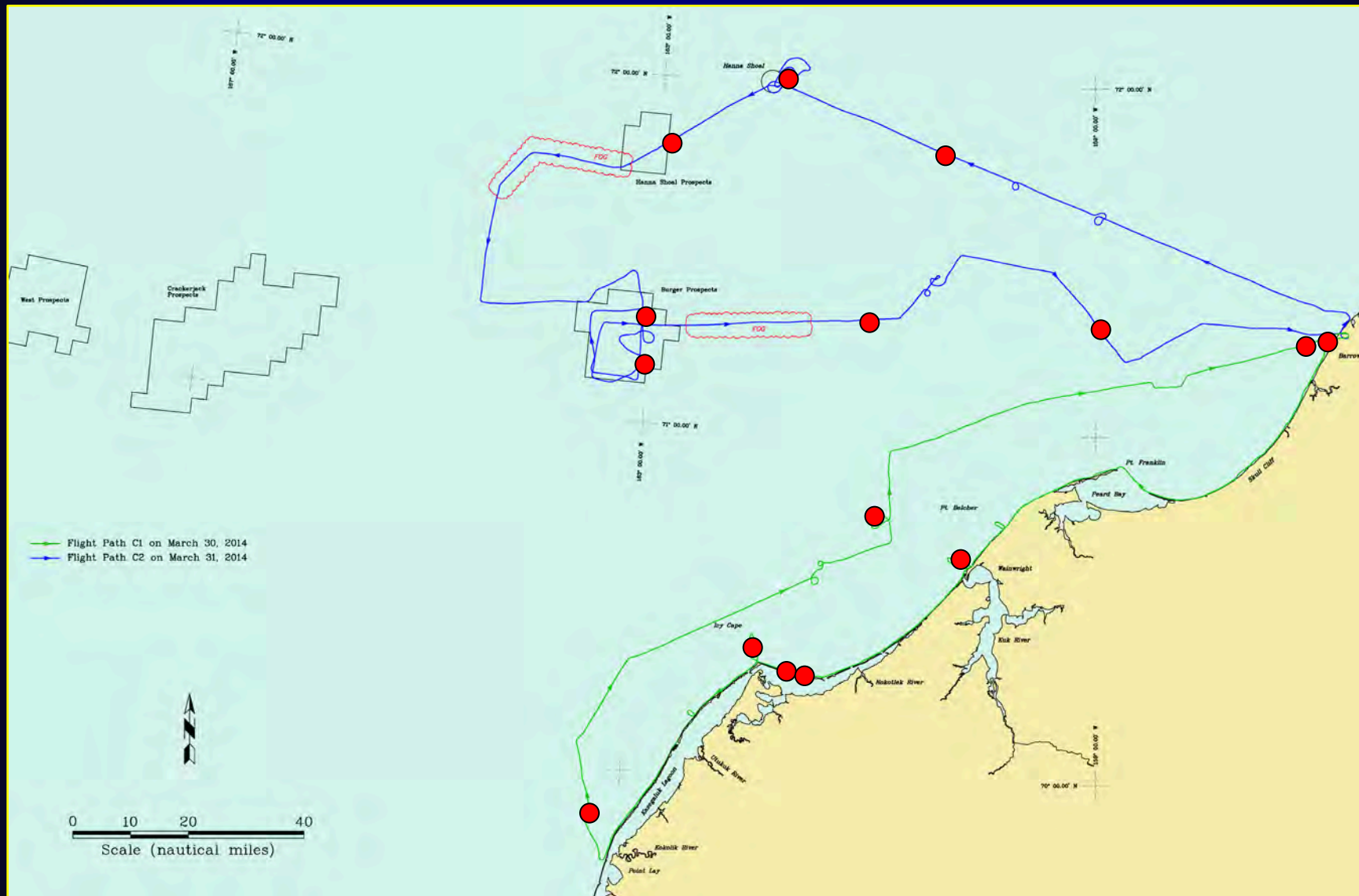
Reconnaissance Flights: March 30 & 31

Hanna Shoal Prospects

- Flat FYI floes with diameters to 2 km
- 10% MYI floes
- Intermittent ridges & rubble with heights to 3 m

Burger Prospects

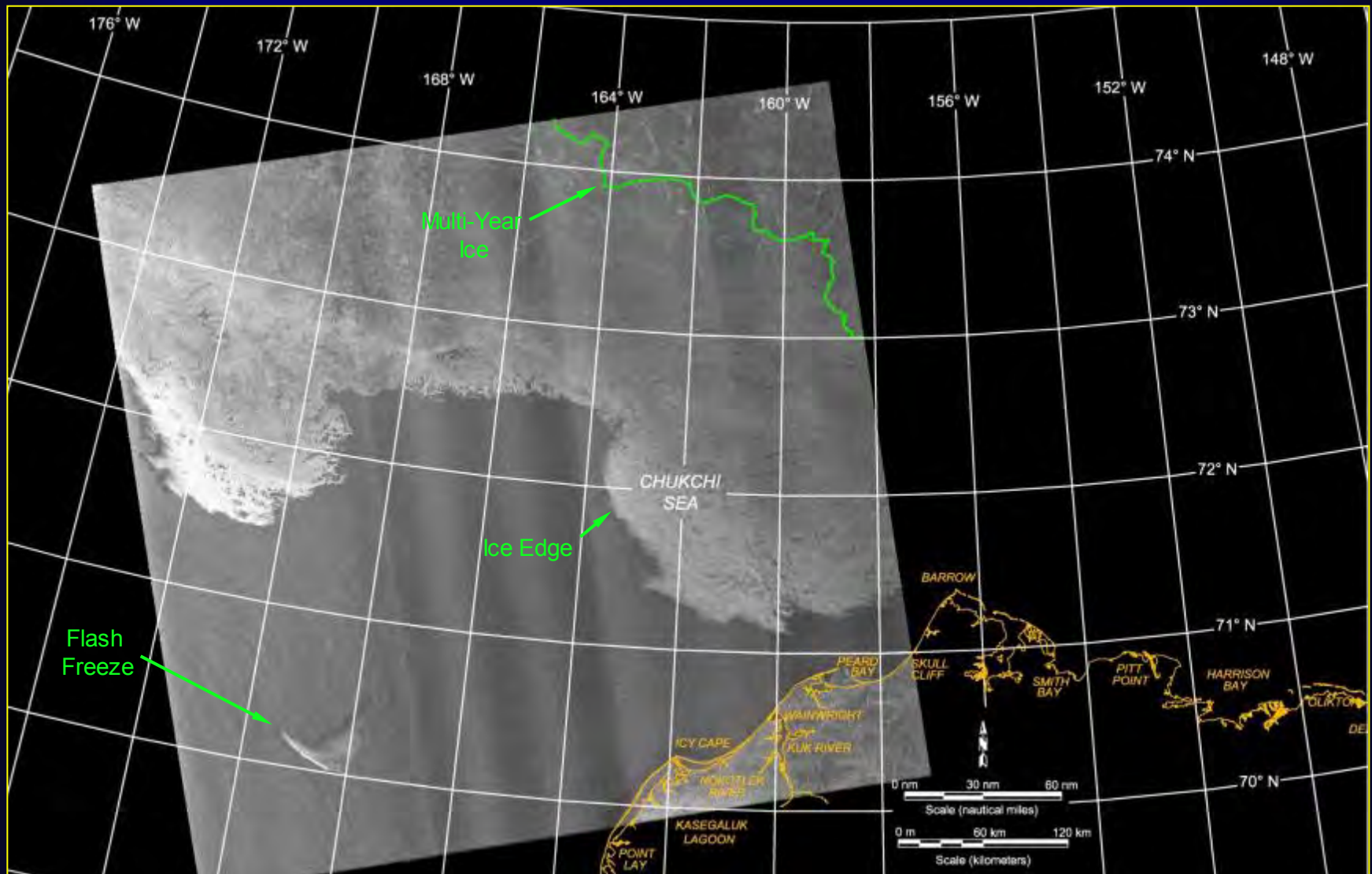
- Partially obscured by fog
- Flat FYI floes with diameters to 3 km
- Modest deformation: intermittent ridges & rubble with heights of 2 to 3 m
- Numerous leads, both open and refreezing



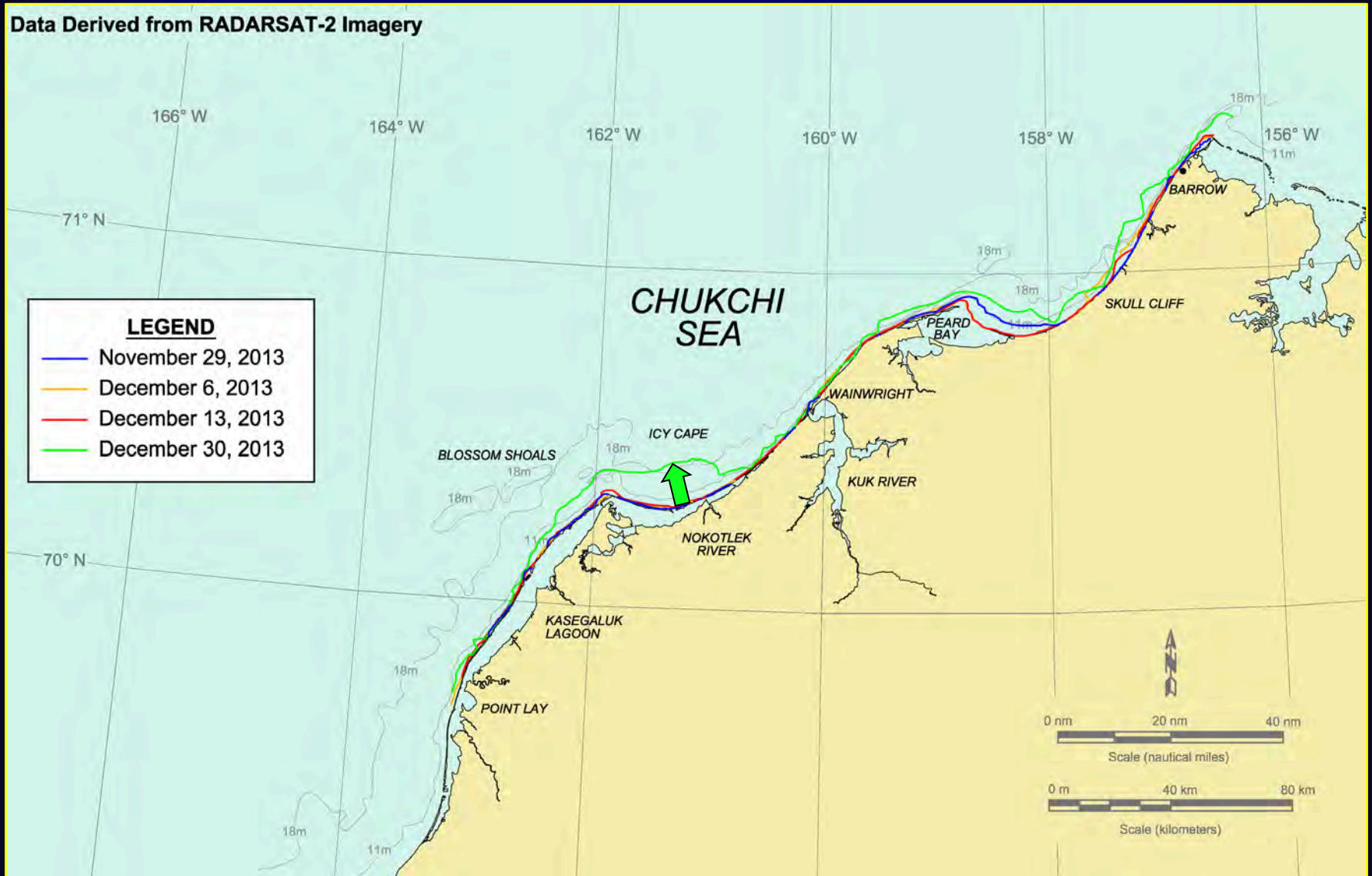


Questions or Comments?

