2019-20 FREEZE-UP STUDY OF ARCTIC SEA ICE IN THE ALASKAN BEAUFORT AND CHUKCHI SEAS
APPENDIX A: DRAWINGS

Prepared for:

U.S. Dept. of the Interior
Bureau of Safety and
Environmental Enforcement
Washington, D.C.

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E: 350,000 | E: 400,000 | E: 450,000 | E: 500,000 | E: 550,000 | E: 600,000 | E: 650,000

N: 7,900,000 | N: 7,850,000 | N: 7,800,000 | N: 7,750,000

151° 00.00' W | 147° 00.00' W | 143° 00.00' W

71° 00.00' N | 70° 00.00' N

Weller Bank
Stamukhi Shoal
Harrison Bay Prospects
Harrison Bay
Thetis Is.
Spy Is.
Nikaitchuq
Oooguruk
Oliktok Point
Jones Is.
Colville River
Kuparuk River
Northstar Prod. Is.
Reindeer Is.
Cross Is.
Dinkum Sands
Narwhal Is.
Jeanette Is.
Stefansson Sound
Liberty Is. Site
Prudhoe Bay
Deadhorse
Sagavanirktok River
McClure Is.
Stockton Is.
Mikkelsen Bay
Maguire Is.
Flaxman Is.
Camden Bay Prospects
Brownlow Point
Camden Bay
Barter Island

B1-01 B1-02 B1-03 B1-04 B1-05 B1-06 B1-07 B1-08 B1-09 B1-10 B1-11 B1-12 B1-13 B1-14 B1-15 B1-16 B1-17 B1-18 B1-19 B1-20 B1-21 B1-22 B1-23 B1-24 B1-25 B1-26 B1-27 B1-28 B1-29 B1-30 B1-31 B1-32 B1-33 B1-34 B1-35 B1-36 B1-37 B1-38 B1-39 B1-40 B1-41 B1-42

B1-V01 B1-V02 B1-V03 B1-V04 B1-V05 B1-V06 B1-V07 B1-V08 B1-V09 B1-V10 B1-V11 B1-V12 B1-V13 B1-V14 B1-V15 B1-V16 B1-V17 B1-V18 B1-V19 B1-V20 B1-V21

iRDG (1m); iRBL (1m) | UDI | FOG | ISL | RDG (2m); RBL (2m) | RFL; PNK | ASL | RFL | RDG (2m) | mCRK | MY (<10%) | P/U (2,5m) | RBL (2m) | RBL (3m) | RDG (3m) | RBL (1m) | P/U (7,0m) | P/U (3,0m) | iRBL (0.5m) | TCK | P/U (2,5m) | P/U (1,3m) | P/U (4,7m) | P/U (7,8m) | P/U (3,5m) | P/U (2,1m) | P/U (1,0m) | P/U (2,3m) | P/U (3,0m) | mRDG (1m); mRBL (1m) | ISL; RDG (2m) | RDG (3m); RBL (3m) | MYI (<10%) | RDG (1m); RBL (1m) | MYI (90%) | MYI (50%) | MYI (10%) | MYI (25%) | MYI (80%); RDG (1m); RBL (1m) | MYI (70%) | iRDG (2m); iRBL (2m) | iRBL (1m) | ASL; RDG (2m) | RDG (1m); RBL (1m) | RDG (3m) | RDG (1m) | mRFL; RDG (2m); RBL (2m) | BRK | RDG (1m); RBL (1m) | RDG (2m); RBL (2m) | RFL; BRK | RFL; RDG (1m); RBL (1m) | RDG (1m); RBL (2m) | RDG (2m); RBL (1m) | RDG (1m); RBL (1m) | MYI (<10%)

0 5 10 20
Scale (nautical miles)

0 20 40
Scale (kilometers)

FLITH PATH LEGEND

- Flight Path B1 on February 22, 2020
- B1-19 Location of Photo B1-19 on Flight B1
- B1-V05 Location of Video B1-V05 on Flight B1
- Subsea Pipeline

ICE FEATURE LEGEND

ASL	Active Shear Line
BRK	Broken Ice
CRK	Crack
ISL	Inactive Shear Line (also • • •)
MYI (_%)	Multi-Year Ice (concentration in %)
PNK	Pancake Ice
P/U (_._m)	Pile-Up (height, encroachment in m)
RBL (_m)	Rubble (height in m)
RDG (_m)	Ridge (height in m)
RFL	Refreezing Lead
TCK (_m)	Thermal Crack Ridge (height in m)
UDI	Undeformed Ice

The prefixes *i* and *m* are used to indicate intermittent features and multiple features, respectively.

NOTES

1. Flight B1 conducted on February 22, 2020, using Aero Commander 690.
2. Horizontal datum is Universal Transverse Mercator, Zone 6 (UTM06N), NAD 83 (meters). Geodetic coordinates are provided relative to NAD 83.

2019-20 FREEZE-UP STUDY
FEBRUARY 2020 AERIAL RECONNAISSANCE OF THE CENTRAL BEAUFORT SEA
FLIGHT PATHS, PHOTO LOCATIONS, AND ICE FEATURES

Scale: 1: 400,000	Checked by: CBL	Drawn by: LAD
Date: 28 April 2020	Sheet: 1 of 1	Revised:
Prepared for: BSEE		
Prepared by: COASTAL FRONTIERS CORPORATION	Drawing No.: CFC-1070-01-001	Rev. 0

E: 350,000 E: 400,000 E: 450,000 E: 500,000 E: 550,000 E: 600,000 E: 650,000

N: 7,950,000 N: 7,900,000 N: 7,850,000 N: 7,800,000

157° 00.00' W 153° 00.00' W 149° 00.00' W

71° 30.00' N 70° 30.00' N

Point Barrow Utqiagvik Admiralty Bay Smith Bay Pitt Point Lonely Cape Halkett Harrison Bay Harrison Bay Prospects Weller Bank Stamukhi Shoal Jones Is. Spy Is. Thetis Is. Dooguruk Oliktok Point Northstar Is. Prod. Reindeer Is. Cross Is. Kuparuk River Prudhoe Bay Colville River Deadhorse

B2-01 B2-02 B2-03 B2-04 B2-05 B2-06 B2-07 B2-08 B2-09 B2-10 B2-11 B2-12 B2-13 B2-14 B2-15 B2-16 B2-17 B2-18 B2-19 B2-20 B2-21 B2-22 B2-23 B2-24 B2-25 B2-26 B2-27 B2-28 B2-29 B2-30 B2-31 B2-32 B2-33 B2-34 B2-35 B2-36 B2-37 B2-38 B2-39 B2-40 B2-41 B2-42 B2-43 B2-44 B2-45 B2-46 B2-47 B2-48 B2-49 B2-50 B2-51 B2-52 B2-53 B2-54 B2-55 B2-56 B2-57 B2-58 B2-59 B2-60 B2-61 B2-62 B2-63 B2-64

B2-V01 B2-V02 B2-V03 B2-V04 B2-V05 B2-V06 B2-V07 B2-V08 B2-V09 B2-V10 B2-V11 B2-V12 B2-V13 B2-V14 B2-V15 B2-V16 B2-V17

RDG (2m); RBL (2m) mRFL mCRK RFL iRDG (2m); iRBL (2m) BKN; RDG (3m); RBL (3m) LFI; RFL ISL iRDG (1m); iRBL (1m) RDG (1m); RBL (1m) PNK iRDG (0.5m); iRBL (0.5m) RDG (3m) RDG (4m) RDG (6m) iRDG (3m); iRBL (3m) RDG (5m) mRBL (5m) RBL (4m) RDG (3m) ASL RBL (3m) RBL (7m) UDI MYI (<10%) RBL (2m) P/U (4,5m) TCK P/U (7,5m) P/U (3,5m) P/U (4,1m) P/U (2,7m) P/U (2,5m) P/U (1,5m) P/U (1,3m) P/U (2,0m) P/U (7,20m) MYI (70%); RDG (2m); RBL (2m) MYI (80%) P/U (3,3m) P/U (4,5m) P/U (5,0m) mRBL (1m); iRBL (1m) mRBL (5m) MYI (30%)

Scale (nautical miles): 0 5 10 20

Scale (kilometers): 0 20 40

FLITH PATH LEGEND

- Flight Path B2 on February 23, 2020
- B2-12 Location of Photo B2-12 on Flight B2
- B2-V07 Location of Video B2-V07 on Flight B2
- Subsea Pipeline

ICE FEATURE LEGEND

ASL	Active Shear Line
BKN	Broken Ice
CRK	Crack
ISL	Inactive Shear Line
LFI	Landfast Ice Edge
LD	Lead
MYI (_%)	Multi-Year Ice (concentration in %)
P/U (_,_m)	Pile-Up (height, encroachment in m)
PNK	Pancake Ice
RBL (_m)	Rubble (height in m)
RDG (_m)	Ridge (height in m)
RFL	Refreezing Lead
TCK (_m)	Thermal Crack Ridge (height in m)
UDI	Undeformed Ice