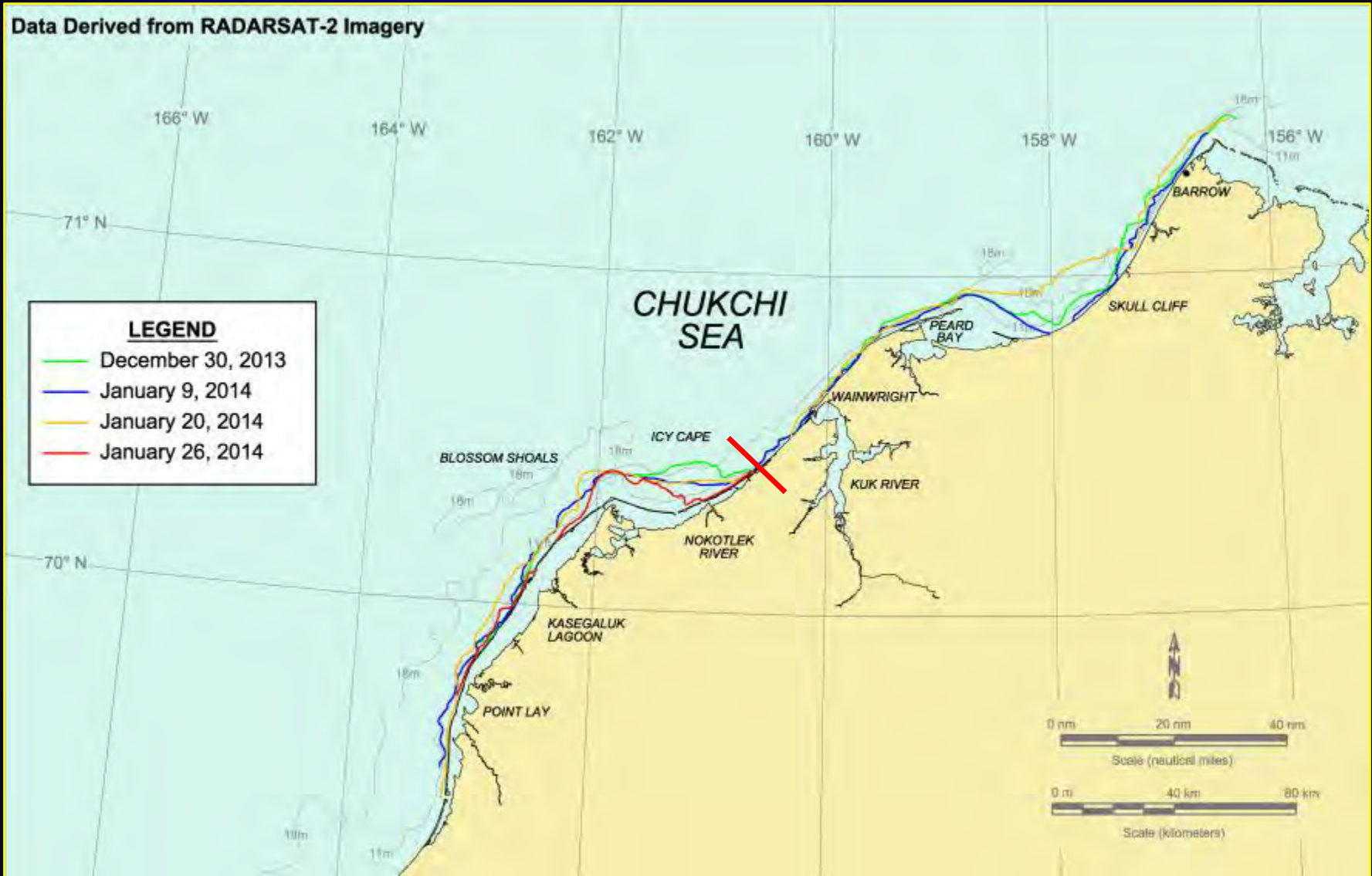
Radarsat-2 Image on Nov 15, 2013



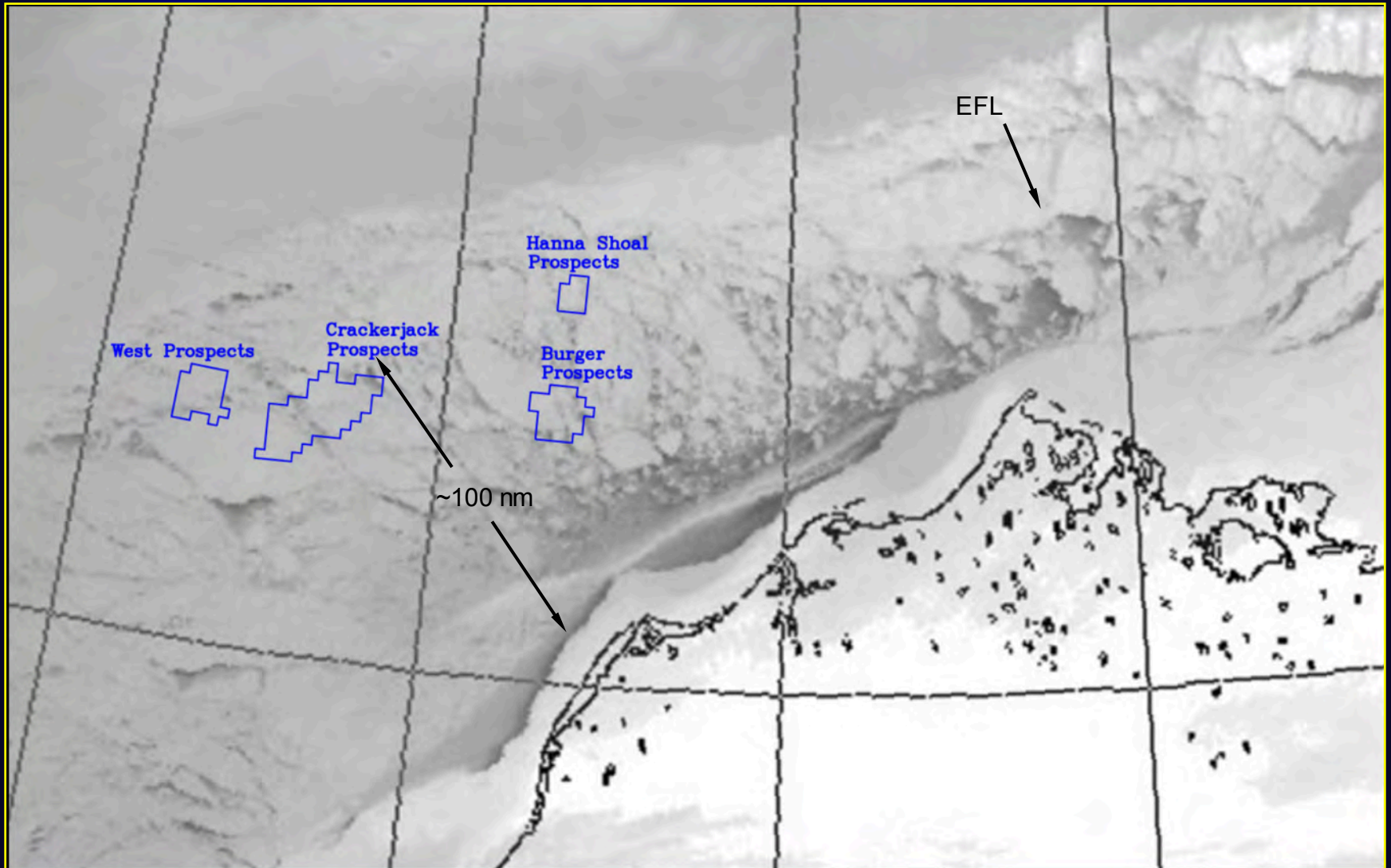
December Landfast Ice Edge



January Landfast Ice Edge

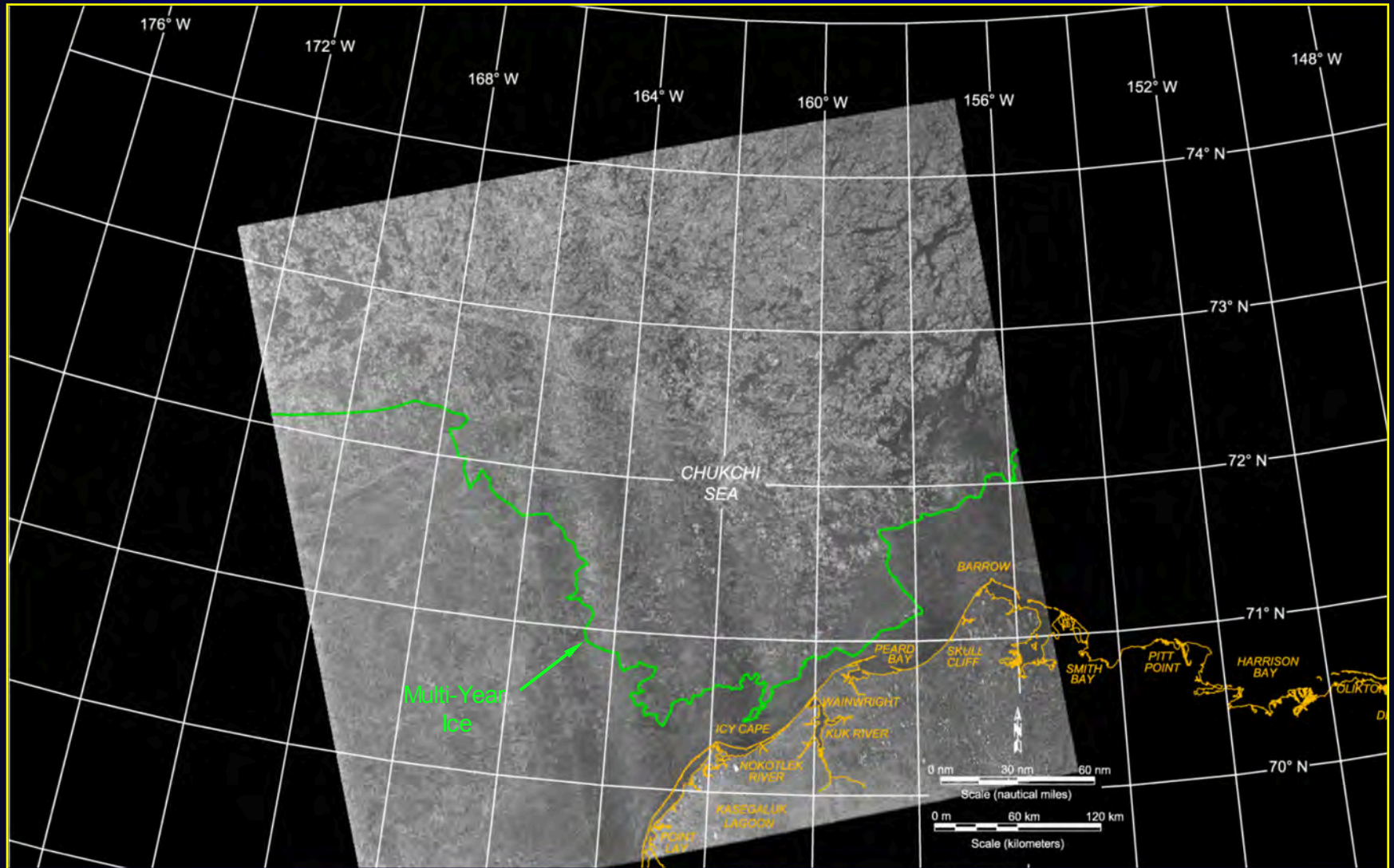


AVHRR Image on Feb 17, 2014



After: National Weather Service, 2014

Radarsat-2 Image on Mar 29, 2014



Lagoon Ice



Flat First-Year Ice in Kasegaluk Lagoon
(looking south)

Landfast Ice



Mixture of Flat & Deformed Ice off Wainwright
(looking northeast)

Landfast Ice



5-m Grounded Rubble Field on Blossom Shoals
(aground since late Dec; looking west)

Flaw Lead



Open Lead off Barrow
(looking north)

Flaw Lead



Nilas and Young Ice in Lead off Point Lay
(looking west)

Offshore Ice Conditions



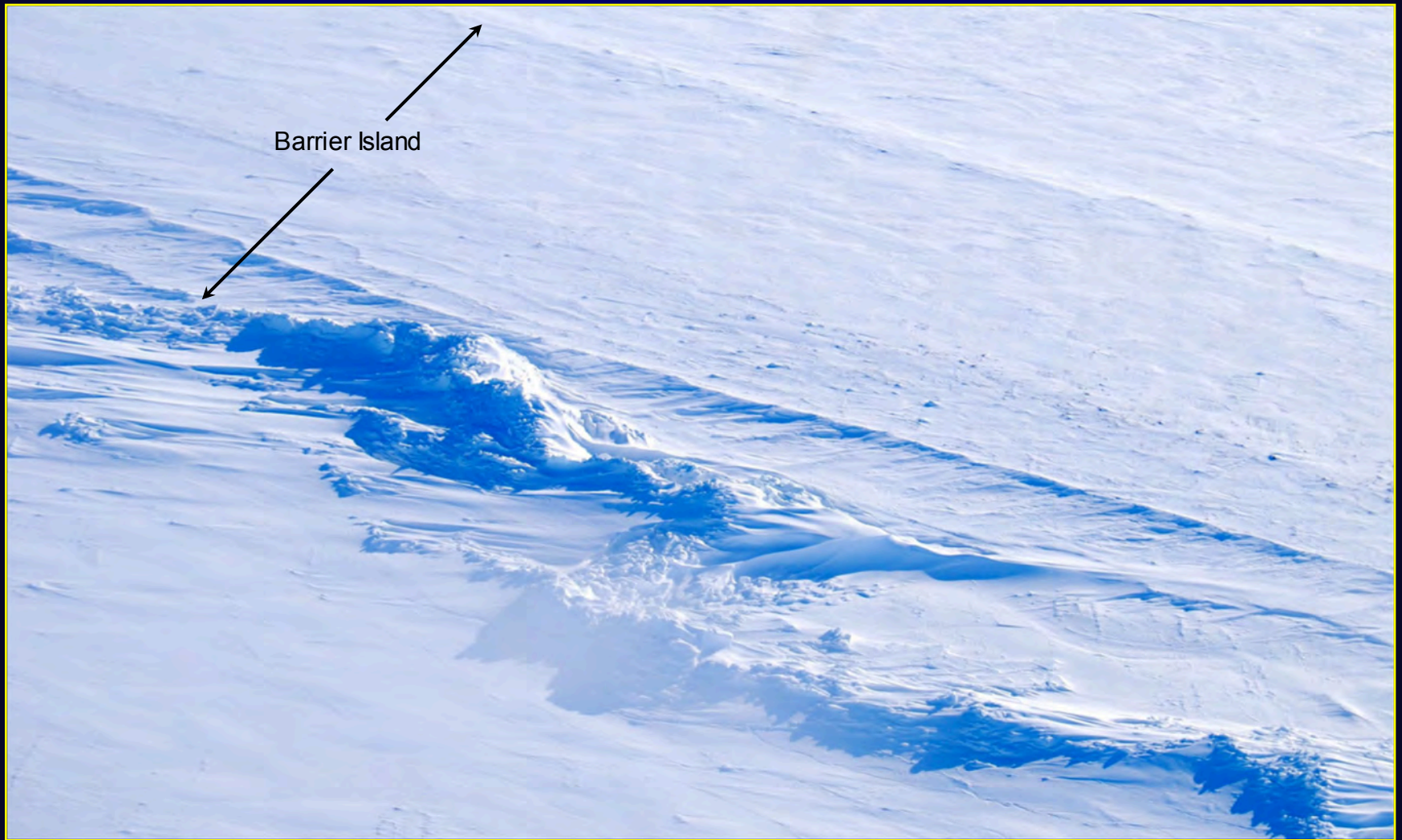
Extensive 3-m Rubble 40 nm West of Barrow
(looking northeast)

Offshore Ice Conditions



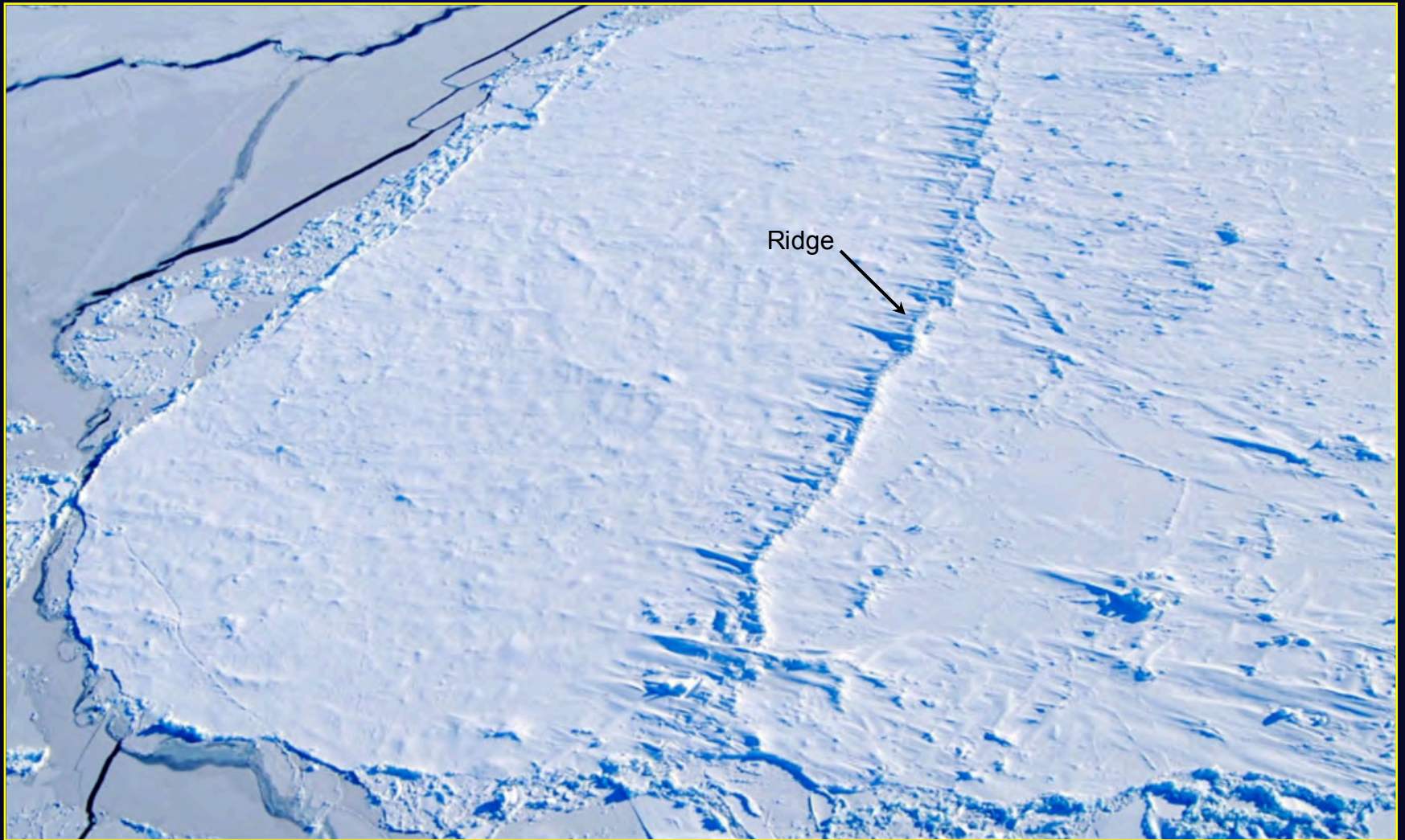
Scattered 3-m Ridges & Rubble 80 nm west of Barrow
(looking north)

Ice Pile-Up



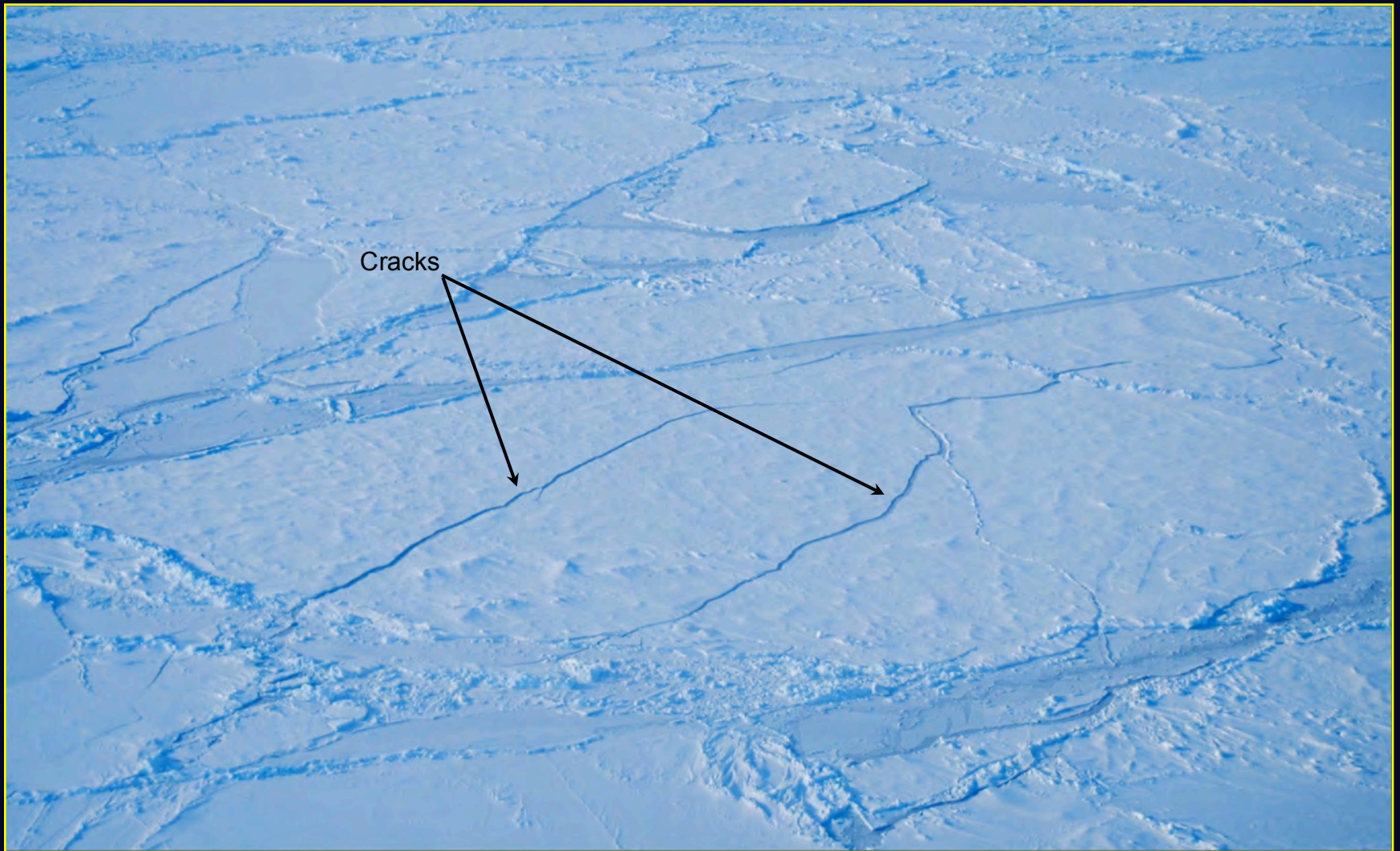
3-m Pile-Up on Barrier Island 5 nm East of Icy Cape
(looking southeast)