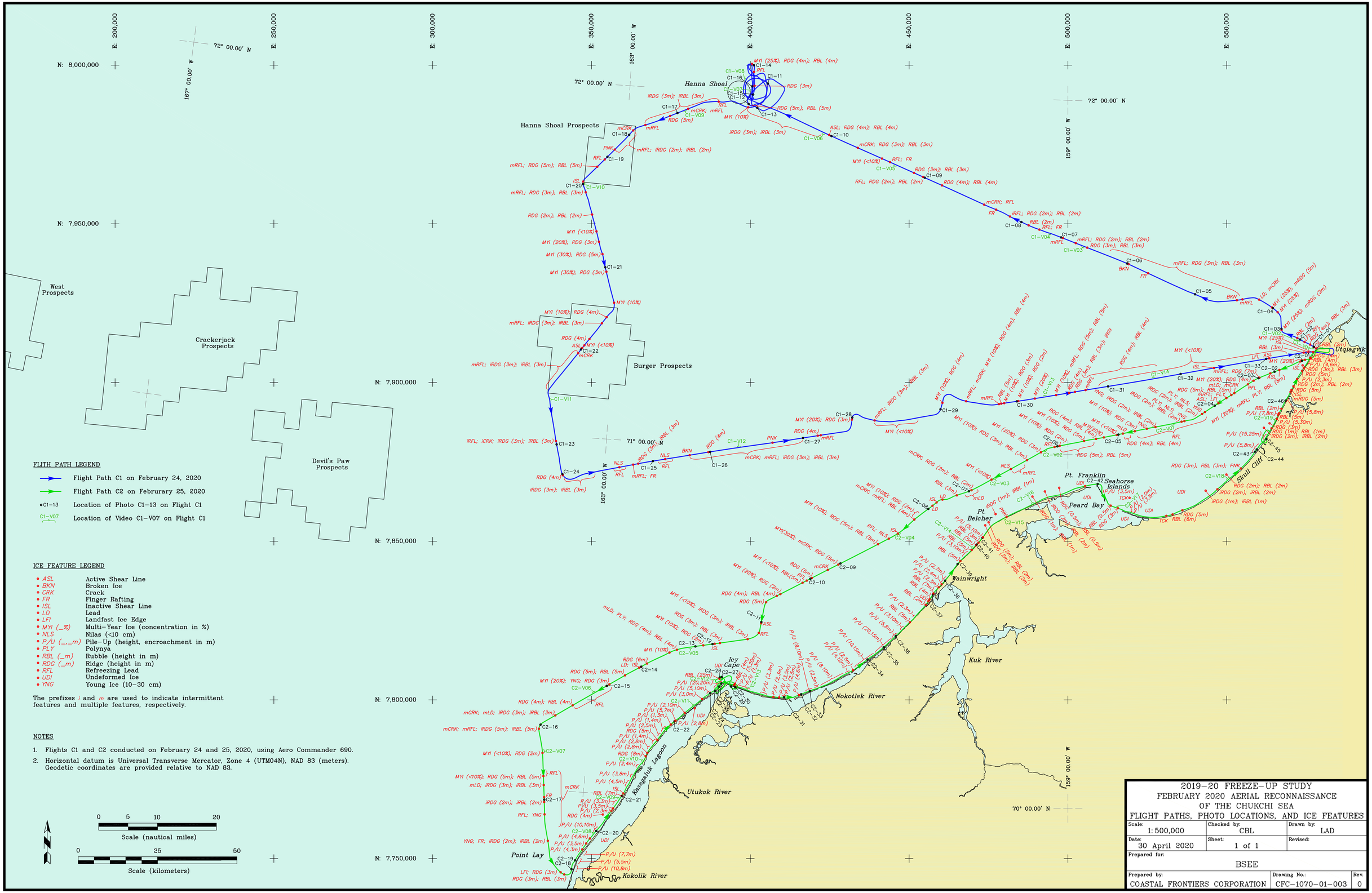
The prefixes *i* and *m* are used to indicate intermittent features and multiple features, respectively.

NOTES

1. Flight B2 conducted on February 23, 2020, using Aero Commander 690.
2. Horizontal datum is Universal Transverse Mercator, Zone 5 (UTM05N), NAD 83 (meters). Geodetic coordinates are provided relative to NAD 83.

2019-20 FREEZE-UP STUDY
FEBRUARY 2020 AERIAL RECONNAISSANCE OF THE WESTERN BEAUFORT SEA
FLIGHT PATH, PHOTO LOCATIONS, AND ICE FEATURES

Scale: 1: 400,000	Checked by: CBL	Drawn by: LAD
Date: 30 April 2020	Sheet: 1 of 1	Revised:
Prepared for: BSEE		
Prepared by: COASTAL FRONTIERS CORPORATION	Drawing No.: CFC-1070-01-002	Rev. 0



FLITH PATH LEGEND

- Flight Path C1 on February 24, 2020
- Flight Path C2 on Februrary 25, 2020
- C1-13 Location of Photo C1-13 on Flight C1
- C1-V07 Location of Video C1-V07 on Flight C1

ICE FEATURE LEGEND

ASL	Active Shear Line
BKN	Broken Ice
CRK	Crack
FR	Finger Rafting
ISL	Inactive Shear Line
LD	Lead
LFI	Landfast Ice Edge
MYI (_%)	Multi-Year Ice (concentration in %)
NLS	Nilas (<10 cm)
P/U (_._m)	Pile-Up (height, encroachment in m)
PLY	Polynya
RBL (_m)	Rubble (height in m)
RDG (_m)	Ridge (height in m)
RFL	Refreezing Lead
UDI	Undeformed Ice
YNG	Young Ice (10–30 cm)

The prefixes *i* and *m* are used to indicate intermittent features and multiple features, respectively.

NOTES

1. Flights C1 and C2 conducted on February 24 and 25, 2020, using Aero Commander 690.
2. Horizontal datum is Universal Transverse Mercator, Zone 4 (UTM04N), NAD 83 (meters). Geodetic coordinates are provided relative to NAD 83.

0 5 10 20
Scale (nautical miles)

0 25 50
Scale (kilometers)

2019–20 FREEZE-UP STUDY
FEBRUARY 2020 AERIAL RECONNAISSANCE OF THE CHUKCHI SEA
FLIGHT PATHS, PHOTO LOCATIONS, AND ICE FEATURES

Scale: 1:500,000	Checked by: CBL	Drawn by: LAD
Date: 30 April 2020	Sheet: 1 of 1	Revised:
Prepared for: BSEE		
Prepared by: COASTAL FRONTIERS CORPORATION	Drawing No.: CFC-1070-01-003	Rev. 0

APPENDIX B

POST-REMOTE IMAGING ACQUISITION REPORTS

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Remote Imaging Acquisition Progress Report No. 1

November 5, 2019 (Revised)

This report pertains to the first pair of RADARSAT-2 images obtained from MDA in support of the 2019-20 Freeze-Up Study of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas under Contract 140E0119C0011. Processed versions of the images, representing derivative products that may be transmitted to BSEE in accordance with MDA's End User License Agreement, are attached as Figures 1 and 2. A description and assessment of each image is provided below.

Image of Beaufort Sea

Date of Acquisition: October 17, 2019

Area of Observation: Alaskan Beaufort Sea extending from east of Barter Island to west of Point Barrow, and as far north as the 74°N parallel.

Principal Objective: Document the beginning of freeze-up, focusing on the semi-protected nearshore regions where the formation of first-year ice is likely to commence.

Findings: Small patches of first-year ice are evident in nearshore areas that include Camden Bay, Stefansson Sound, the Sagavanirktok River Delta, Prudhoe Bay, Gwydyr Bay, the Colville River Delta, Harrison Bay, Smith Bay, and Admiralty Bay. Pack ice is conspicuously absent from the entire region shown in the image.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the nascent ice canopy until the next RADARSAT-2 image acquisition covering the Beaufort Sea, which occurred on October 31, 2019.

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Image of Chukchi Sea

Date of Acquisition: October 19, 2019

Area of Observation: Alaskan Chukchi Sea extending from east of Point Barrow to south of Point Lay, as far north as the 74°N parallel, and as far west as the 170°W meridian.

Principal Objective: Document the beginning of freeze-up, focusing on the semi-protected nearshore regions where the formation of first-year ice is likely to commence.

Findings: First-year ice is evident in Kasegaluk Lagoon and the Kuk River. As in the case of the October 17th image of the Beaufort Sea, pack ice is conspicuously absent from the region shown in this image of the Chukchi.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the nascent ice canopy until the next RADARSAT-2 image acquisition covering the Chukchi Sea, which occurred on October 29, 2019.