Multi-Year Ice



MYI Floe with 5-m Ridge 20 nm West of Wainwright
(looking southeast)

Multi-Year Ice



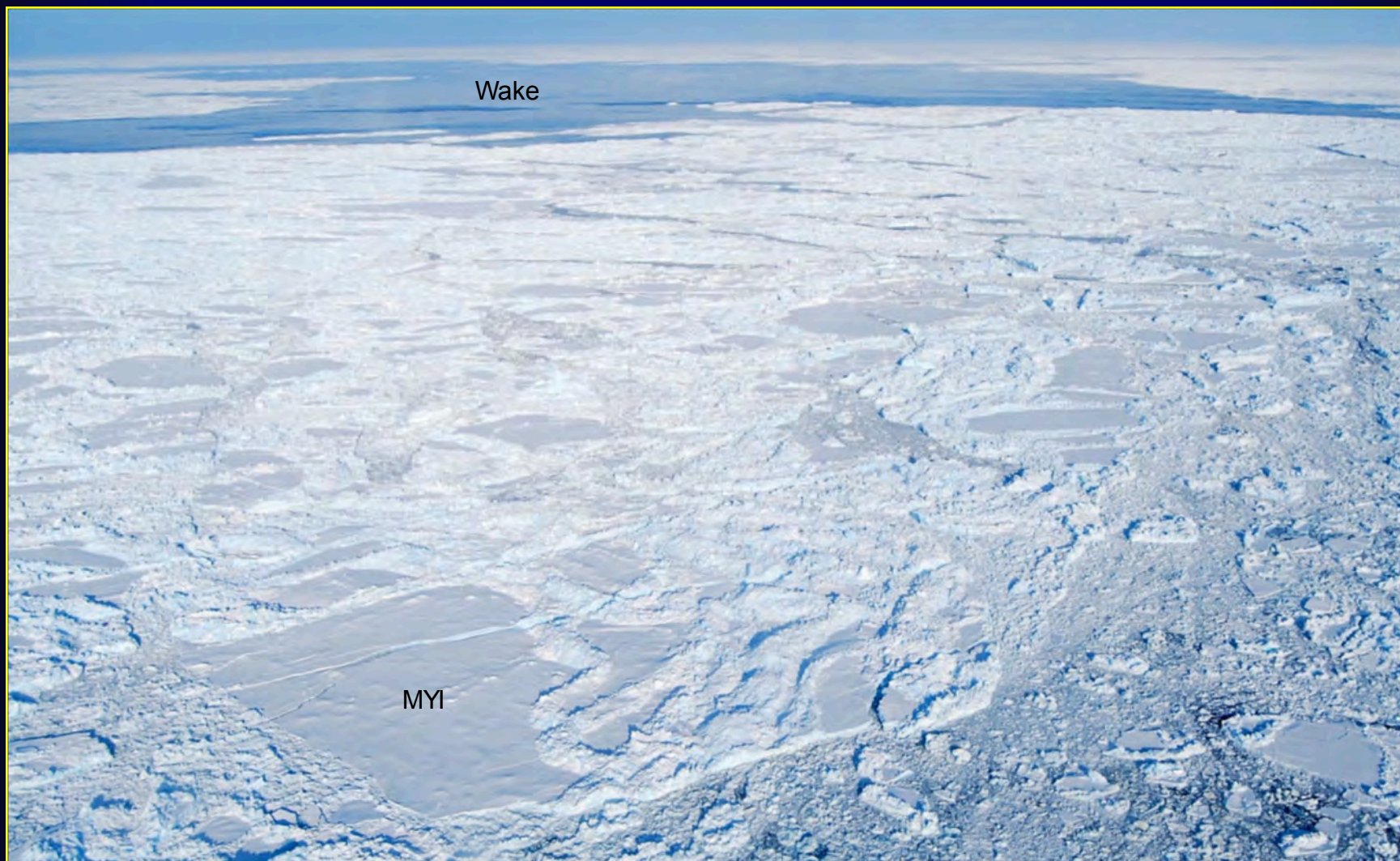
Cracked MYI Floe 80 nm West of Barrow
(looking southwest)

Multi-Year Ice



Small MYI Floes in Landfast Ice off Barrow
(looking southeast)

Katie's Floeberg on Hanna Shoal



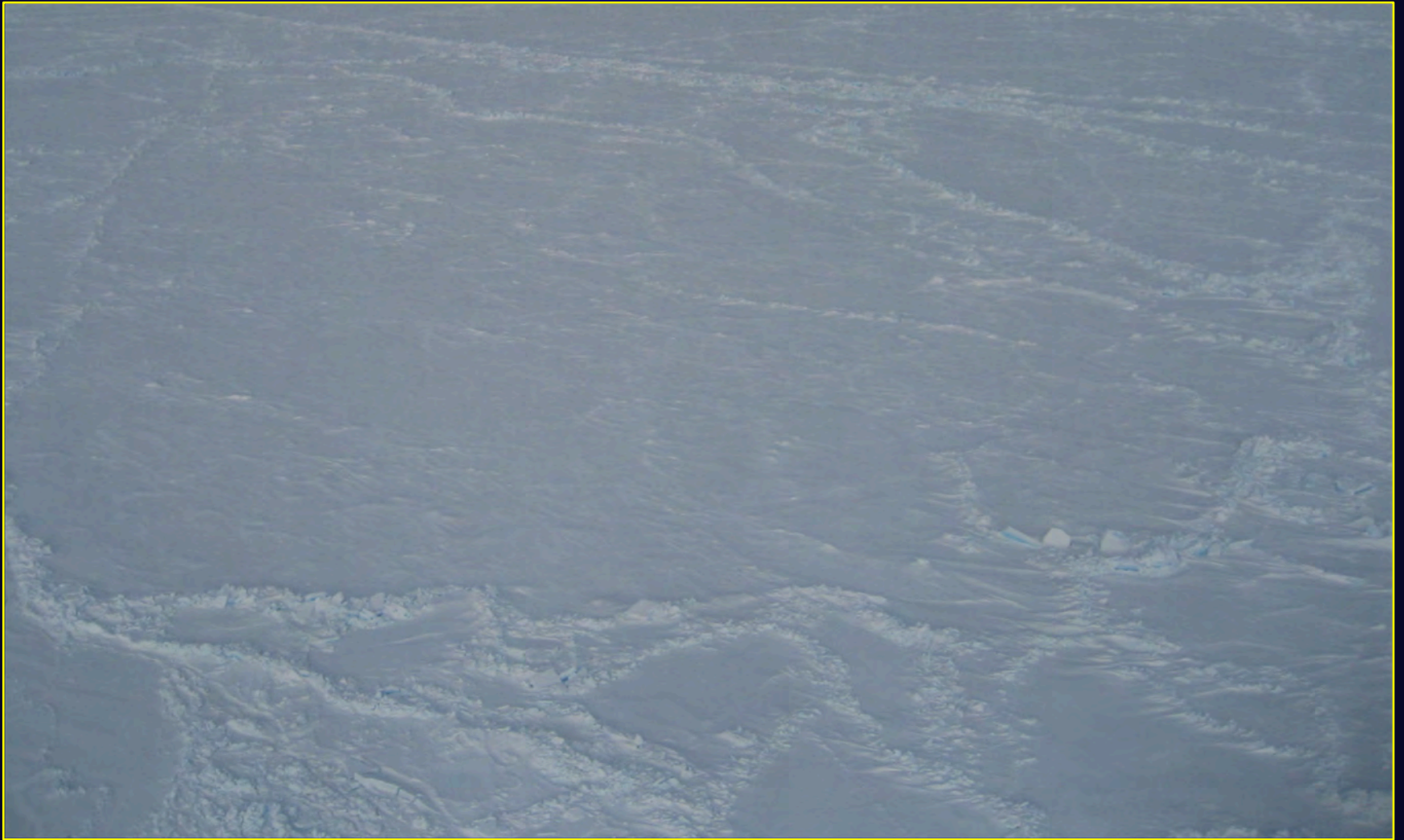
4 x 8 km; 20% MYI
(looking northwest)

Katie's Floeberg on Hanna Shoal



8-m Rubble on East Side
(looking north)

Hanna Shoal Prospects



First-Year Ice with 3-m Ridges & Rubble
(looking northwest)

Burger Prospects



First-Year Ice with Intermittent 3-m Ridges & 2-m Rubble
(looking east)

Burger Prospects



Broken First-Year Ice with Multiple Leads
(looking east)

2013-14 Beaufort Sea Freeze-Up

➤ Meteorological Overview

➤ Early Freeze-Up

- Late Summer
- October
- November

➤ Late Freeze-Up

- December
- January

➤ Mid-Winter

- February
- March
- Late March Reconnaissance Flights

2013-14 Meteorological Overview

➤ Air Temperatures

- Normal to above normal
- Particularly warm in Oct, Nov, and Jan

➤ Winds

- Westerlies prevailed 57% of the time
- Average monthly speed
 - Highest in Jan 15 kt
 - Lowest in Oct & Mar 8 kt

➤ Storms

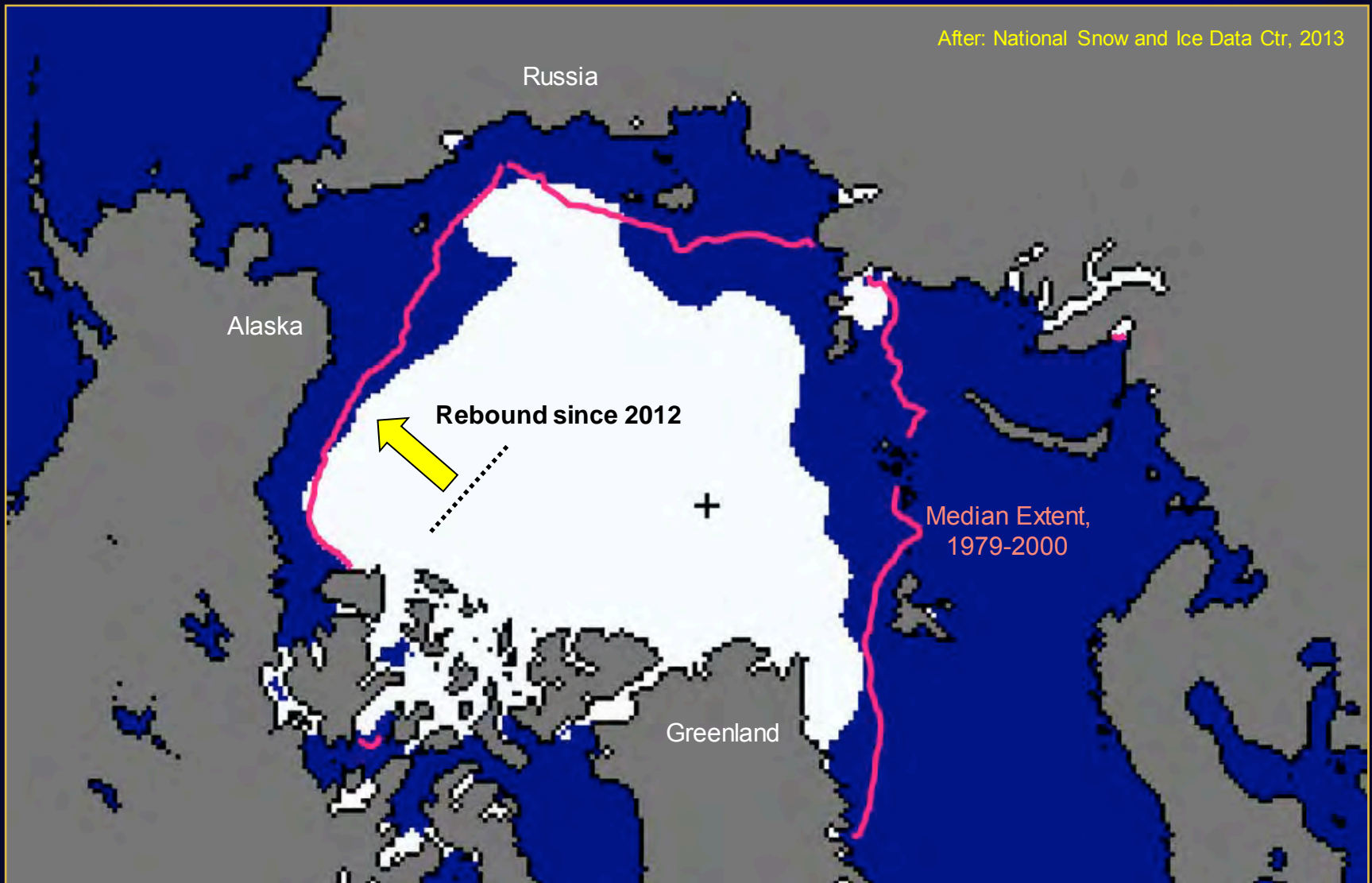
- 20 storms (>15 kt)
 - 9 easterlies & 11 westerlies
 - Highest wind speed: 29 kt
 - Longest Duration: 10 days
- } Easterly in Dec-Jan