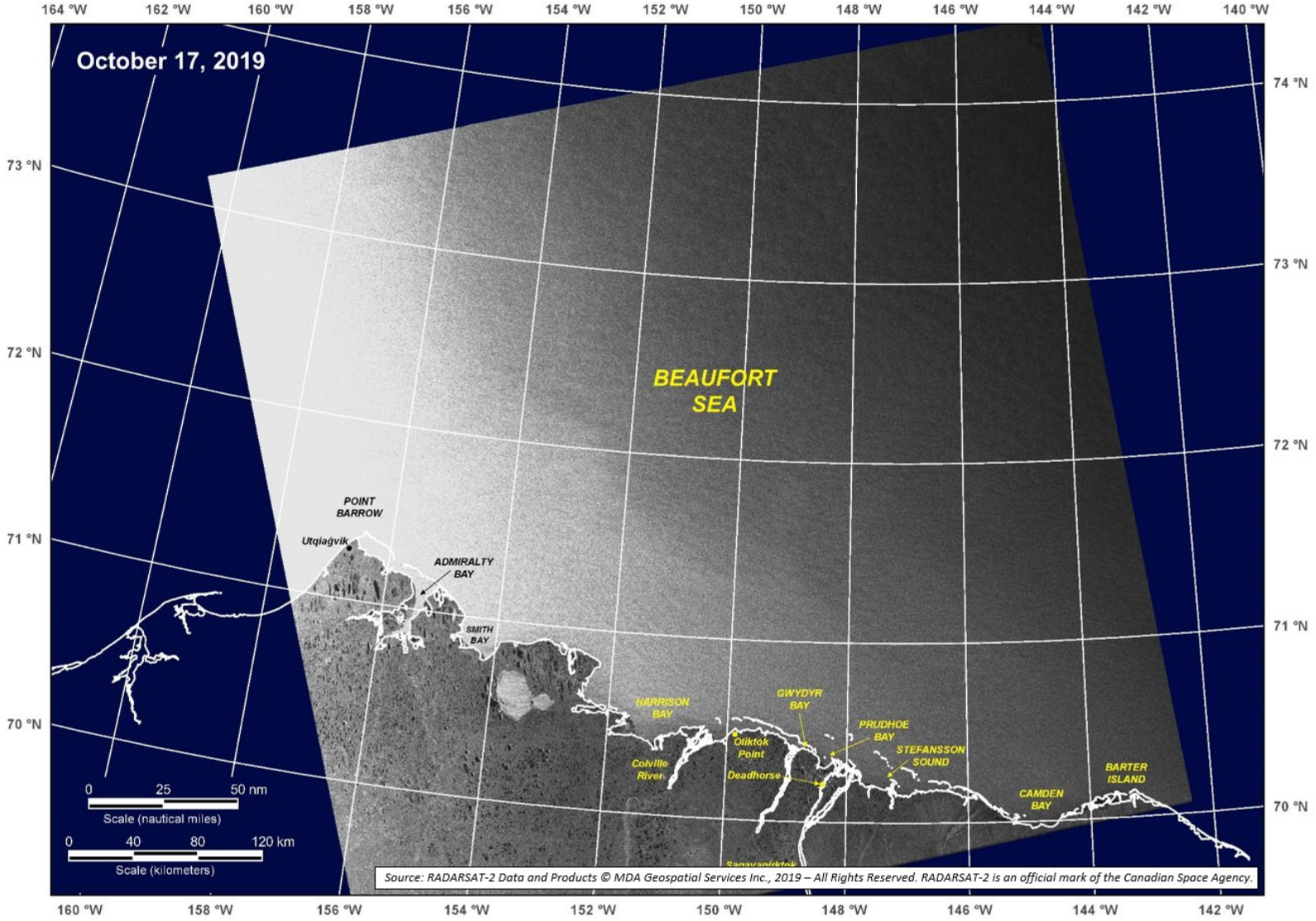

Figure 1. RADARSAT-2 Image of Beaufort Sea

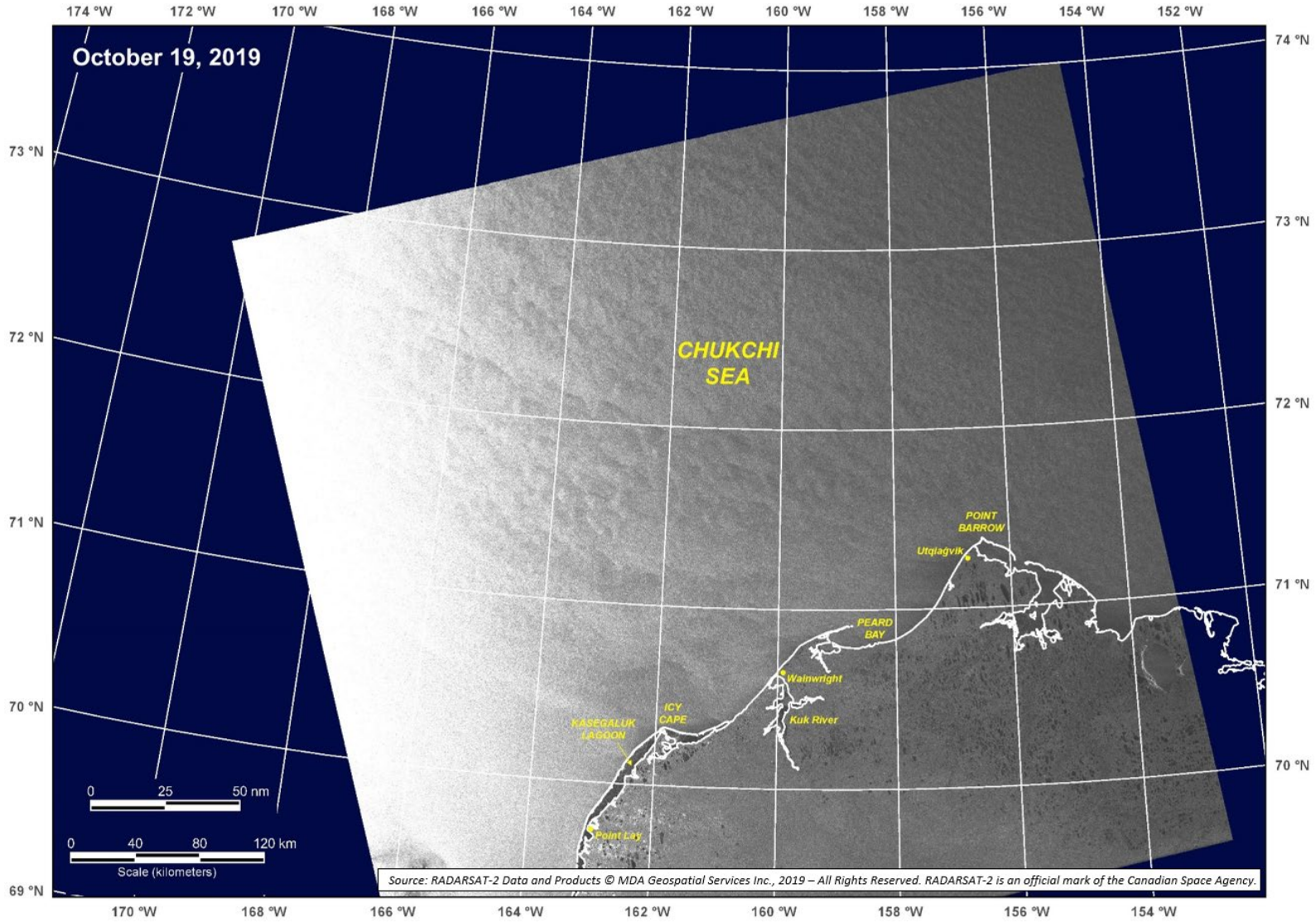

Figure 2. RADARSAT-2 Image of Chukchi Sea

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Remote Imaging Acquisition Progress Report No. 2

November 11, 2019

This report pertains to the second pair of RADARSAT-2 images obtained from MDA in support of the 2019-20 Freeze-Up Study of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas under Contract 140E0119C0011. Processed versions of the images, representing derivative products that may be transmitted to BSEE in accordance with MDA's End User License Agreement, are attached as Figures 1 and 2. A description and assessment of each image is provided below.

Image of Beaufort Sea

Date of Acquisition: October 31, 2019

Area of Observation: Alaskan Beaufort Sea extending from east of Barter Island to Admiralty Bay, and north of the 74°N parallel.

Principal Objective: Document the progress of early freeze-up, focusing on the semi-protected nearshore regions where the formation of first-year ice has commenced.

Findings: The first-year ice evident in the RADARSAR-2 image obtained on October 17th expanded modestly in the semi-protected waters of Smith Bay, Harrison Bay, Prudhoe Bay, and Camden Bay during the two-week period between images. More substantial expansion occurred in Stefansson Sound and Simpson Lagoon.

Young pack ice is evident in the eastern portion of the image, extending from the vicinity of the 71°N parallel to north of the 74°N parallel, and as far west as the 145°W meridian.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the expanding ice canopy until the next RADARSAT-2 image acquisition covering the Beaufort Sea, which is scheduled for November 17, 2019.

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Image of Chukchi Sea

Date of Acquisition: October 29, 2019

Area of Observation: Alaskan Chukchi Sea extending from east of Point Barrow to south of Point Lay, as far north as the vicinity of the 74°N parallel, and as far west as the 172°W meridian.

Principal Objective: Document the progress of early freeze-up, focusing on the semi-protected nearshore regions where the formation of first-year ice has commenced.

Findings: First-year ice covers the majority of Kasegaluk Lagoon and the Kuk River. In addition, ice formation is evident in Peard Bay and immediately east of Point Barrow in Admiralty Bay and Elson Lagoon. No pack ice is evident in this image.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the nascent ice canopy until the next RADARSAT-2 image acquisition covering the Chukchi Sea, which is scheduled for November 15, 2019.