Sea Ice Minimum Extent in 2012



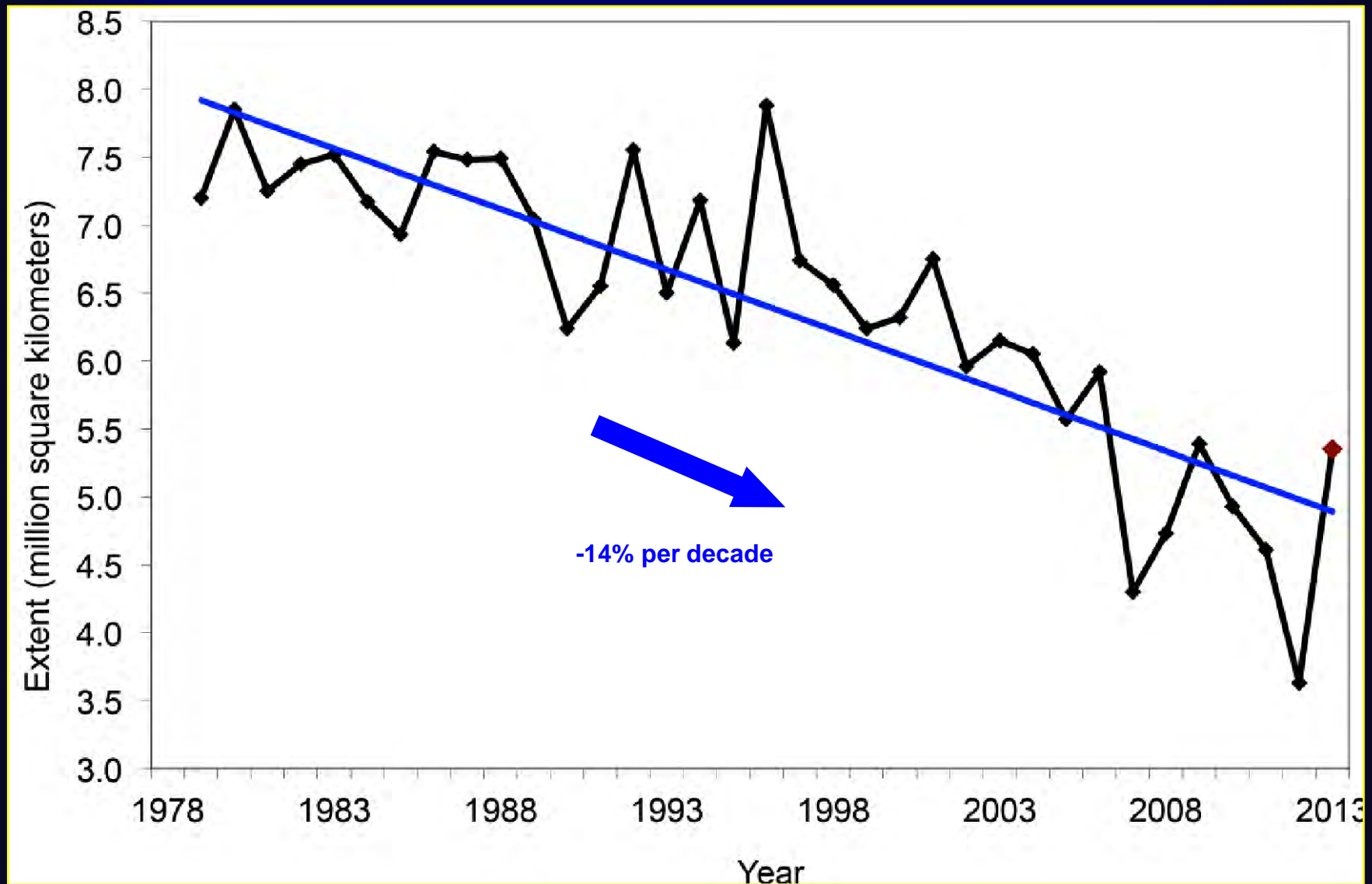
Sep 16, 2012: Lowest on Record by 18%

Sea Ice Minimum Extent in 2013

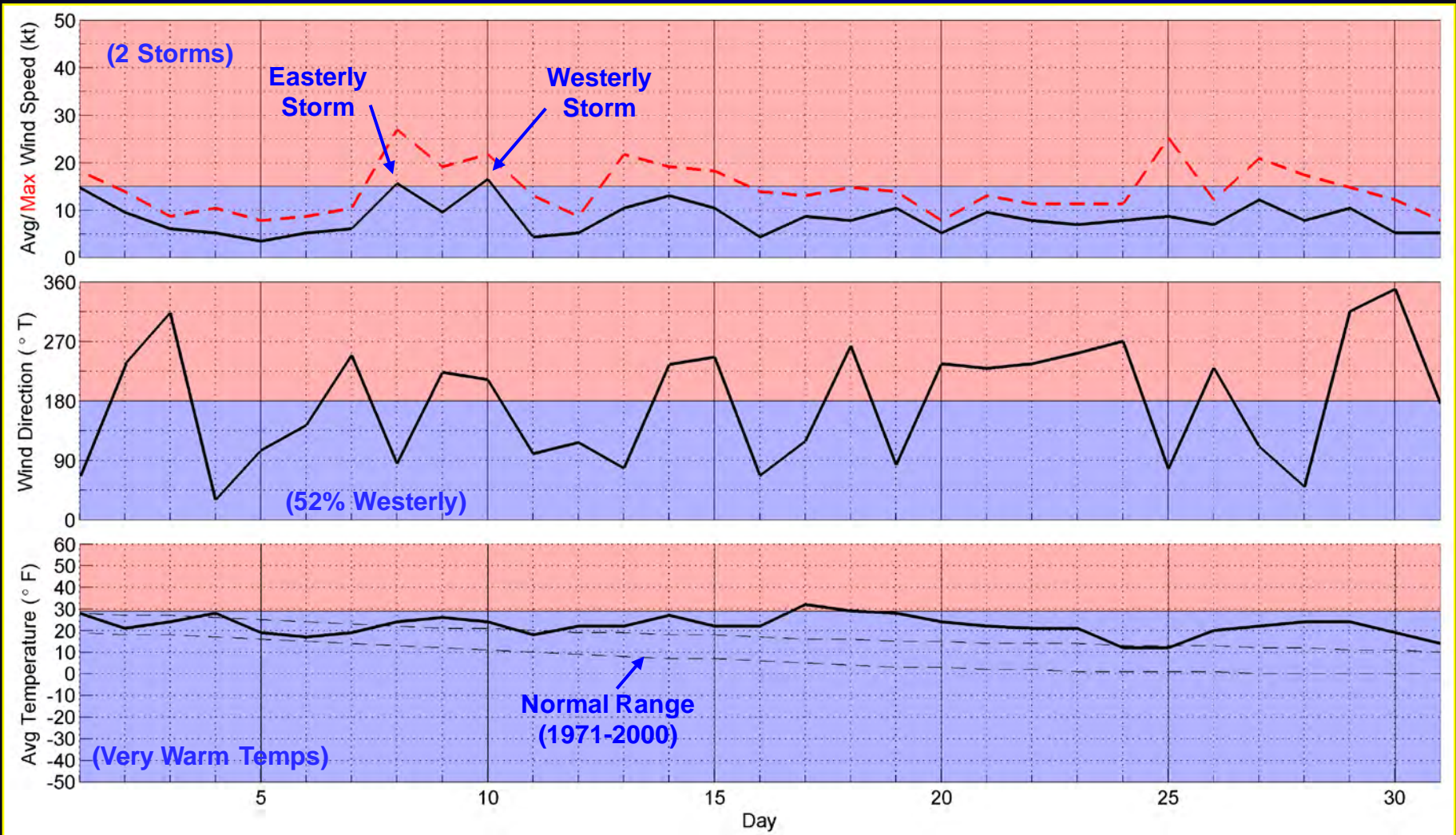


Sep 13, 2013: Highest since 2009

Average Sea Ice Extent in September: 1979 - 2013



October Meteorological Conditions



Deadhorse Airport

October Overview

Ice Cover

- Nearshore ice began to form in late September
- Freeze-up progressed slowly until mid-October due to warm temperatures
- Nearshore freeze-up occurred on Oct 26 in response to sub-freezing temperatures and absence of storms

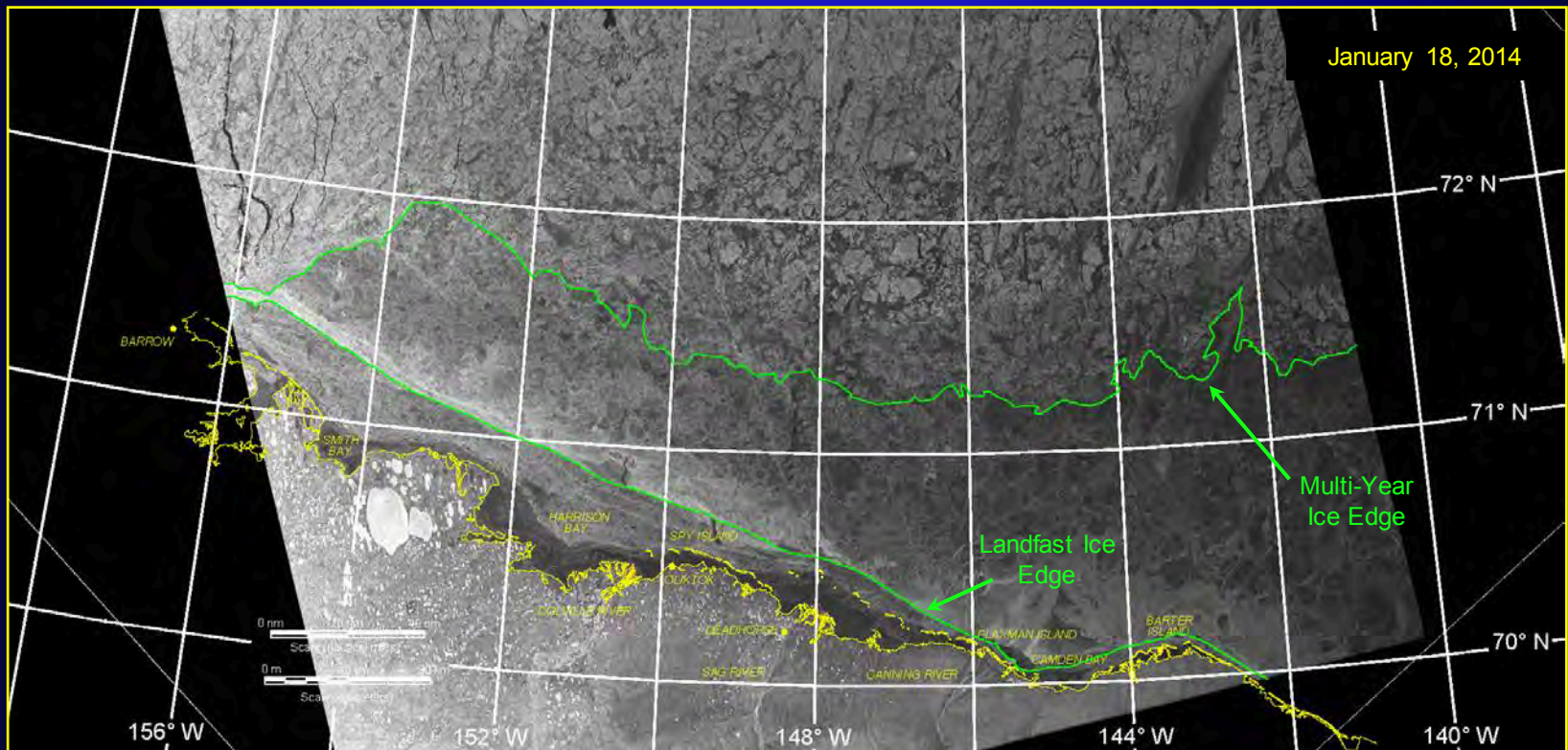
Computed Ice Thickness

- 23 cm for undisturbed ice at month-end, using method of Lebedev and accumulated FDD at Deadhorse Airport

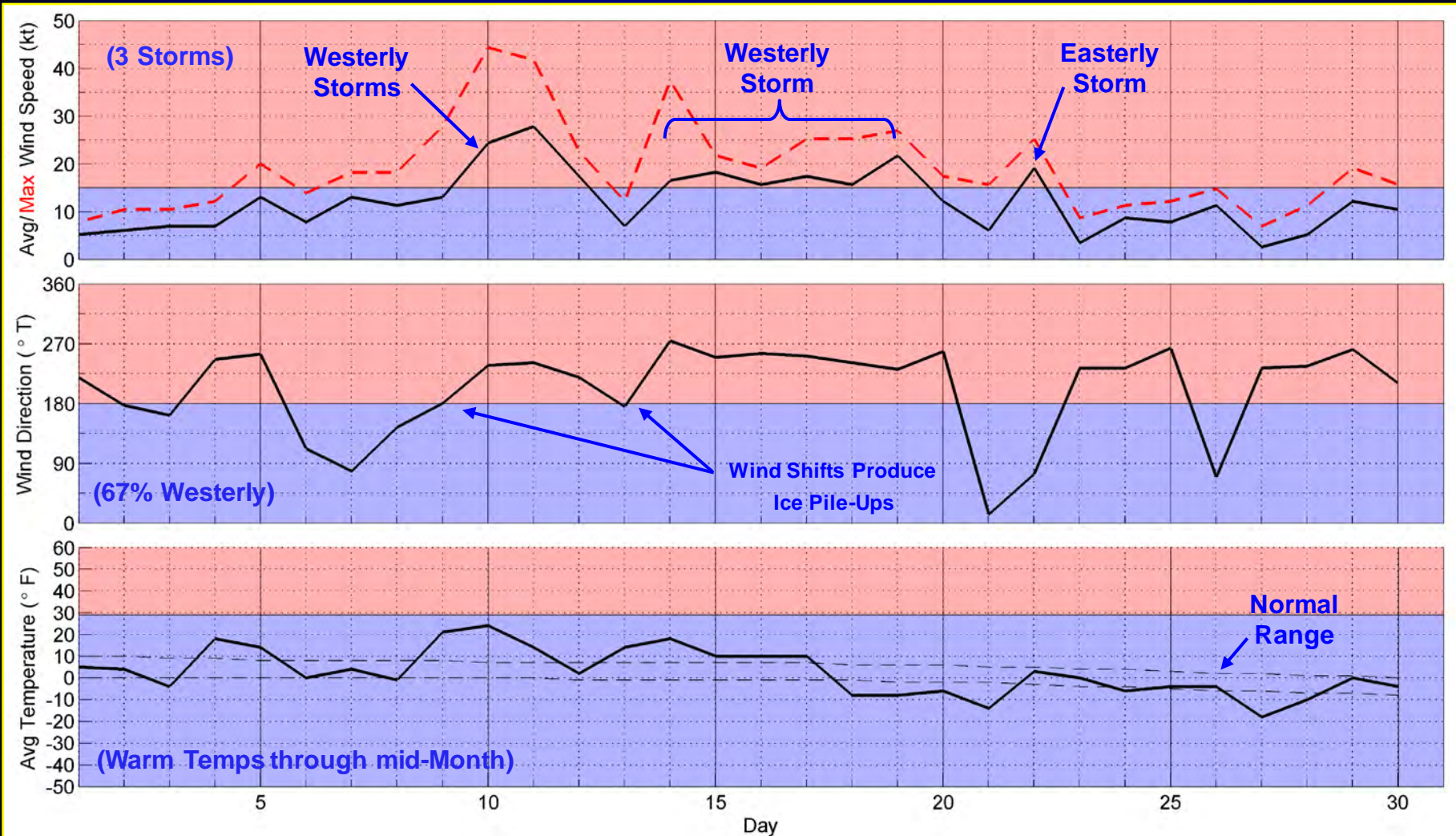
October Overview

Multi-Year Ice

- Present throughout freeze-up and early winter but well offshore
- Sole exception: vicinity of Point Barrow



November Meteorological Conditions



Deadhorse Airport

November Overview

Ice Cover

- Basin-wide freeze-up occurred on Nov 20 in response to sub-zero temperatures
- Nascent ice canopy remained intact after Nov 20

Computed Ice Thickness

- 23 cm  52 cm (+29 cm)

November Overview

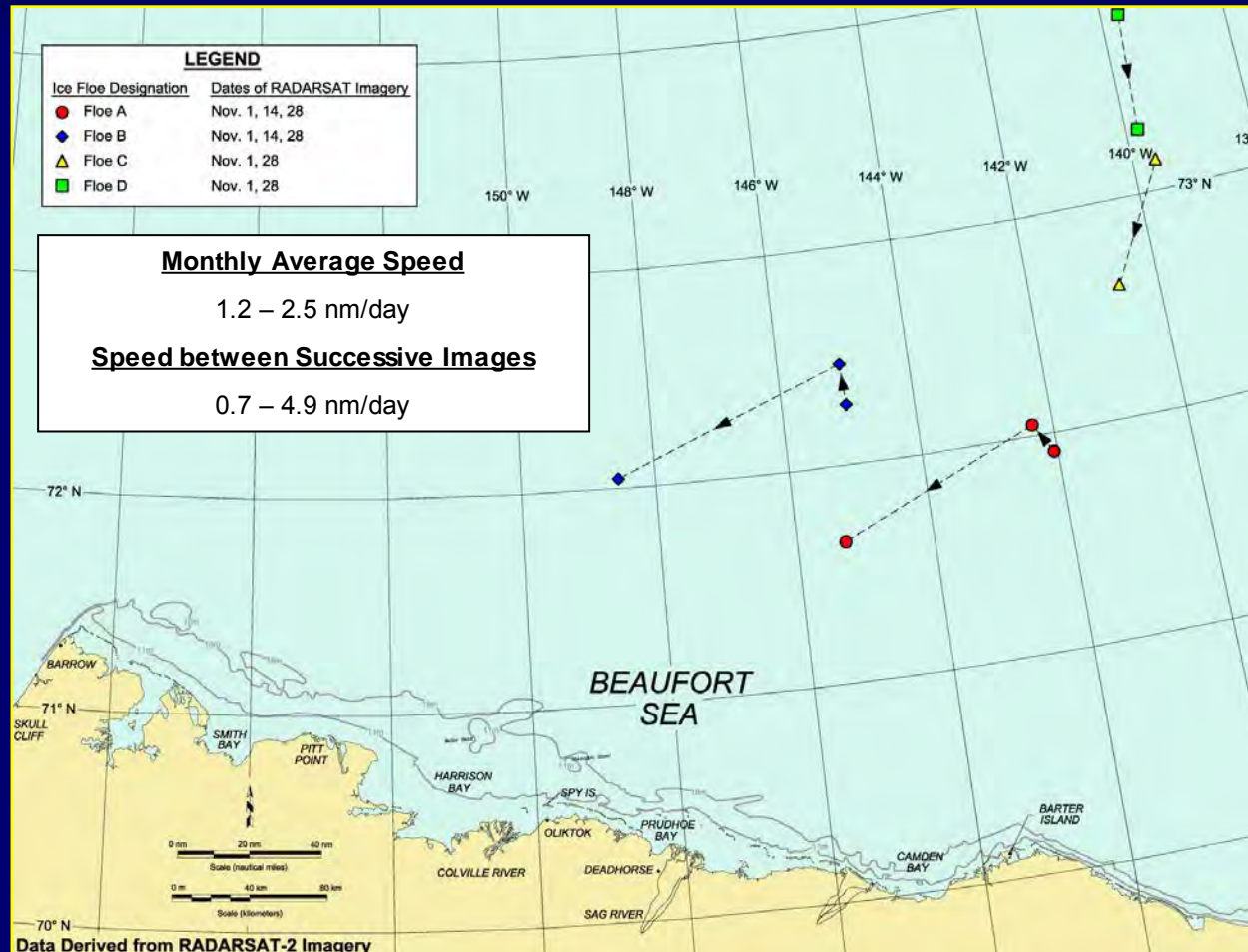
Landfast Ice

- Confined to semi-protected areas at beginning of month
- Slow growth due to westerly winds and 2 westerly storms