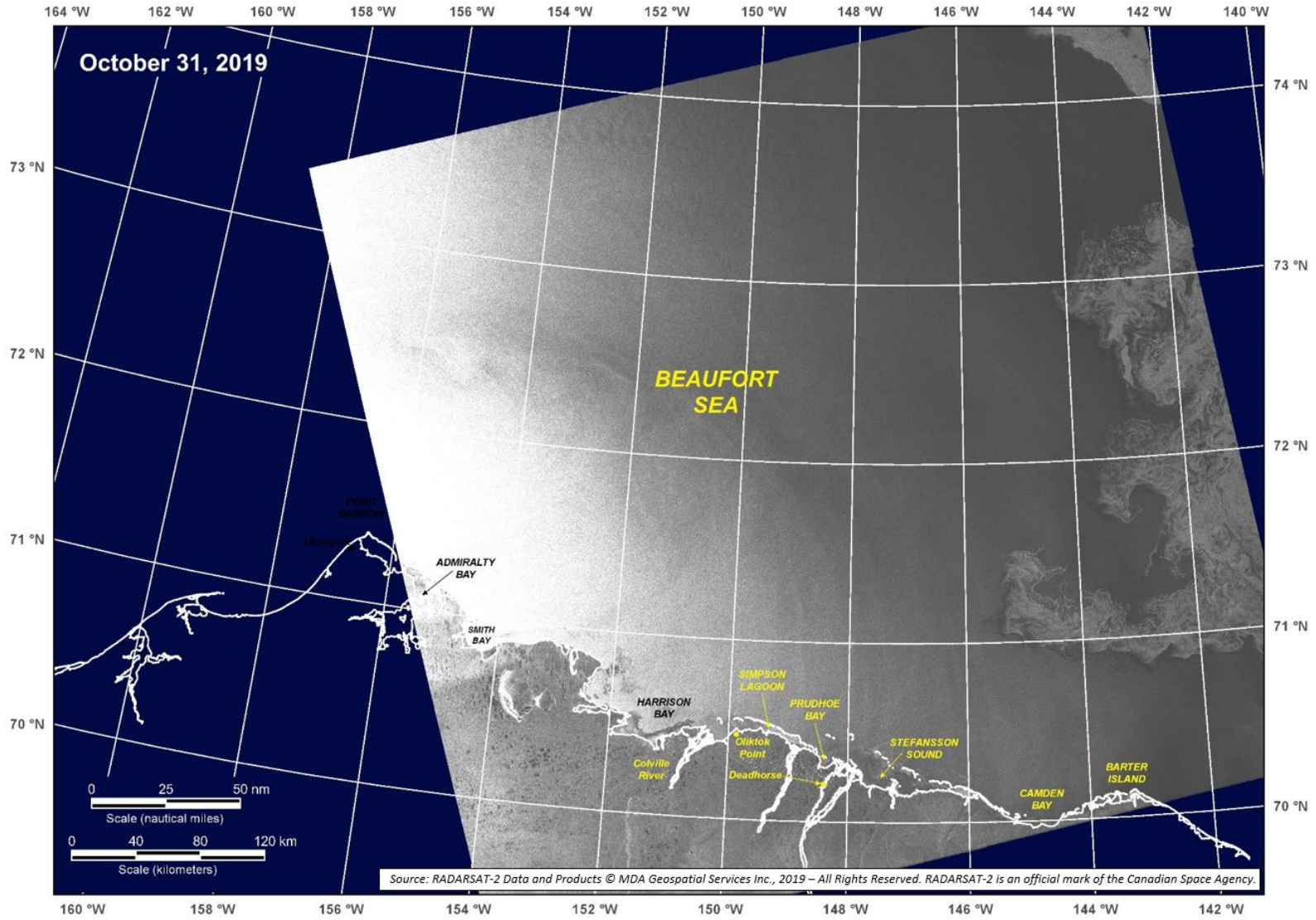

Figure 1. RADARSAT-2 Image of Beaufort Sea

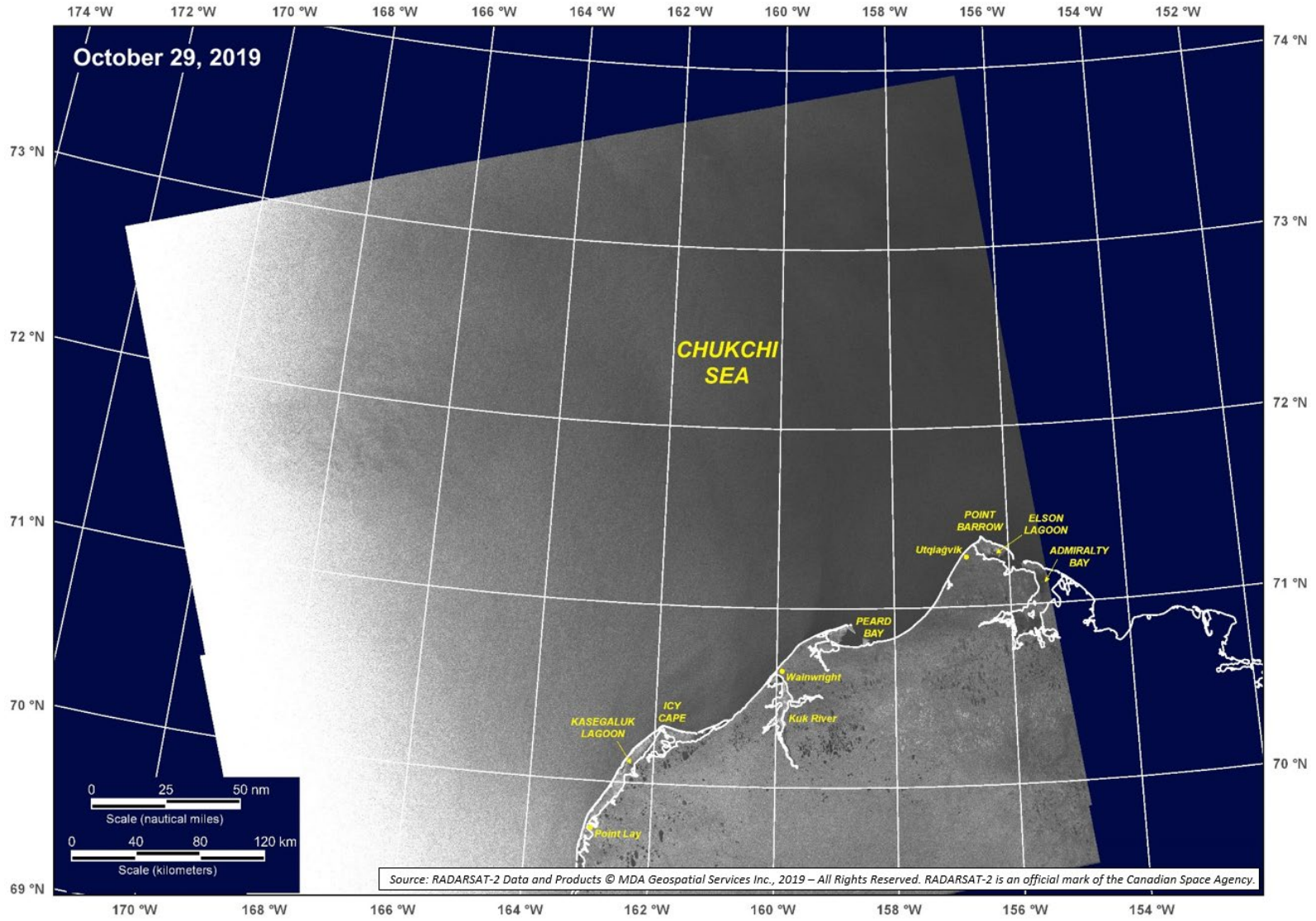

Figure 2. RADARSAT-2 Image of Chukchi Sea

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Remote Imaging Acquisition Progress Report No. 3

November 21, 2019

This report pertains to the third pair of RADARSAT-2 images obtained from MDA in support of the 2019-20 Freeze-Up Study of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas under Contract 140E0119C0011. Processed versions of the images, representing derivative products that may be transmitted to BSEE in accordance with MDA's End User License Agreement, are attached as Figures 1 and 2. A description and assessment of each image is provided below.

Image of Beaufort Sea

Date of Acquisition: November 17, 2019

Area of Observation: Alaskan Beaufort Sea extending from east of Barter Island to west of Point Barrow, and north of the 74°N parallel.

Principal Objective: Document the accelerating pace of freeze-up, including the expansion of first-year ice in the nearshore region ice cover and the growth of pack ice in the offshore region.

Findings: The first-year ice in the nearshore region continued to expand during the first two weeks of November, producing coverage that ranged from substantial to complete in the semi-protected lagoon areas between Point Barrow and Barter Island. Farther offshore, the pack ice expanded dramatically, with coverage exceeding 80% from the eastern boundary of the image to the vicinity of Harrison Bay. Between Harrison Bay and Point Barrow, open water and new ice predominated south of the 71°30'N parallel. A prominent flaw lead was present between the nearshore ice and pack ice, reflecting the occurrence of westerly winds that began on November 14th and continued through the time of image acquisition.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the expanding ice canopy until the next RADARSAT-2 image acquisition covering the Beaufort Sea, which is scheduled for December 4, 2019.

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Image of Chukchi Sea

Date of Acquisition: November 15, 2019

Area of Observation: Alaskan Chukchi Sea extending from Point Barrow to south of Point Lay, as far north as the vicinity of the 74°N parallel, and as far west as the 173°W meridian.

Principal Objective: Document the progress of early freeze-up, focusing on the nearshore regions and the initial appearance of pack ice.

Findings: First-year ice coverage exceeds 80% in Kasegaluk Lagoon, the Kuk River, and Peard Bay. In addition, a thin band of young ice extends along the unprotected coast between Point Barrow and Utqiaġvik, where it diverges offshore until tapering out approximately 60 nautical miles to the southwest.

First-year pack ice is evident in the northeastern portion of the image, extending from the 72°30'N parallel to the northern boundary of the image, and as far west as the 162°W meridian. In addition, the formation of grease ice (a thin, soupy layer of small needle-like ice crystals clumped together, which makes the ocean surface resemble an oil slick) appears to be occurring north of a line that extends from the vicinity of Peard Bay to 70°N, 168°W.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the nascent ice canopy until the next RADARSAT-2 image acquisition covering the Chukchi Sea, which is scheduled for November 29, 2019.