Ice Pile-Ups

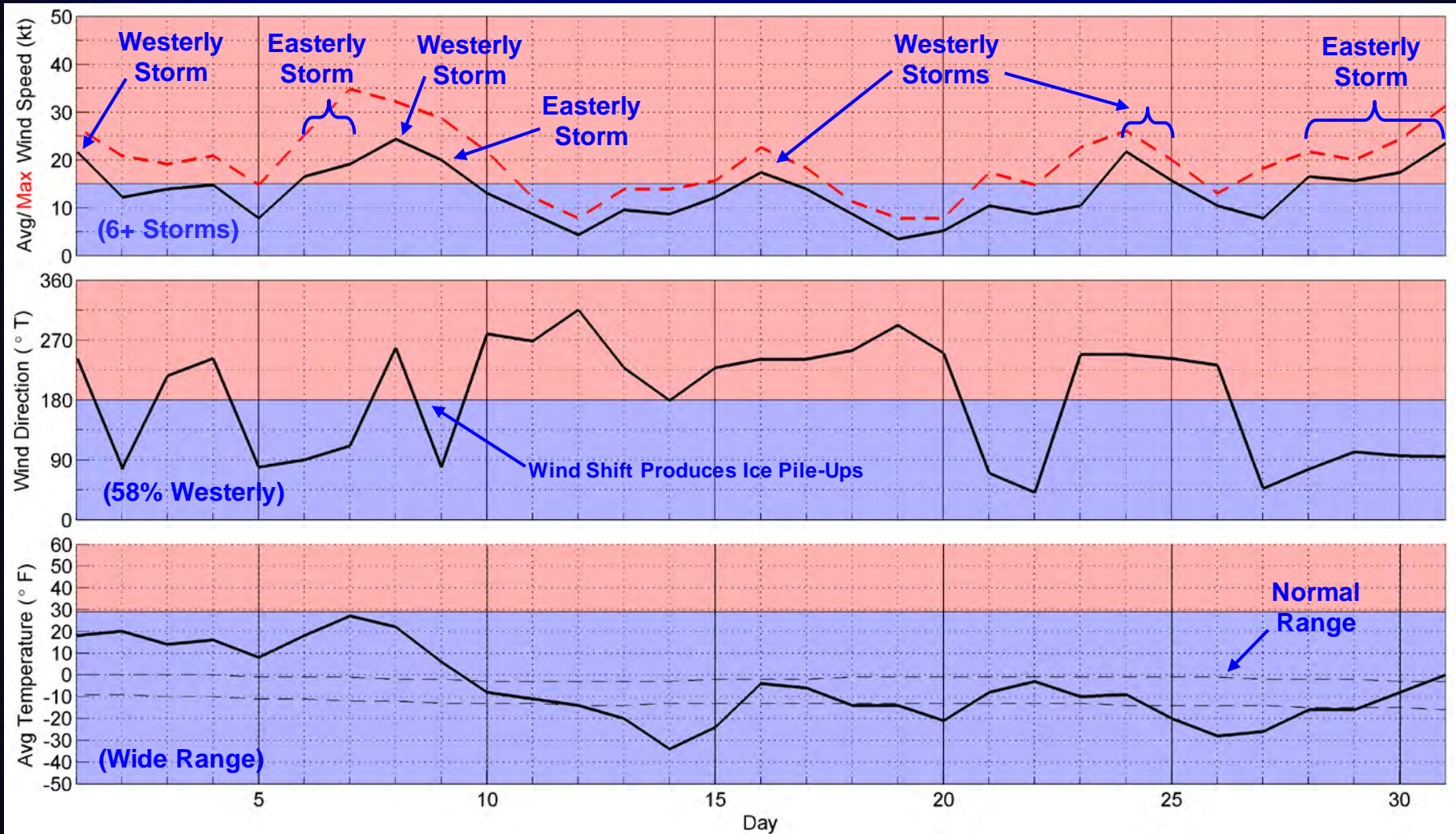
- Nov 21-22: 23 pile-ups created by wind shift (SE → SW)
- Nov 14: 6 pile-ups created by wind shift (S → WNW)

November Multi-Year Ice Movement



- Nov 1 – 14: Beaufort Gyre balanced by westerly winds
- Nov 14 - 28: Beaufort Gyre re-established by easterly winds

December Meteorological Conditions



Deadhorse Airport

December Overview

Computed Ice Thickness

- 52 cm → 79 cm (+27 cm)

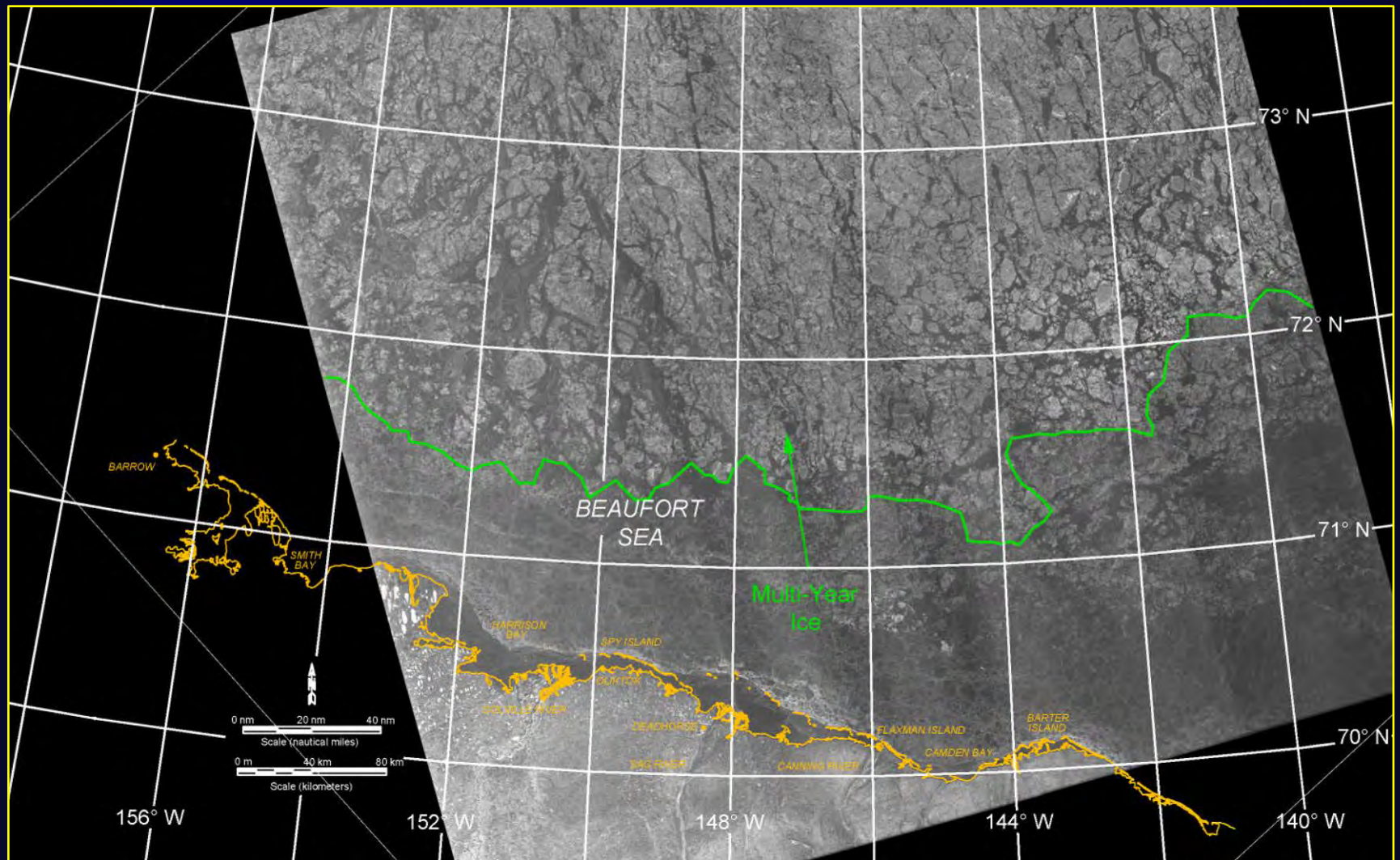
Landfast Ice

- Modest changes in response to mixture of easterly and westerly storms

Ice Pile-Ups

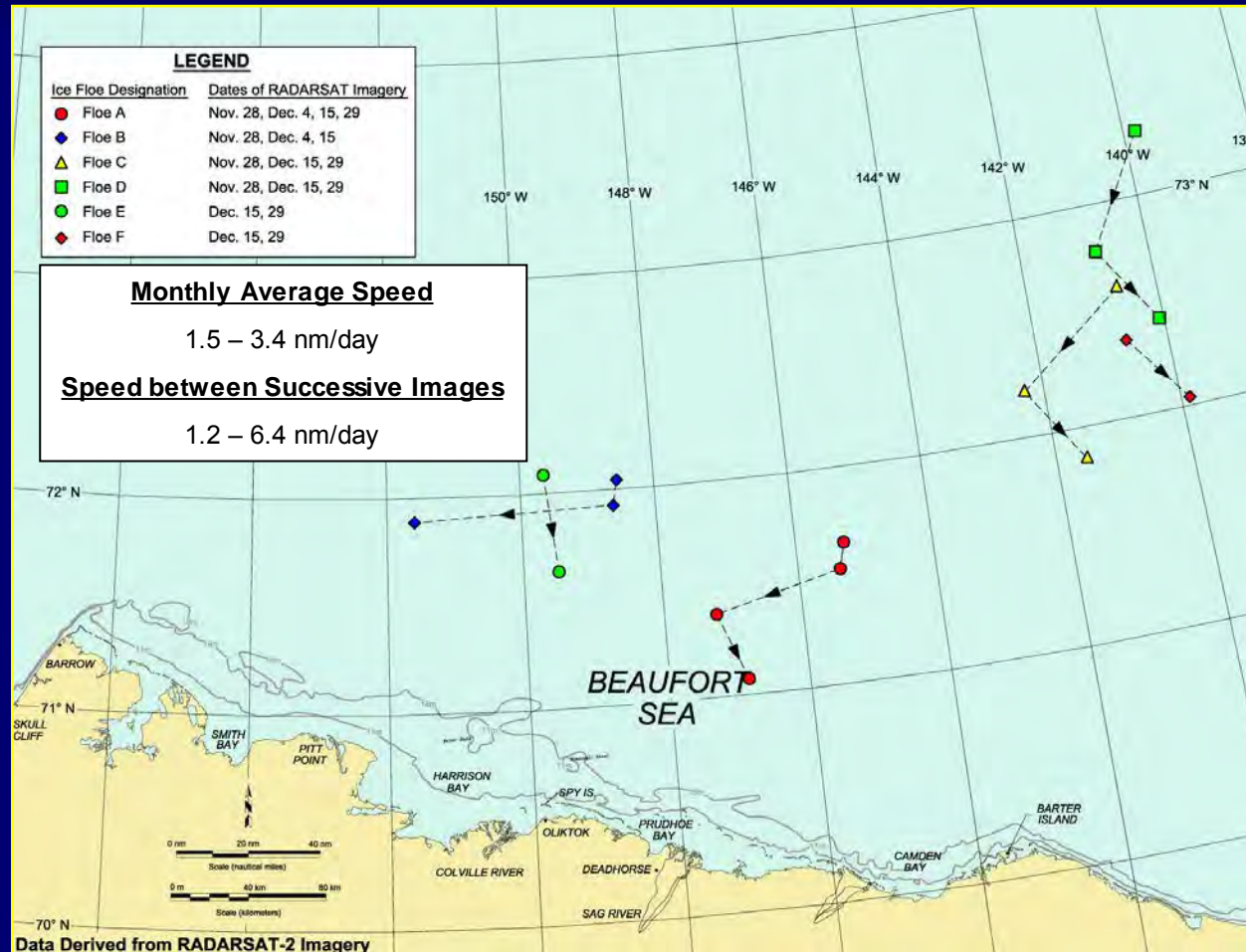
- Dec 8: 17 pile-ups created by wind shift (W → E)

RADARSAT-2 Image on December 15



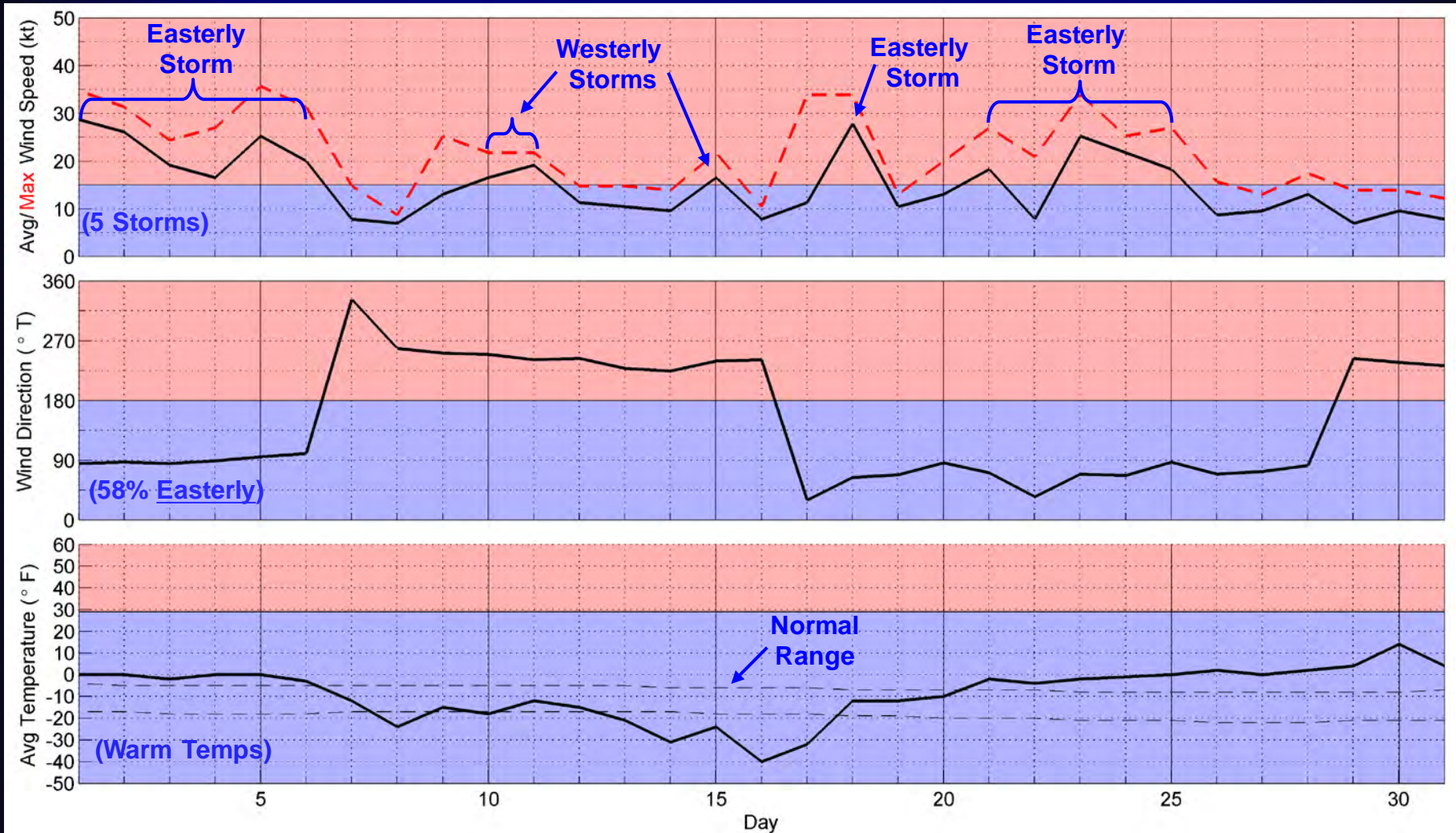
After: RADARSAT-2 Data and Products © MacDonald Dettweiler and Associates Ltd., 2013 – All Rights Reserved

December Multi-Year Ice Movement



- Zigzag trajectories in response to succession of westerly & easterly storms
- Low monthly average speeds