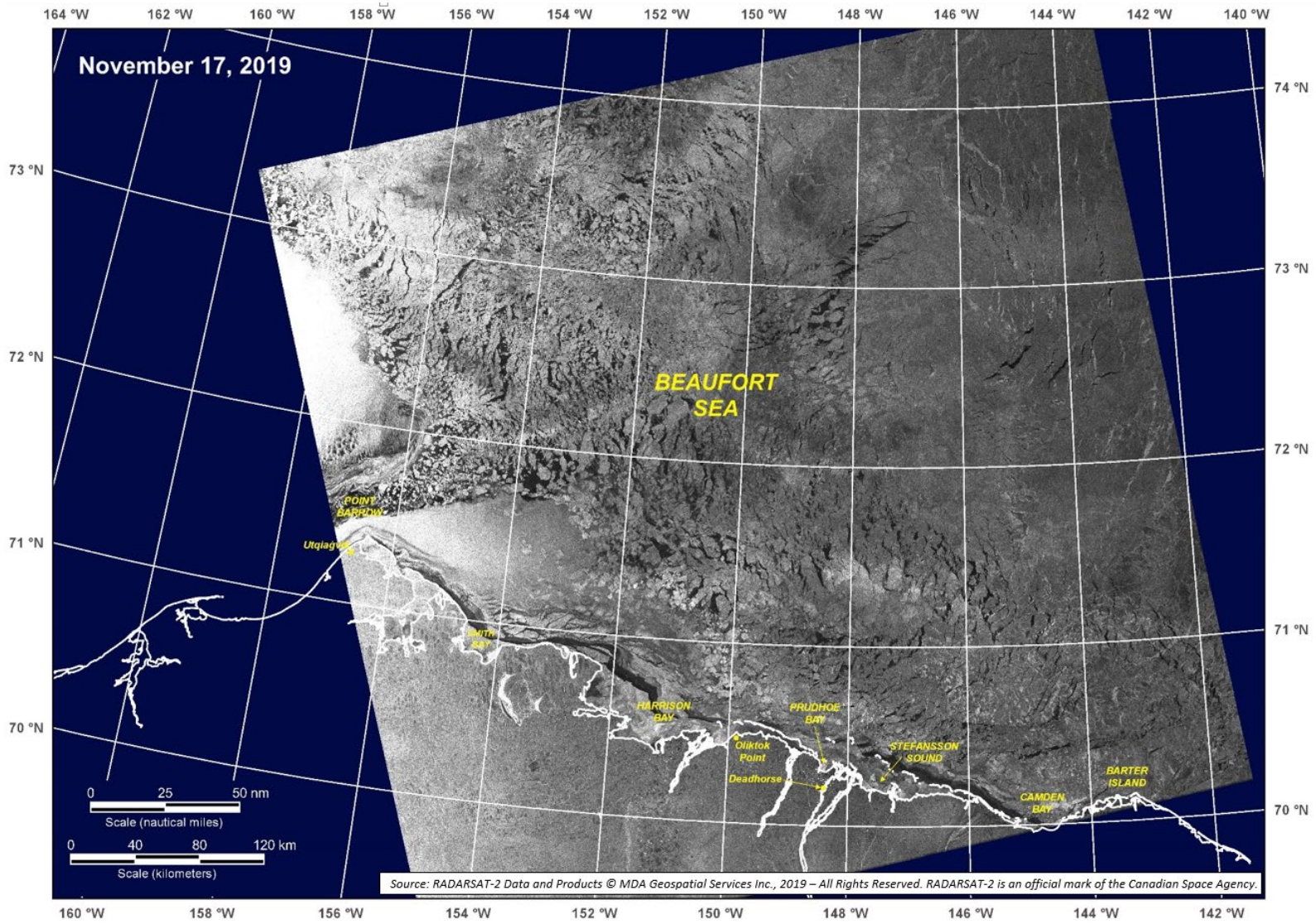

Figure 1. RADARSAT-2 Image of Beaufort Sea

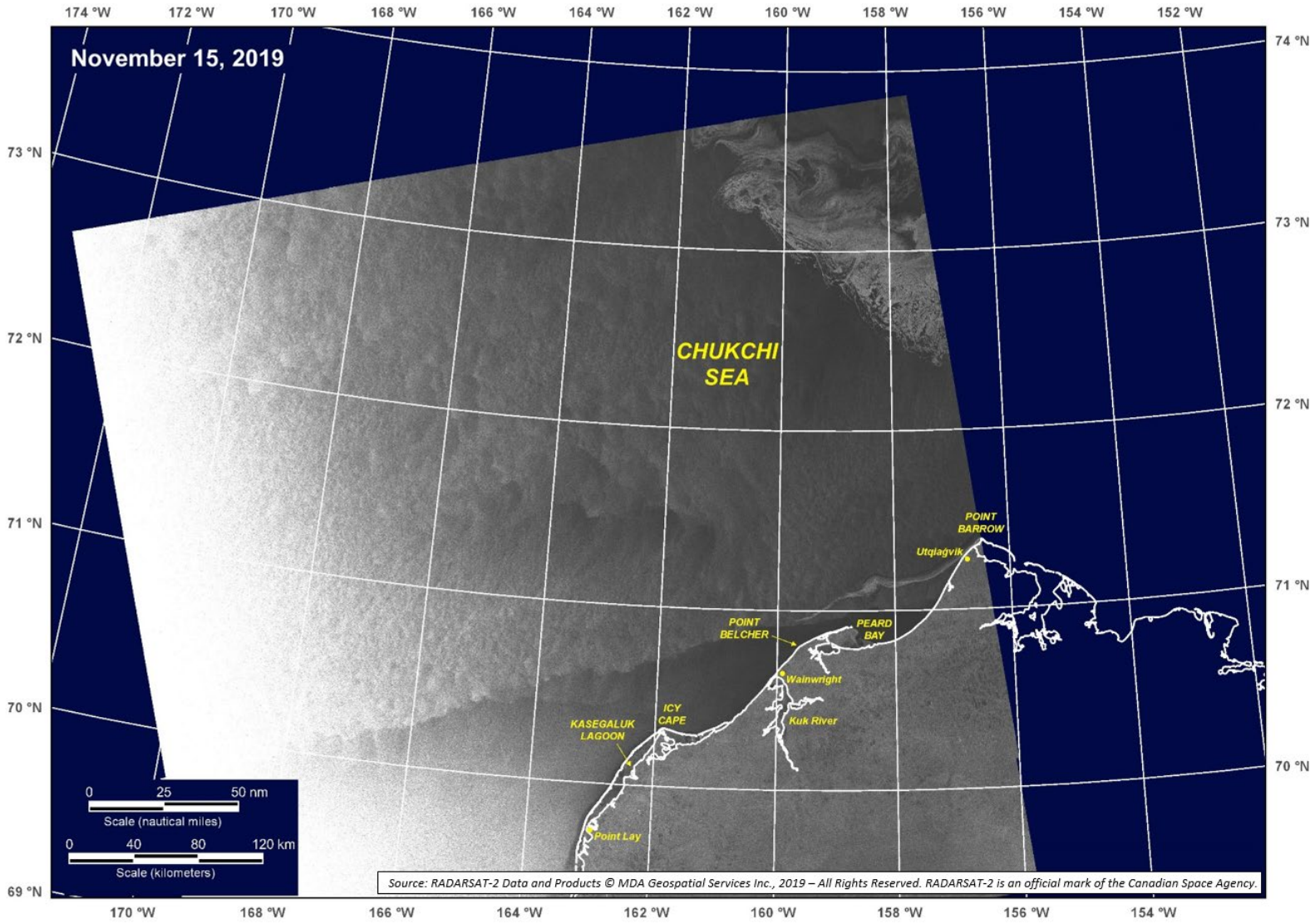

Figure 2. RADARSAT-2 Image of Chukchi Sea

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Remote Imaging Acquisition Progress Report No. 4

December 12, 2019

This report pertains to the fourth pair of RADARSAT-2 images obtained from MDA in support of the 2019-20 Freeze-Up Study of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas under Contract 140E0119C0011. Processed versions of the images, representing derivative products that may be transmitted to BSEE in accordance with MDA's End User License Agreement, are attached as Figures 1 and 2. A description and assessment of each image is provided below.

Image of Beaufort Sea

Date of Acquisition: December 4, 2019

Area of Observation: Alaskan Beaufort Sea extending from east of Barter Island to west of Point Barrow, and north of the 74°N parallel.

Principal Objective: Document the progress of basin-wide freeze-up and the growth of landfast ice.

Findings: Ice covered virtually all of the Alaskan Beaufort Sea when the image was obtained on December 4th, with open water limited to scattered small leads concentrated in the region between the 153°W meridian and Point Barrow. The image suggests that multi-year floes were present in the ice canopy, a finding supported by Canadian Ice Service ice charts and VIIRS satellite imagery from this time frame. Closer to shore, landfast ice was evident in semi-protected waters that included Stefansson Sound and Harrison Bay.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the ice canopy until the next RADARSAT-2 image acquisition covering the Beaufort Sea, which is scheduled for December 18, 2019.

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Image of Chukchi Sea

Date of Acquisition: November 29, 2019

Area of Observation: Alaskan Chukchi Sea extending from east of Point Barrow to south of Point Lay, north of the 74°N parallel, and west of the 171°W meridian.

Principal Objective: Document the progress of freeze-up, focusing on the nearshore region and expansion of the pack ice.

Findings: Kasegaluk Lagoon, the Kuk River, and Peard Bay were completely covered by first-year ice when the image was obtained on November 29th. In addition, patches of new ice were present in the exposed coastal waters between the Kuk River and Ledyard Bay.

Offshore, the pack ice experienced minimal expansion since the prior RADARSAT-2 image was acquired on November 15th. With the exception of a small tongue located at the northern edge of the image in the vicinity of 170°W meridian, the pack ice was confined to the region north of the 71°45'N parallel and east of the 161°W meridian.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the expanding ice canopy until the next RADARSAT-2 image acquisition covering the Chukchi Sea, which is scheduled for December 16, 2019.

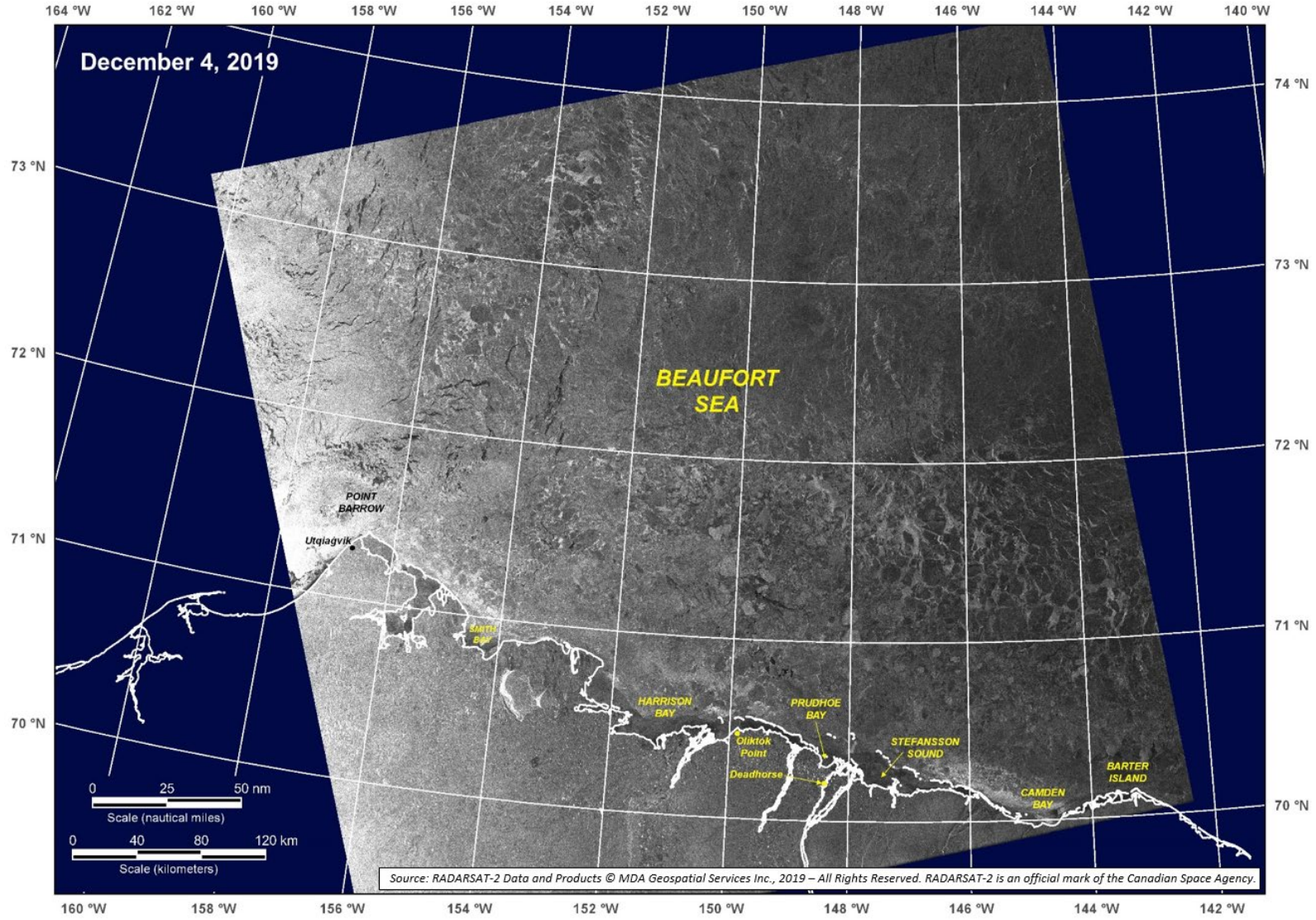

Figure 1. RADARSAT-2 Image of Beaufort Sea

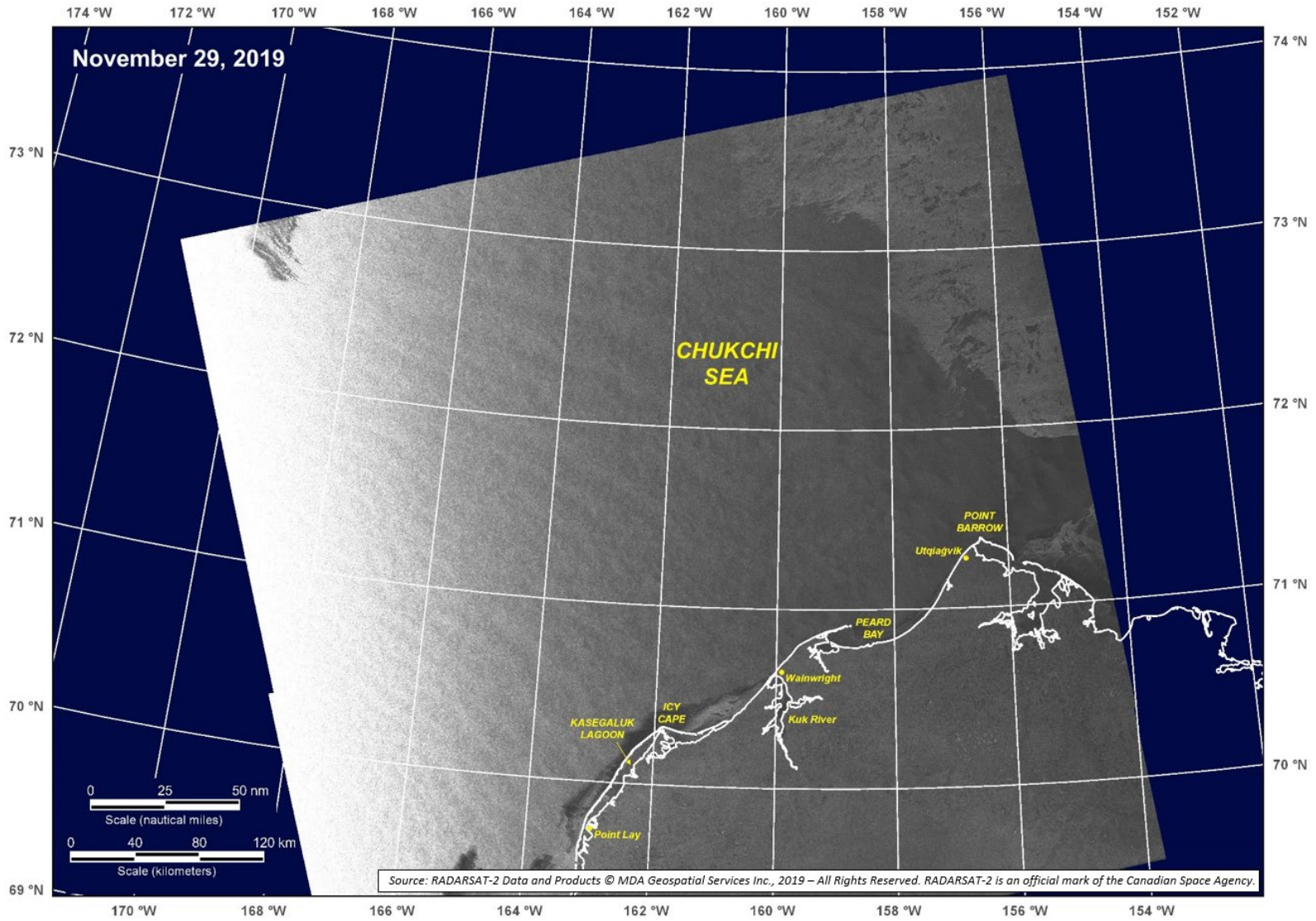

Figure 2. RADARSAT-2 Image of Chukchi Sea

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Remote Imaging Acquisition Progress Report No. 5

December 24, 2019

This report pertains to the fifth pair of RADARSAT-2 images obtained from MDA in support of the 2019-20 Freeze-Up Study of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas under Contract 140E0119C0011. Processed versions of the images, representing derivative products that may be transmitted to BSEE in accordance with MDA's End User License Agreement, are attached as Figures 1 and 2. A description and assessment of each image is provided below.

Image of Beaufort Sea

Date of Acquisition: December 18, 2019

Area of Observation: Alaskan Beaufort Sea extending from east of Barter Island to the vicinity of Point Barrow, and north of the 74°N parallel.

Principal Objective: Document the growth of landfast ice and the condition of the ice canopy.

Findings: The landfast ice zone expanded offshore during the first half of December, with the greatest increase occurring between Prudhoe Bay and Point Barrow. Pack ice covered the region seaward of the landfast ice zone, the sole exception being a series of small leads and polynyas (linear and areal openings in the ice, respectively) located south of the 71°30'N parallel between the 146°W and 152°W meridians. As in the case of the image obtained on December 4th, multi-year floes of varying sizes were present in the pack ice.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the ice canopy until the next RADARSAT-2 image acquisition covering the Beaufort Sea, which is scheduled for January 4, 2020.

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Image of Chukchi Sea

Date of Acquisition: December 16, 2019

Area of Observation: Alaskan Chukchi Sea extending from east of Point Barrow to the 172°W meridian, and from south of Point Lay to the 74°N parallel.

Principal Objective: Document the progress of freeze-up, including the growth of the pack ice and the state of the landfast ice zone.

Findings: The pack ice in the Alaskan Chukchi Sea expanded dramatically during the first half of December, with coverage approaching 75% when the image was acquired on December 16th. Landfast ice, while persisting in protected areas that included Kasegaluk Lagoon and the Kuk River, was absent from the exposed coastal waters.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the expanding ice canopy until the next RADARSAT-2 image acquisition covering the Chukchi Sea, which is scheduled for January 2, 2020.

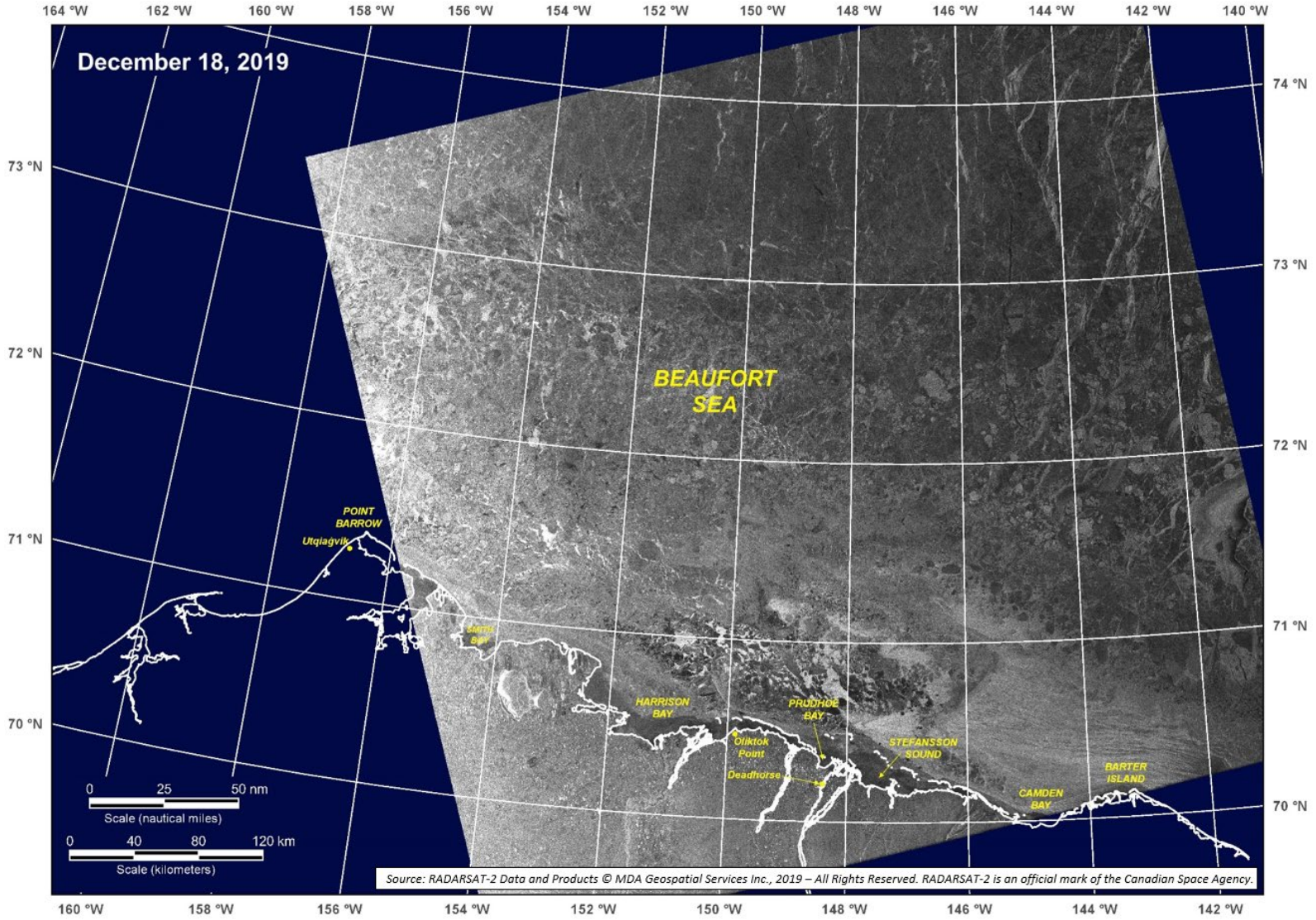

Figure 1. RADARSAT-2 Image of Beaufort Sea

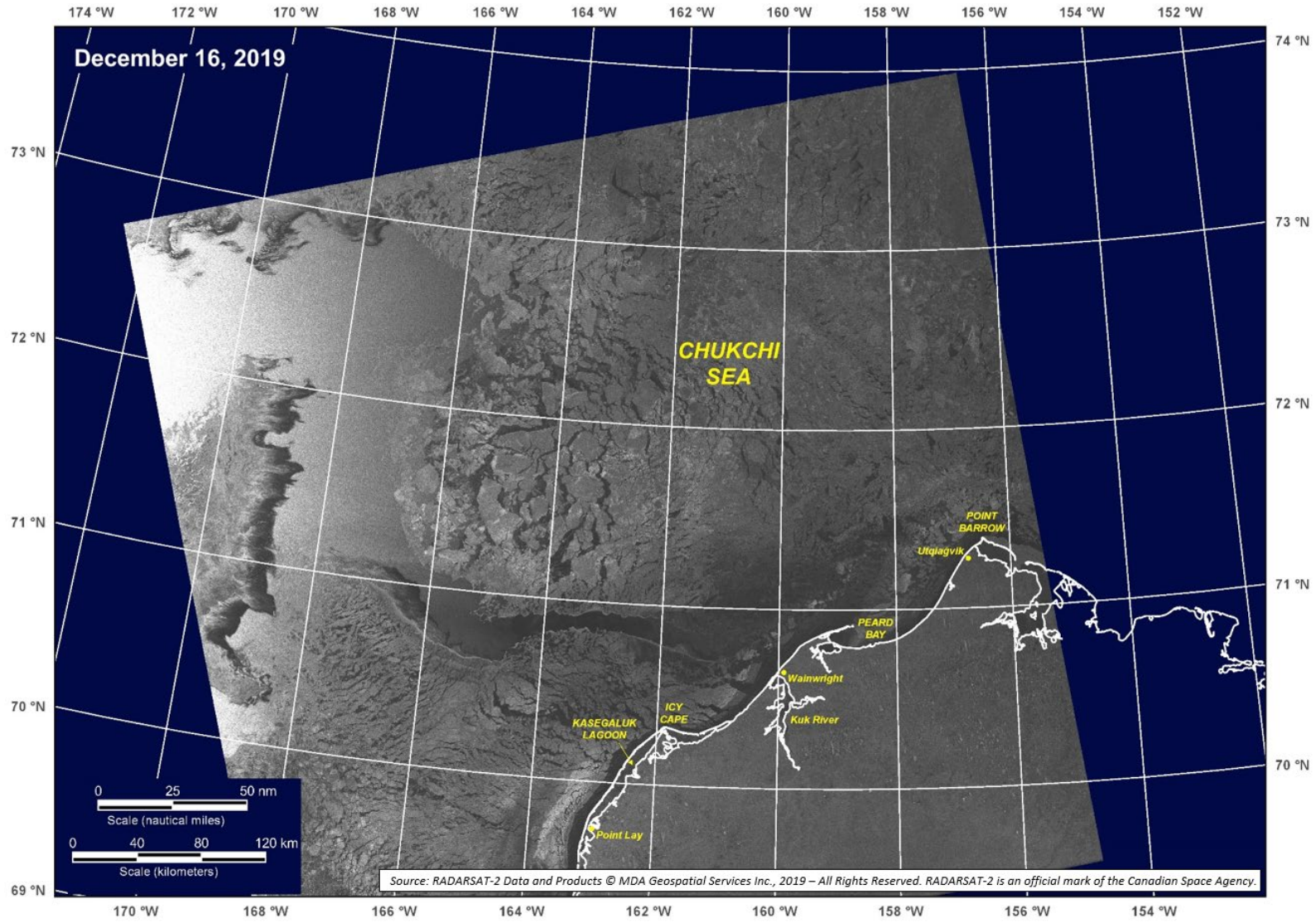

Figure 2. RADARSAT-2 Image of Chukchi Sea

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Remote Imaging Acquisition Progress Report No. 6

January 9, 2020

This report pertains to the sixth pair of RADARSAT-2 images obtained from MDA in support of the 2019-20 Freeze-Up Study of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas under Contract 140E0119C0011. Processed versions of the images, representing derivative products that may be transmitted to BSEE in accordance with MDA's End User License Agreement, are attached as Figures 1 and 2. A description and assessment of each image is provided below.