January Meteorological Conditions



Deadhorse Airport

January Overview

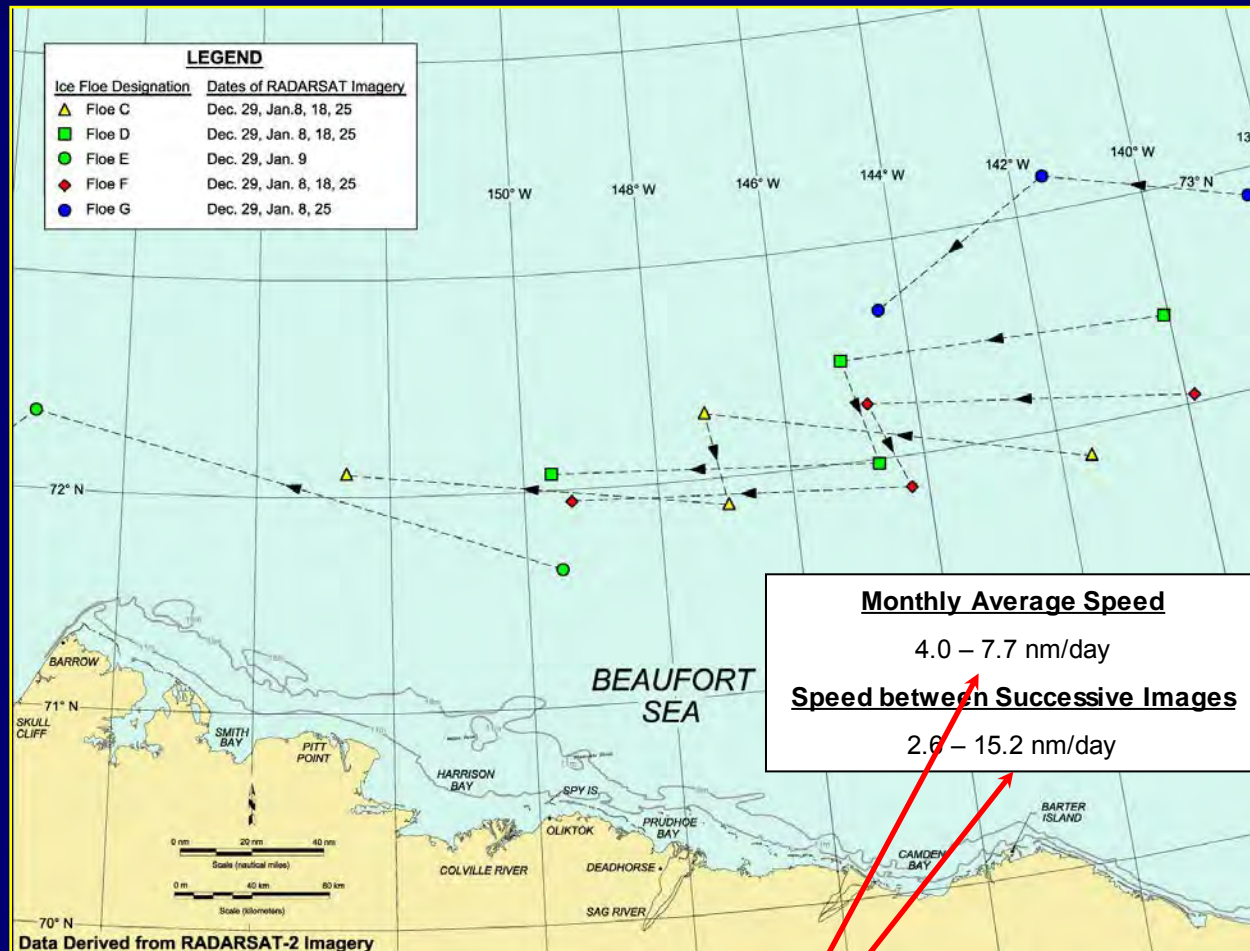
Computed Ice Thickness

➤ 79 cm → 102 cm (+23 cm)

Landfast Ice

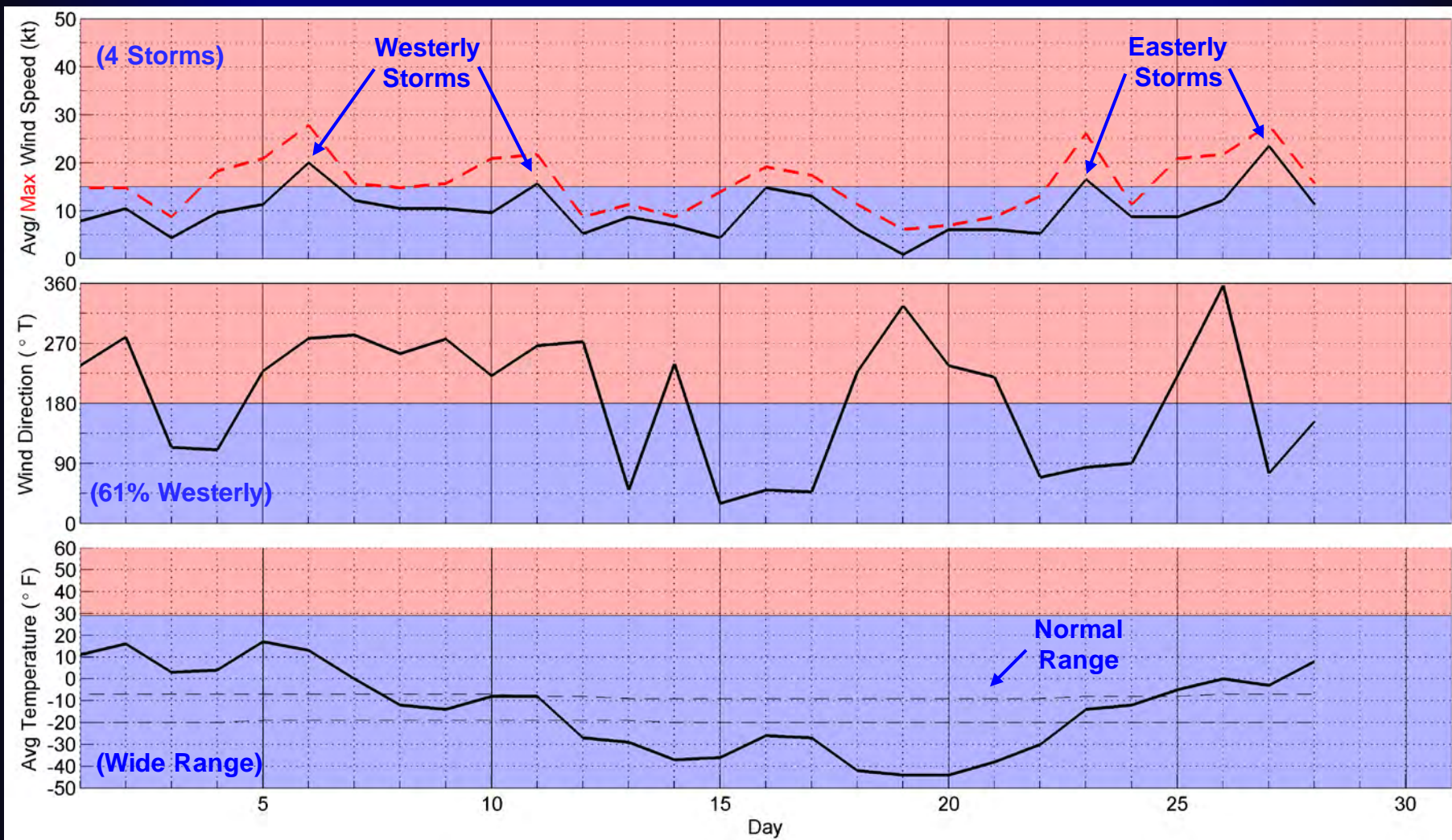
- Dec 29 – Jan 8: Substantial advance due to easterly storm, with firm grounding on Weller Bank & Stamukhi Shoal
- Jan 18 – 25: “Stable Extension” (Mahoney, *et al.*, 2012) past 18-m isobath maintained by compression

January Multi-Year Ice Movement



- Substantial westerly displacements in response to easterly winds
- Highest speeds during study period

February Meteorological Conditions



Deadhorse Airport

February Overview

Computed Ice Thickness

- 102 cm → 123 cm (+21 cm)

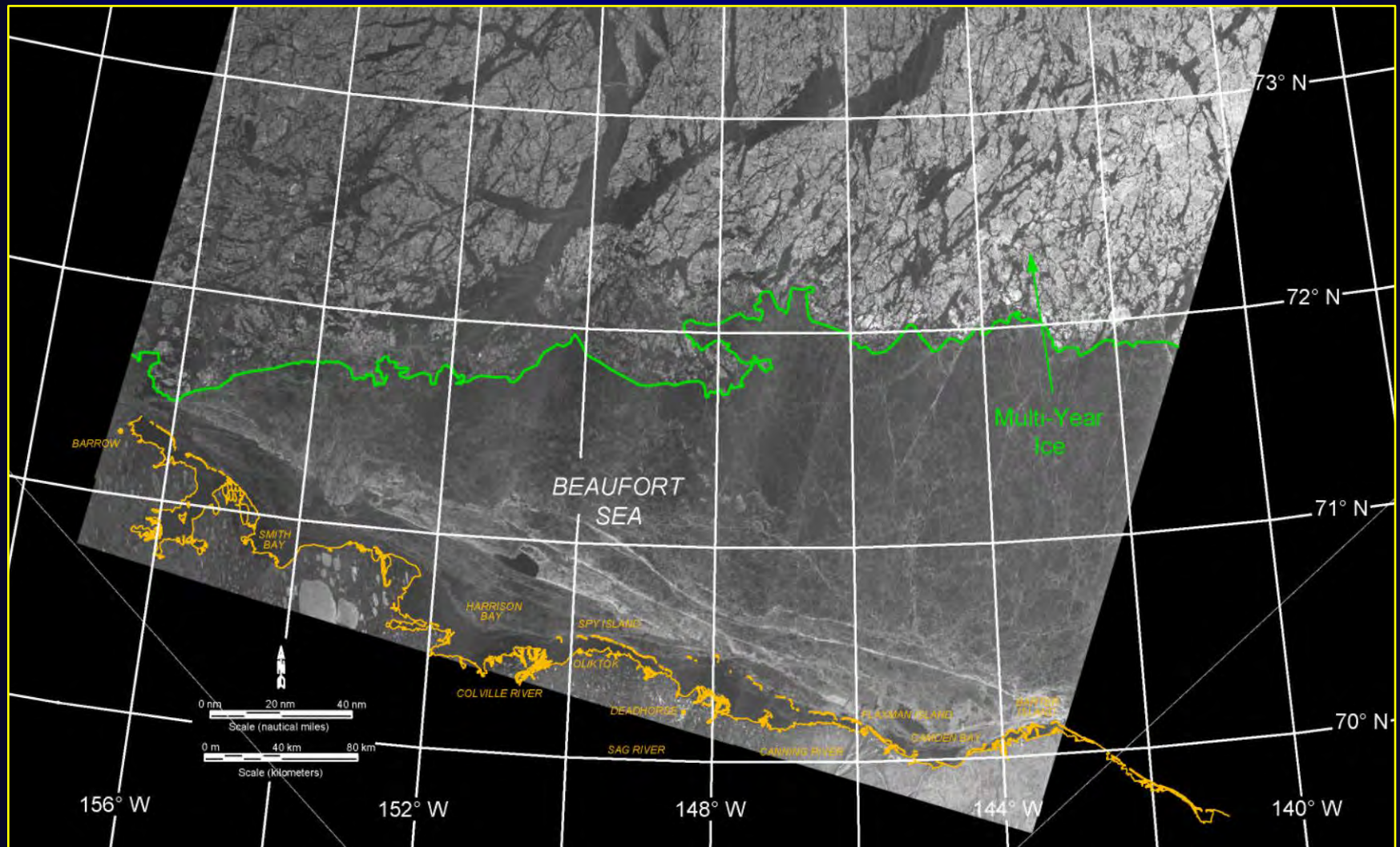
Landfast Ice

- Ice remained firmly grounded on Weller Bank & Stamukhi Shoal
- Partial loss of stable extension

February Landfast Ice Edge

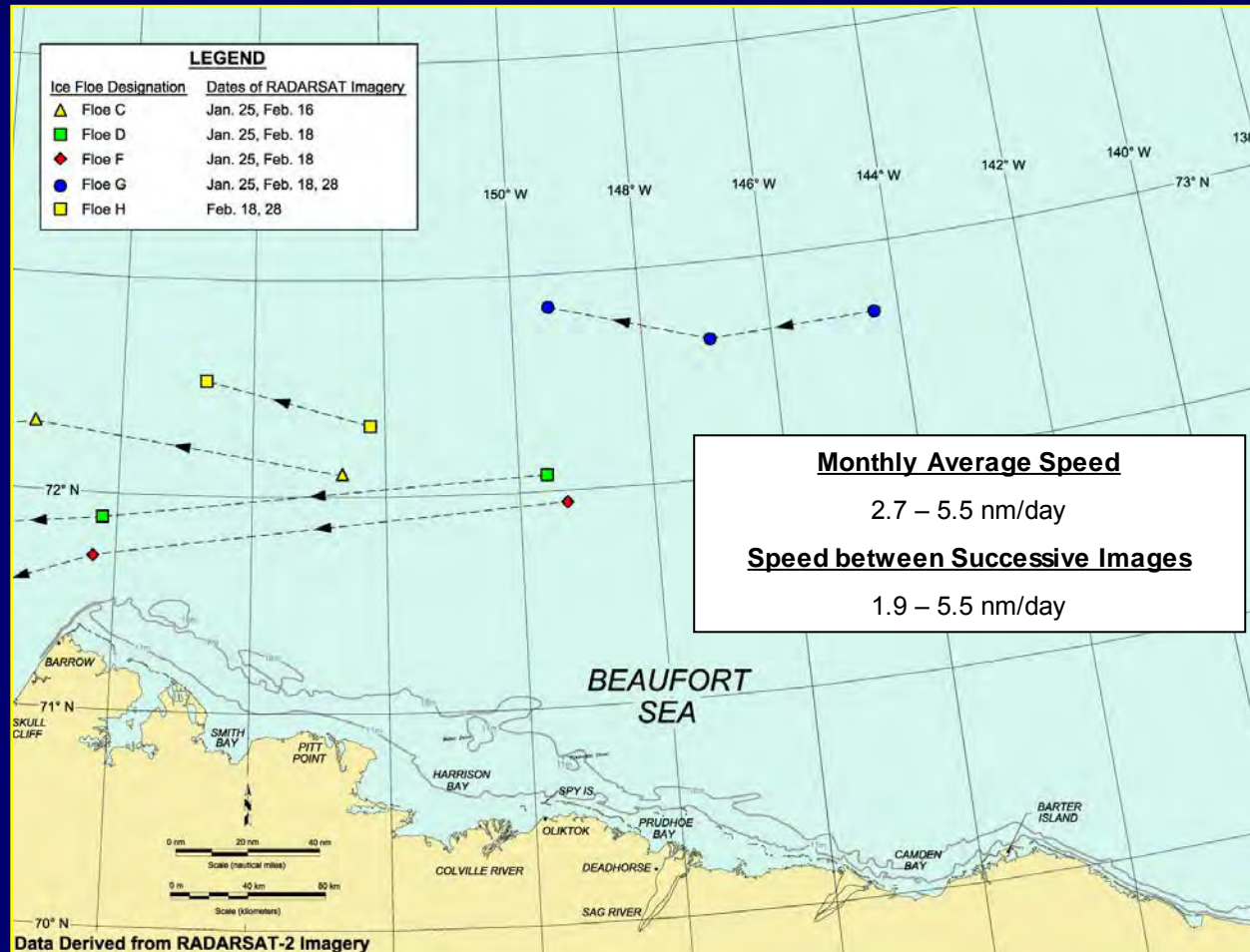


RADARSAT-2 Image on February 18



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February Multi-Year Ice Movement



- Moderate westerly displacements and speeds reflecting resurgence of westerly winds
- Higher speeds at southern boundary of permanent pack ice

February Telemetry Buoy Movement

Deployment

- 11 Buoys
- Feb 24 – Mar 31

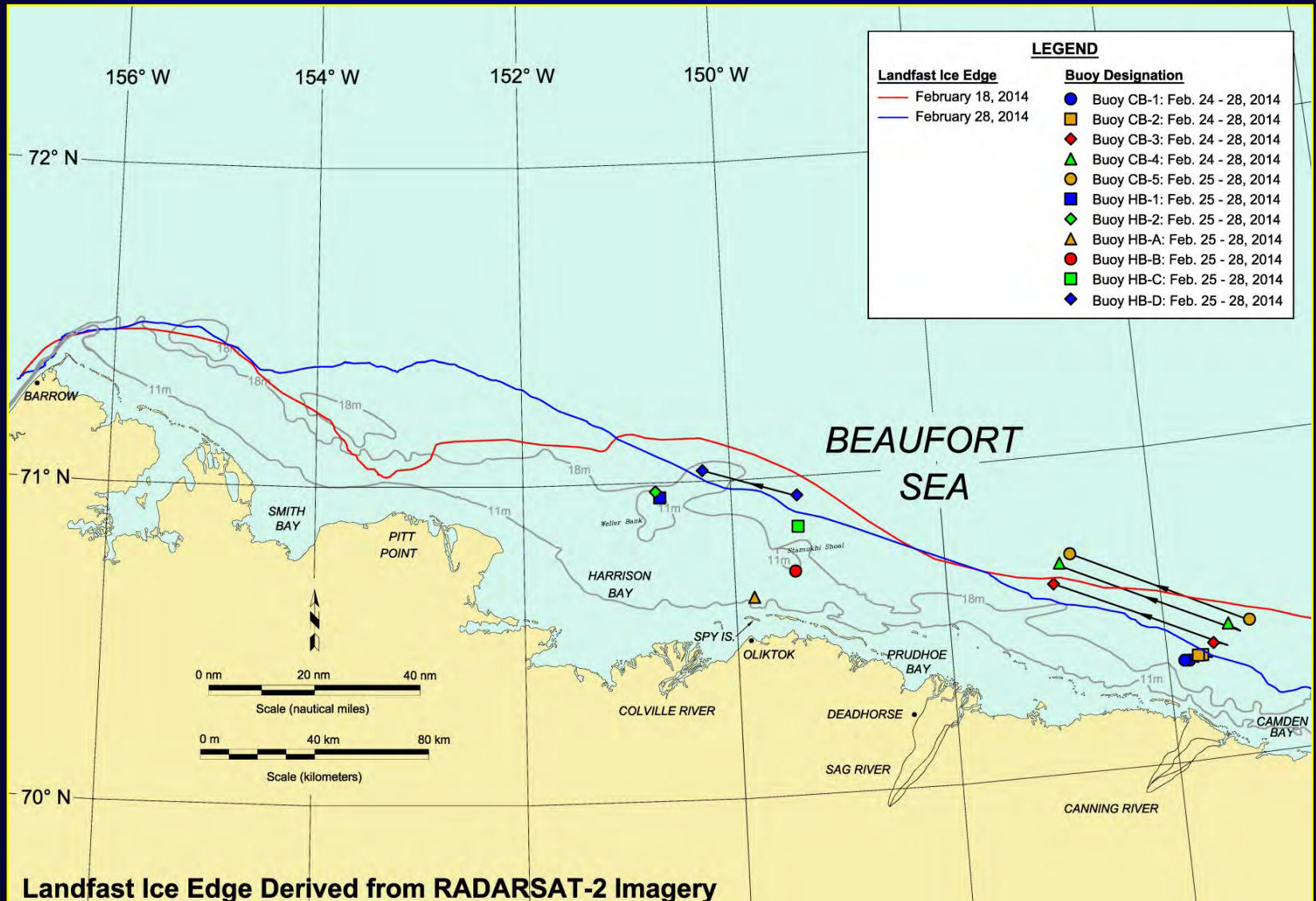
Harrison Bay & Weller Bank

- | | |
|------------------------------------|------------|
| ➤ 5 buoys in landfast ice zone | stationary |
| ➤ 1 buoy outside landfast ice zone | moved WNW |

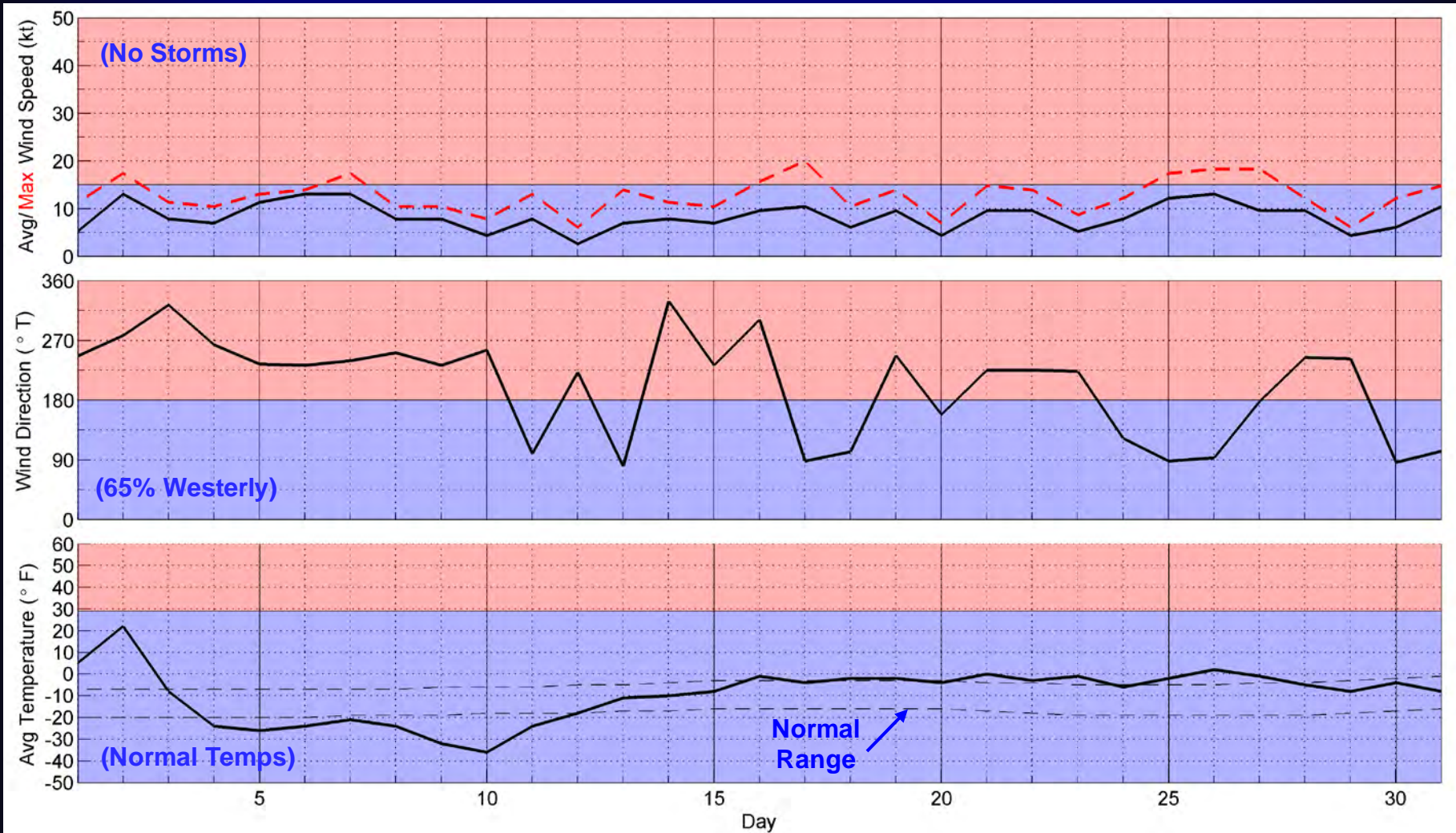
Camden Bay

- | | |
|-------------------------------------|-------------------|
| ➤ 2 buoys in landfast ice zone | nearly stationary |
| ➤ 3 buoys outside landfast ice zone | moved WNW |
| ➤ Maximum daily speed | 0.85 kt |
| ➤ Wind speed (easterly storm) | 23 kt |
| ➤ Wind factor | 3.7% |

February Telemetry Buoy Tracks



March Meteorological Conditions



Deadhorse Airport

March Overview

Computed Ice Thickness

- 123 cm → 141 cm (+18 cm)

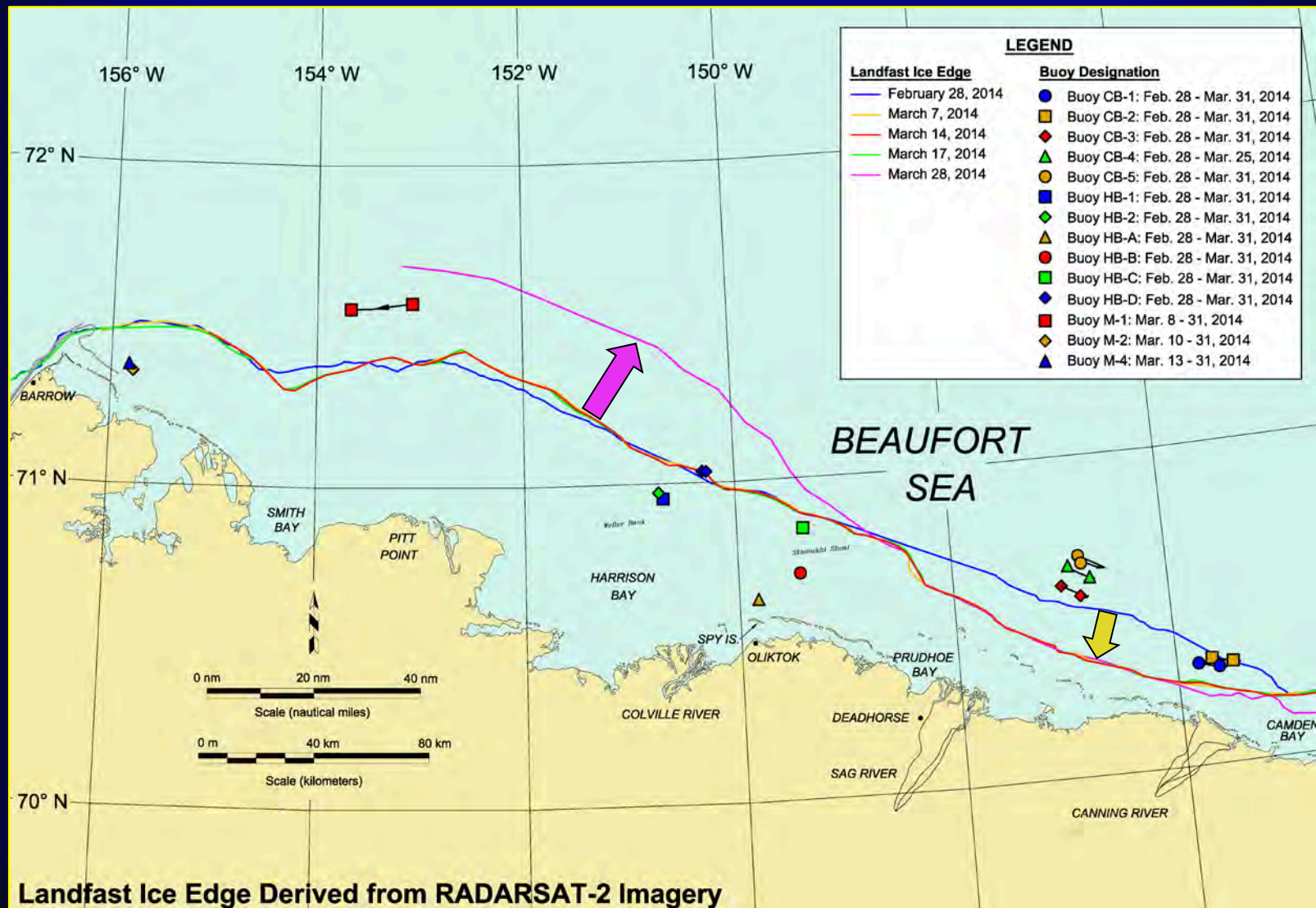
Landfast Ice

- Feb 28 – Mar 7: Retreat east of Prudhoe Bay (westerly winds)
- Mar 16 – 28: Advance west of Prudhoe Bay (mixed winds)

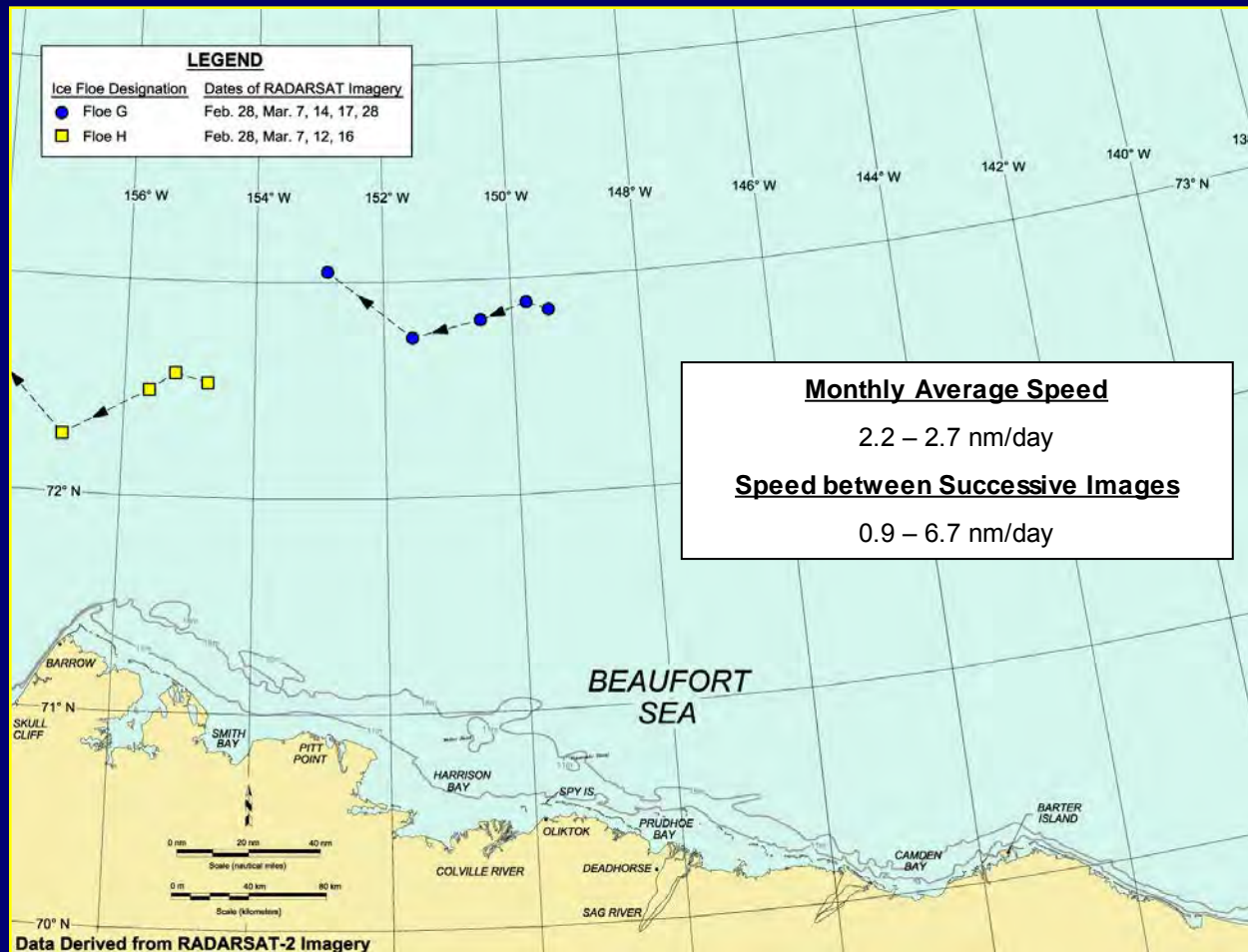
Telemetry Buoys

- 14 buoys (3 added in Mar)
- 8 buoys remained stationary (landfast ice zone)
- 6 buoys experienced small westerly displacements
- Max speed 0.31 kt (no storms)

March Landfast Ice Edge and Telemetry Buoy Tracks



March Multi-Year Ice Movement



- Moderate westerly displacements & speeds reflecting predominance of westerly winds & absence of easterly storms

Reconnaissance Flights: March 28-30

Lagoon Ice (inside barrier islands)

- Primarily flat and featureless; 1-2 m rubble in Stefansson Sound
- 6 thermal cracks between Long Island and Mikkelsen Bay

Landfast Ice & Shear Zone

- Seaward Edge: 18-m isobath east of Prudhoe Bay
stable extension west of Prudhoe Bay
- Shear Zone: Stable & well-grounded
- Harrison Bay: Grounded ridges & rubble to 6 m on Stamukhi Shoal; 20 m on Weller Bank
- Barrier Is.: 5-nm band of grounded ridges & rubble to 8 m
- Camden Bay: Less consolidated with rubble to 5 m

Reconnaissance Flights: March 28-30

Ice Pile-Ups

- 46 pile-ups between Harrison Bay & Camden Bay
- Probable causes: wind shifts on Nov 9-10, Nov 14 & Dec 8
- Direction of Approach: SW, NW, & NE quadrants
- Locations: 39 on barrier islands, 3 on mainland shore;
4 on man-made facilities
- Dimensions:
 - Heights 1 – 8 m
 - Lengths 50 – 2,600 m
 - Encroachment Distances 0 – 20 m
 - Block Thickness 30 – 60 cm