Image of Beaufort Sea

Date of Acquisition: January 4, 2020

Area of Observation: Alaskan Beaufort Sea extending from Camden Bay to west of Point Barrow, and north of the 74°N parallel.

Principal Objective: Document the extent of landfast ice and the condition of the ice canopy.

Findings: The landfast ice zone remained static during the second half of December, with no significant expansion. When the RADARSAT-2 image was obtained on January 4th, the pack ice was highly consolidated except in the vicinity of Point Barrow, where patches of open water were present. As in the case of previous RADARSAT-2 images, multi-year floes of varying size were present in the pack ice.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the ice canopy until the next RADARSAT-2 image acquisition covering the Beaufort Sea, which is scheduled for January 18, 2020.

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Image of Chukchi Sea

Date of Acquisition: January 2, 2020

Area of Observation: Alaskan Chukchi Sea extending from Point Barrow to west of the 172°W meridian, and from south of Point Lay to north of the 73°30'N parallel.

Principal Objective: Document the progress of freeze-up, including the growth of the pack ice and the state of the landfast ice zone.

Findings: The landfast ice zone expanded dramatically during the second half of December. When the RADARSAT-2 image was obtained on January 2nd, a continuous strip of landfast ice extended from Point Barrow to south of Point Lay. Pack ice covered the region seaward of the landfast ice zone, with small polynyas present to the west of Peard Bay and scattered small leads located farther offshore.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the expanding ice canopy until the next RADARSAT-2 image acquisition covering the Chukchi Sea, which is scheduled for January 16, 2020..

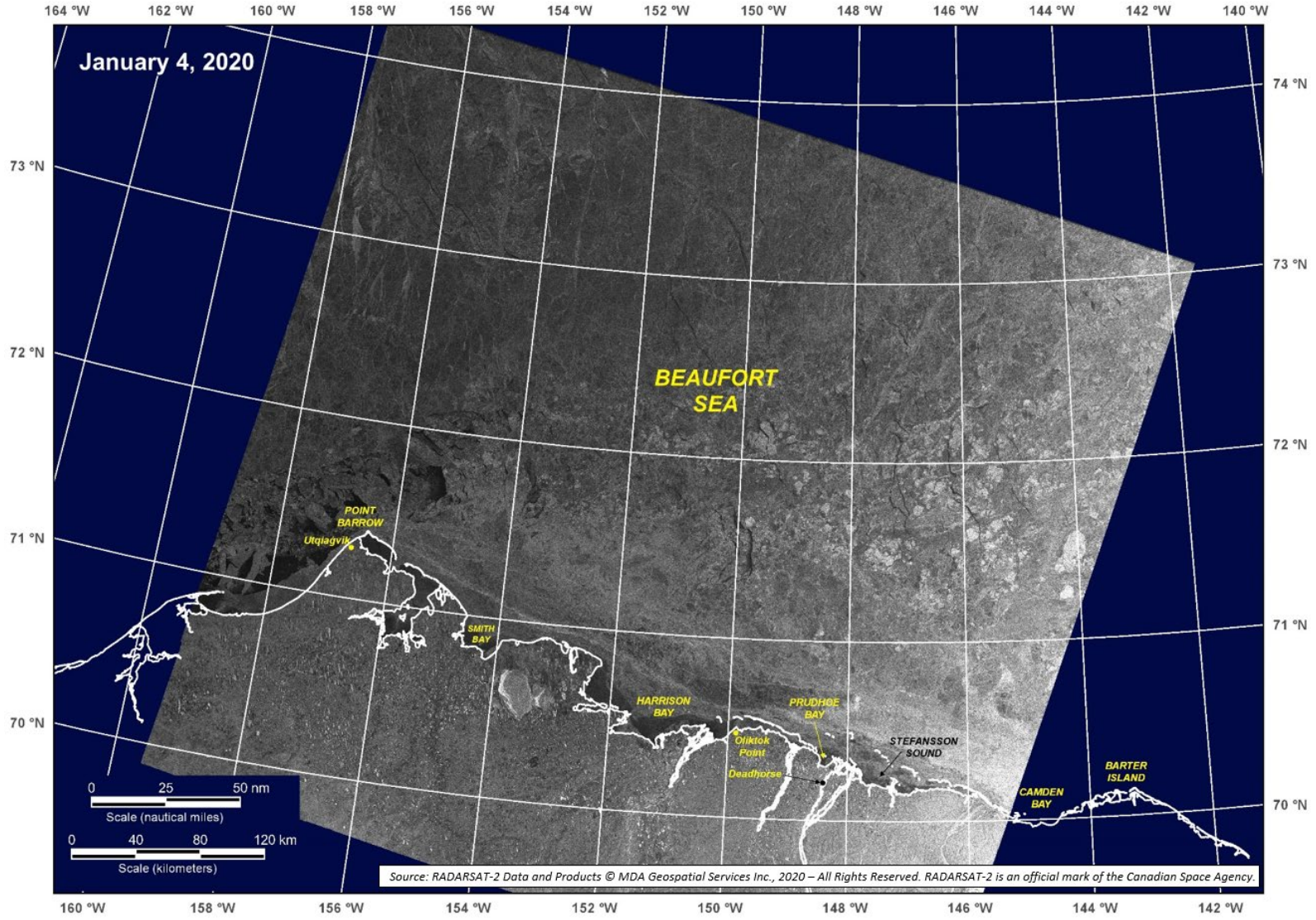

Figure 1. RADARSAT-2 Image of Beaufort Sea

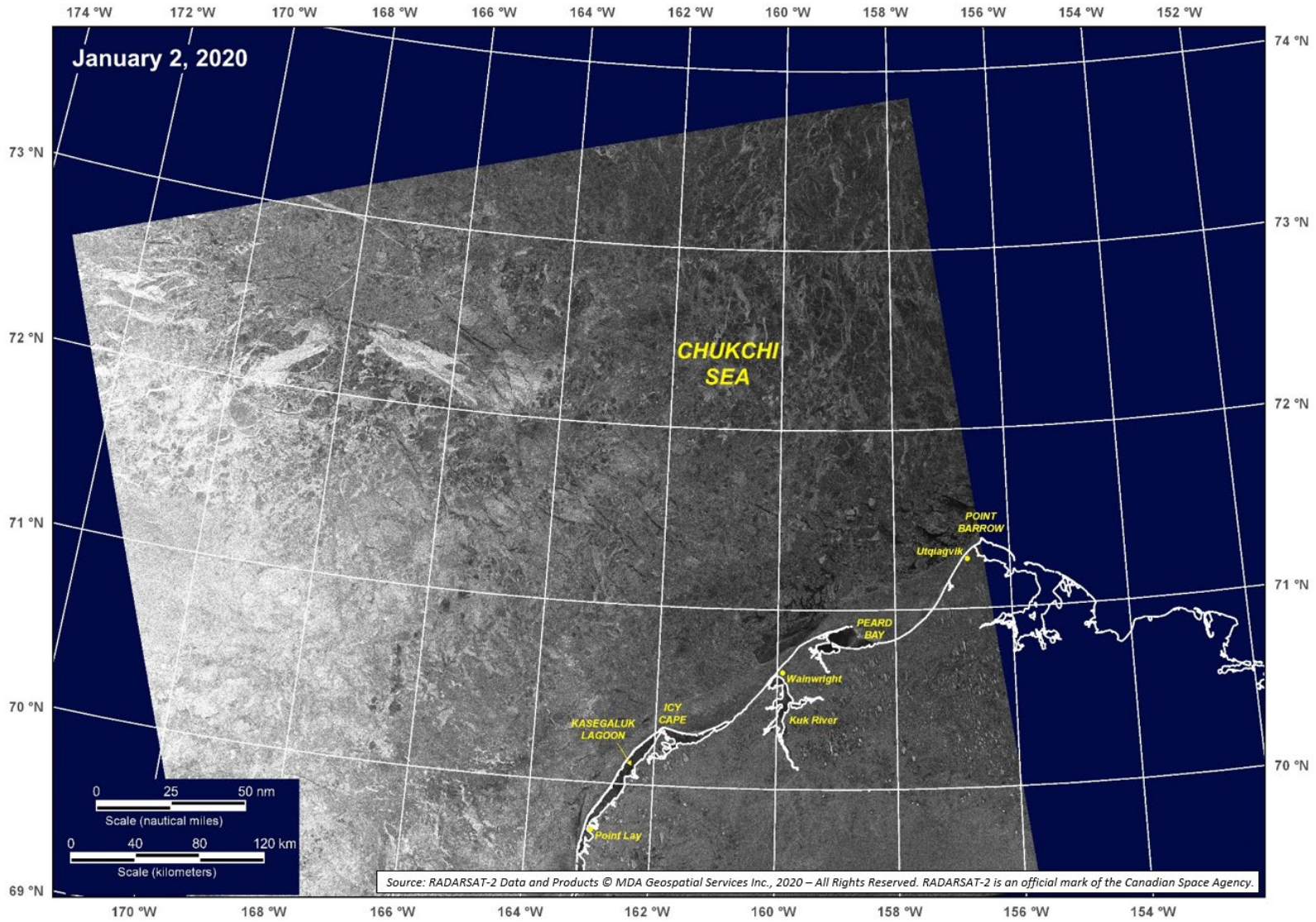

Figure 2. RADARSAT-2 Image of Chukchi Sea

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Remote Imaging Acquisition Progress Report No. 7

January 22, 2020

This report pertains to the seventh pair of RADARSAT-2 images obtained from MDA in support of the 2019-20 Freeze-Up Study of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas under Contract 140E0119C0011. Processed versions of the images, representing derivative products that may be transmitted to BSEE in accordance with MDA's End User License Agreement, are attached as Figures 1 and 2. A description and assessment of each image is provided below.

Image of Beaufort Sea

Date of Acquisition: January 18, 2020

Area of Observation: Alaskan Beaufort Sea extending from Barter Island to Point Barrow, and north of the 74°N parallel.

Principal Objective: Document the extent of landfast ice, the condition of the pack ice, and the absence or presence of multi-year ice.

Findings: During the first half of January, the landfast ice edge retreated to the coast between Point Barrow and Smith Bay, advanced seaward between Smith Bay and Prudhoe Bay, and remained essentially static to the east of Prudhoe Bay. Of particular note was the apparent grounding of the landfast ice on Weller Bank, one of its two customary anchor points to the north of Harrison Bay. At the time of image acquisition, a prominent flaw lead (a linear expanse of open water adjacent to the landfast ice edge) was present where the landfast ice edge had retreated between Barrow and Smith Bay. Multi-year ice floes of varying size were present in the pack ice, with the greatest concentration located off Barter Island.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the ice canopy until the next RADARSAT-2 image acquisition covering the Beaufort Sea, which is scheduled for February 4, 2020.