Reconnaissance Flights: March 28-30

Shell Prospects

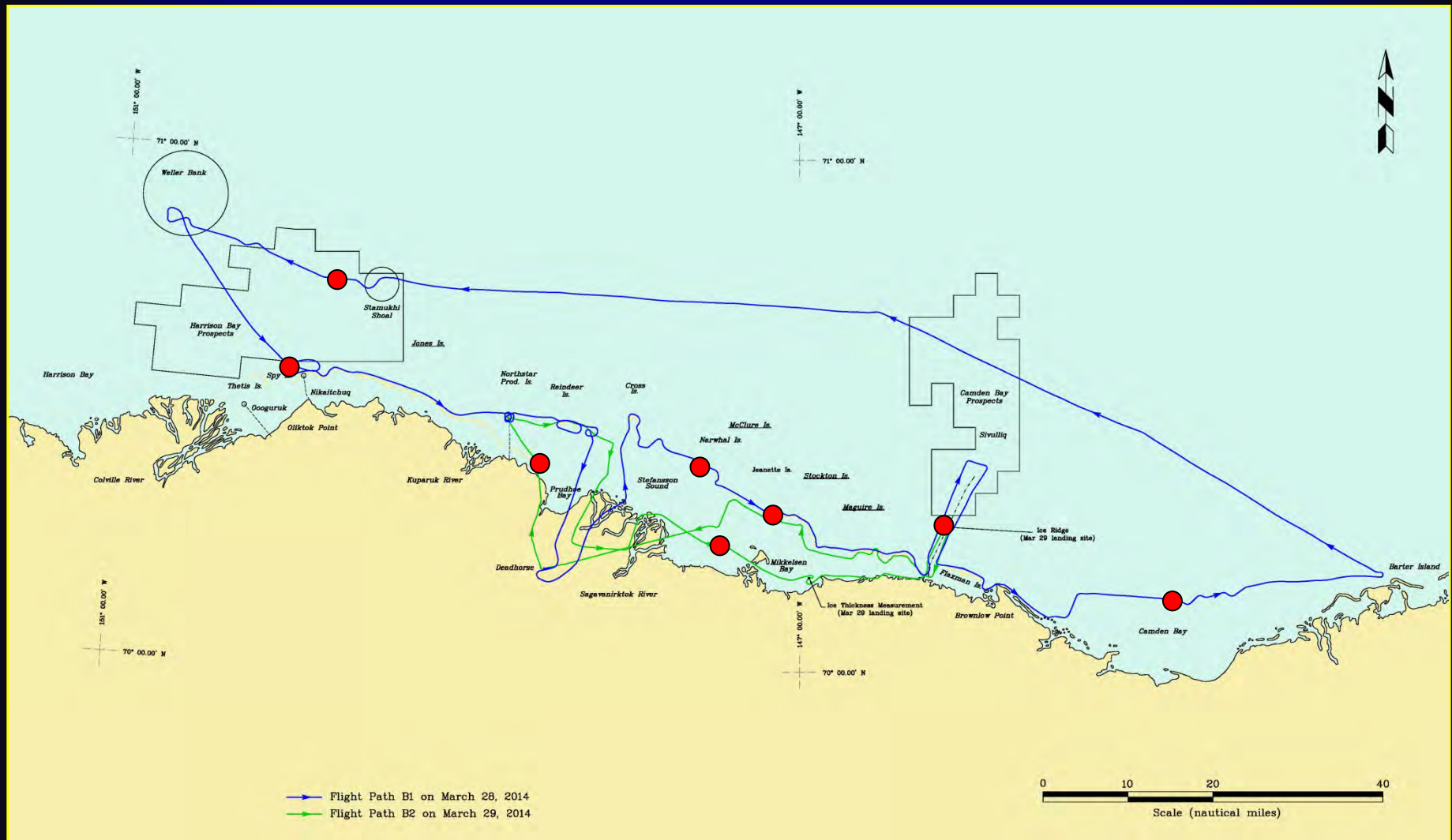
➤ Sivulliq Pipeline Route

- Leffingwell Lagoon: flat ice
- LFI outside Mary Sachs Entrance (5 nm): rubble heights to 3 m
ridge heights to 5 m
- Seaward Edge of LFI: 11.8-m grounded ridge
- Offshore (7 nm): rubble heights to 3 m

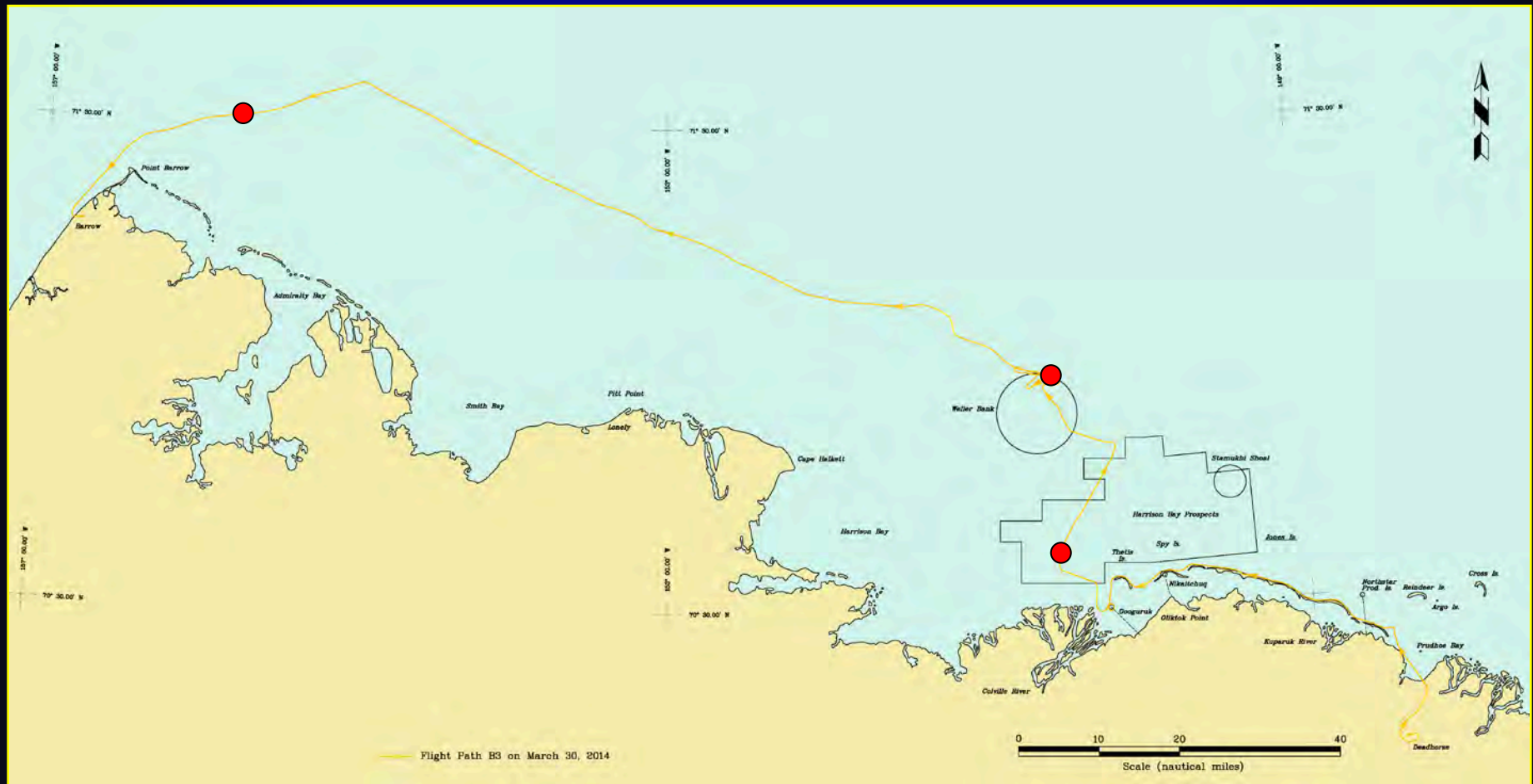
➤ Harrison Bay Prospects

- Stable ice contained within LFI zone
- Ridge & rubble heights increased from 2 m in southwest to 6 m in northeast (Stamukhi Shoal)

Reconnaissance Flights: March 28 & 29



Reconnaissance Flight: March 30



Comments or Questions?



November Landfast Ice Edge



Ice Pile-Up



5-m Pile-Up on SW end of Narwhal Island
(looking southeast)

December Landfast Ice Edge



January Landfast Ice Edge

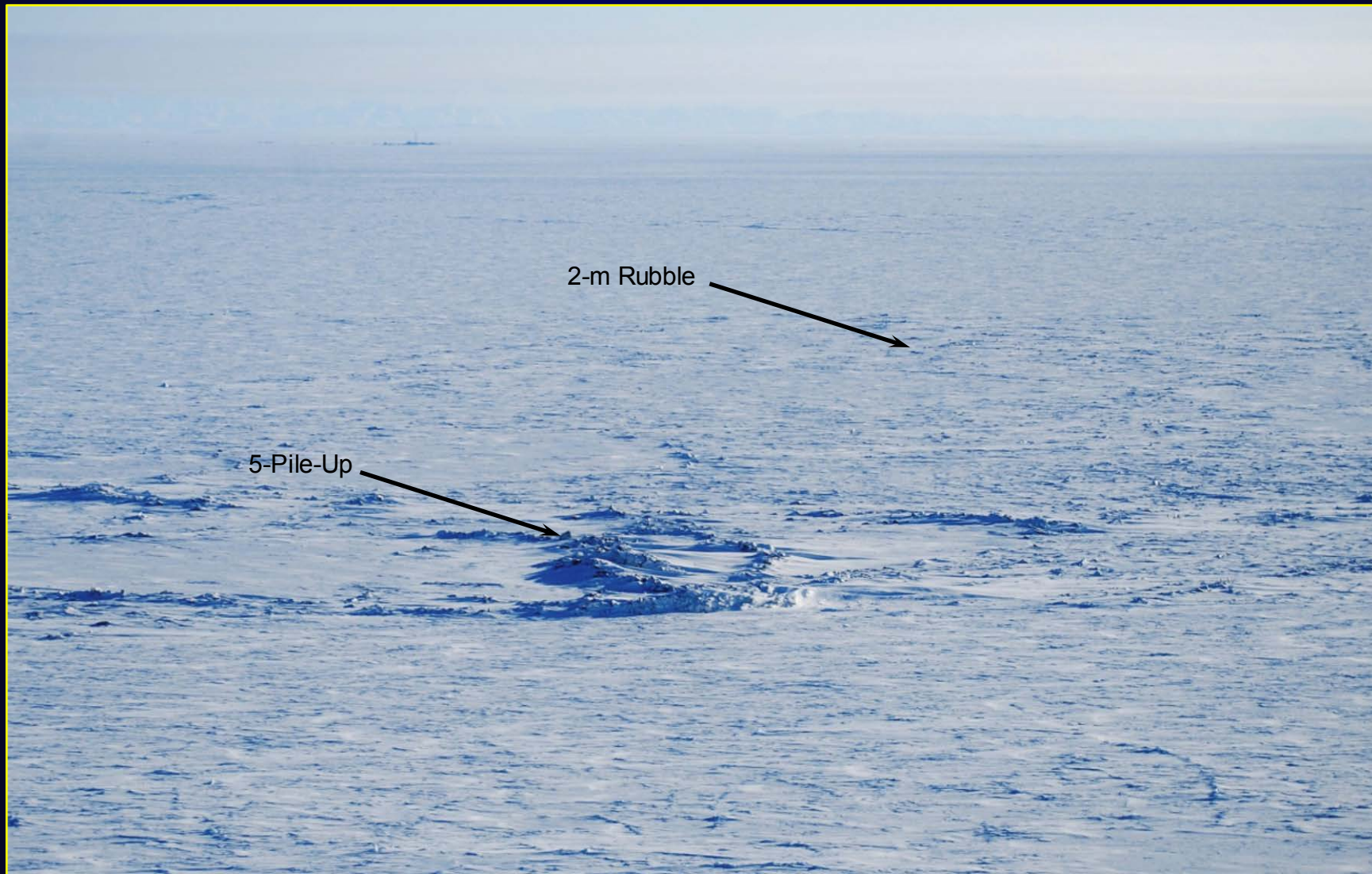


Lagoon Ice



Flat Ice in Simpson Lagoon between Spy Is. Drillsite & Oliktok Point
(looking southeast)

Lagoon Ice



2-m Rubble in Stefansson Sound; 5-m pile-up on Pole Is.
(looking southeast)

Thermal Crack



1-m Ridge in Stefansson Sound
(looking southeast)

Shear Zone



20-m Grounded Ridge on Weller Bank
(looking southwest)

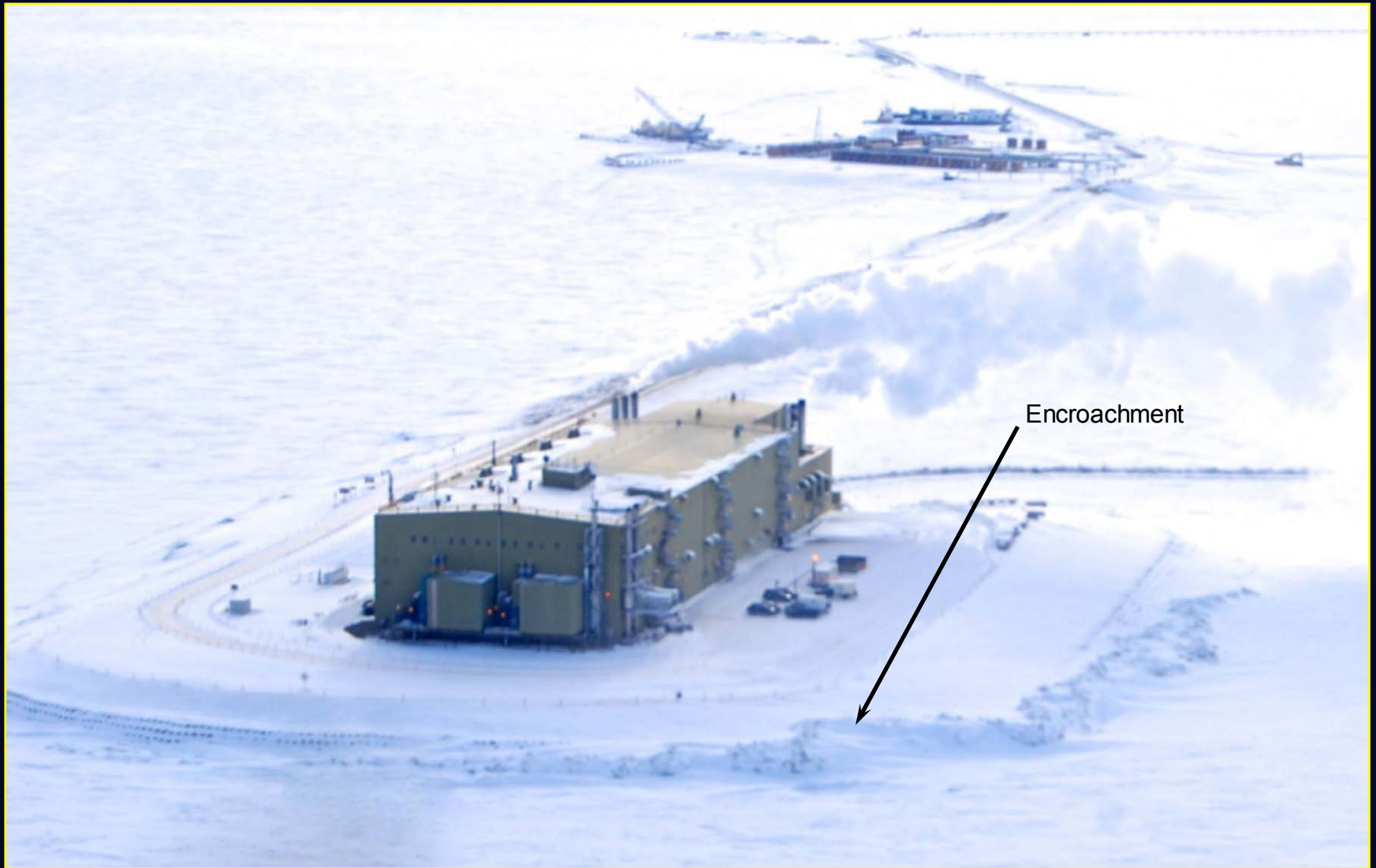
Ice Pile-Up



Narwhal Island

5-m Pile-Up on SW end of Narwhal Island
(looking southeast)

Ice Pile-Up



8-m Pile-Up with 20-m Encroachment on West Dock STP Pad
(looking south)

Camden Bay



Shear Ridge at Landfast Ice Edge
(looking southeast)

Sivulliq Pipeline Route

Flat Ice in Leffingwell Lagoon



3-m Rubble in LFI 3 nm off Mary Sachs Entrance



1- to 3-m Rubble & Refreezing Lead at Seaward End



Sivulliq Pipeline Route



11.8-m Grounded Ridge at Seaward Edge of Landfast Ice
(looking south)

Sivulliq Pipeline Route



Late-Season Ridge Reflecting Shear Followed by Compression
(looking southeast)

Harrison Bay Prospects



2-m Ridges & Rubble in SW portion
(looking west)

Harrison Bay Prospects



5-m Ridges & Rubble in NE portion
(looking southwest)

Extended Flaw Lead



15 nm NE of Point Barrow
(looking northwest)