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Image of Chukchi Sea

Date of Acquisition: January 16, 2020

Area of Observation: Alaskan Chukchi Sea extending from east of Point Barrow to west of the 171°W meridian, and from south of Point Lay to north of the 74°N parallel.

Principal Objective: Document the extent of landfast ice, the condition of the pack ice, and the absence or presence of multi-year ice.

Findings: In sharp contrast to the second half of December, when the landfast ice zone expanded dramatically, virtually all such ice was removed from the region seaward of the protected coastal lagoons during the first half of February. Although pack ice covered the entire offshore region, it contained numerous leads. Scattered floes that appeared to consist of multi-year ice were present to the northwest of Point Barrow.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the ice canopy until the next RADARSAT-2 image acquisition covering the Chukchi Sea, which is scheduled for February 2, 2020.

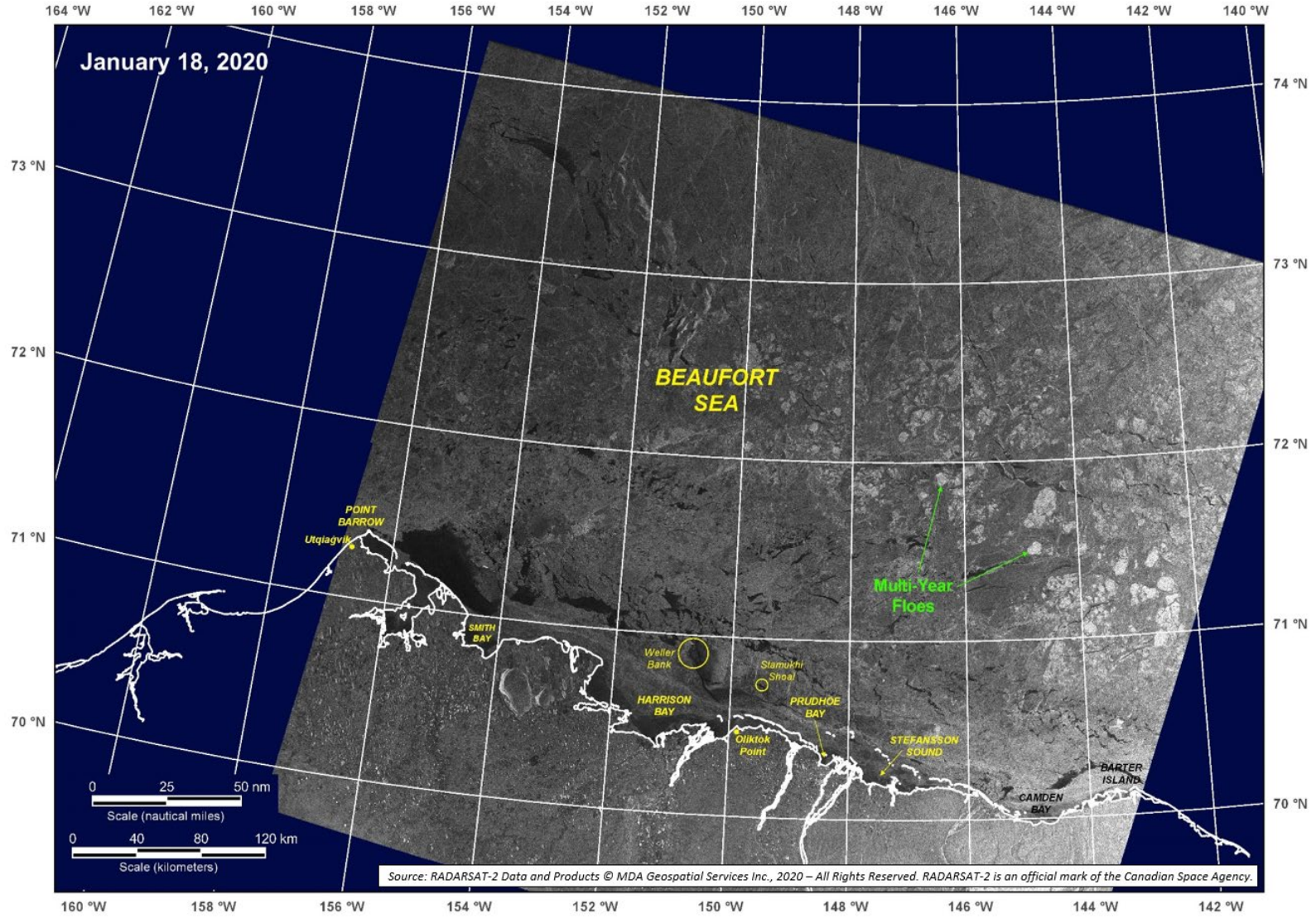

Figure 1. RADARSAT-2 Image of Beaufort Sea

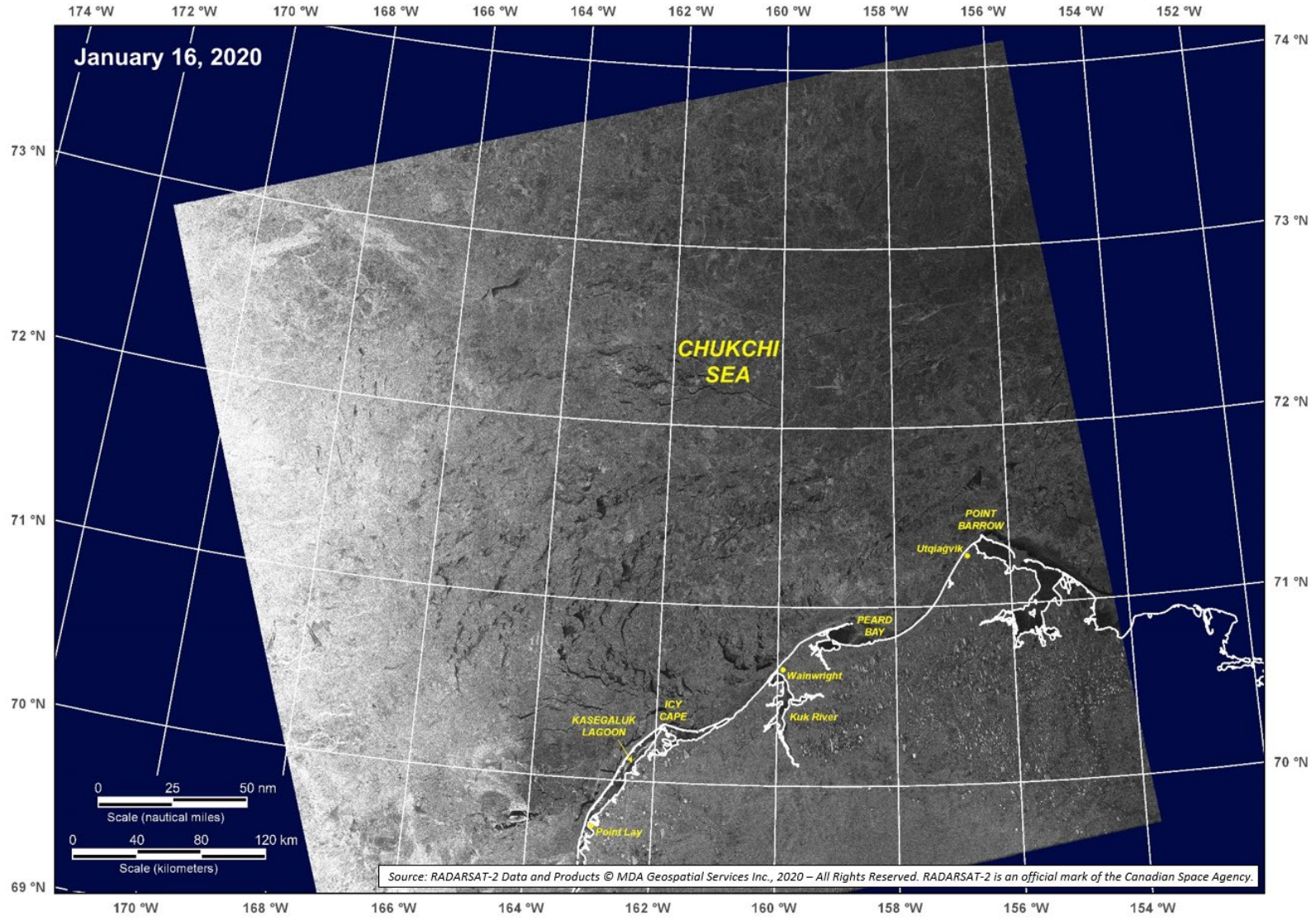

Figure 2. RADARSAT-2 Image of Chukchi Sea

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Remote Imaging Acquisition Progress Report No. 8

February 14, 2020

This report describes the eigth pair of RADARSAT-2 images obtained from MDA in support of the 2019-20 Freeze-Up Study of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas under Contract 140E0119C0011. Processed versions of the images, representing derivative products that may be transmitted to BSEE in accordance with MDA's End User License Agreement, are attached as Figures 1 and 2. A description and assessment of each image is provided below.

Image of Beaufort Sea

Date of Acquisition: February 4, 2020

Area of Observation: Alaskan Beaufort Sea extending from eastern Camden Bay to west of Point Barrow, and north of the 74°N parallel.

Principal Objective: Document the extent of landfast ice, the condition of the pack ice, and the absence or presence of multi-year ice.

Findings: The landfast ice edge experienced only minor changes between mid-January and early February. Of particular interest was the absence of grounding on Stamukhi Shoal, which typically serves as an anchor point for landfast ice. The pack ice was relatively compact, the sole exception consisting of a narrow, refreezing lead located between 10 and 35 nautical miles offshore between Point Barrow and Harrison Bay. Multi-year ice was present in the pack ice, with the highest concentrations and largest floe sizes located in the eastern portion of the study area.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the ice canopy until the next RADARSAT-2 image acquisition covering the Beaufort Sea, which is scheduled for February 21, 2020.

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Image of Chukchi Sea

Date of Acquisition: February 2, 2020

Area of Observation: Alaskan Chukchi Sea extending from east of Point Barrow to west of the 172°W meridian, and from south of Point Lay to the 74°N parallel.

Principal Objective: Document the extent of landfast ice, the condition of the pack ice, and the absence or presence of multi-year ice.

Findings: The landfast ice rebounded from its retreat in early January, attaining a maximum width of 10 nautical miles to the east of Icy Cape when the image was acquired on February 2. The pack ice was unusually compact for the Chukchi, with no major leads or polynyas (linear and areal openings in the icy canopy, respectively). As in the case of the image obtained on January 16, multi-year ice floes were present to the northwest of Point Barrow.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images will be used to provide supplemental information on the ice canopy until the next RADARSAT-2 image acquisition covering the Chukchi Sea, which is scheduled for February 19, 2020.

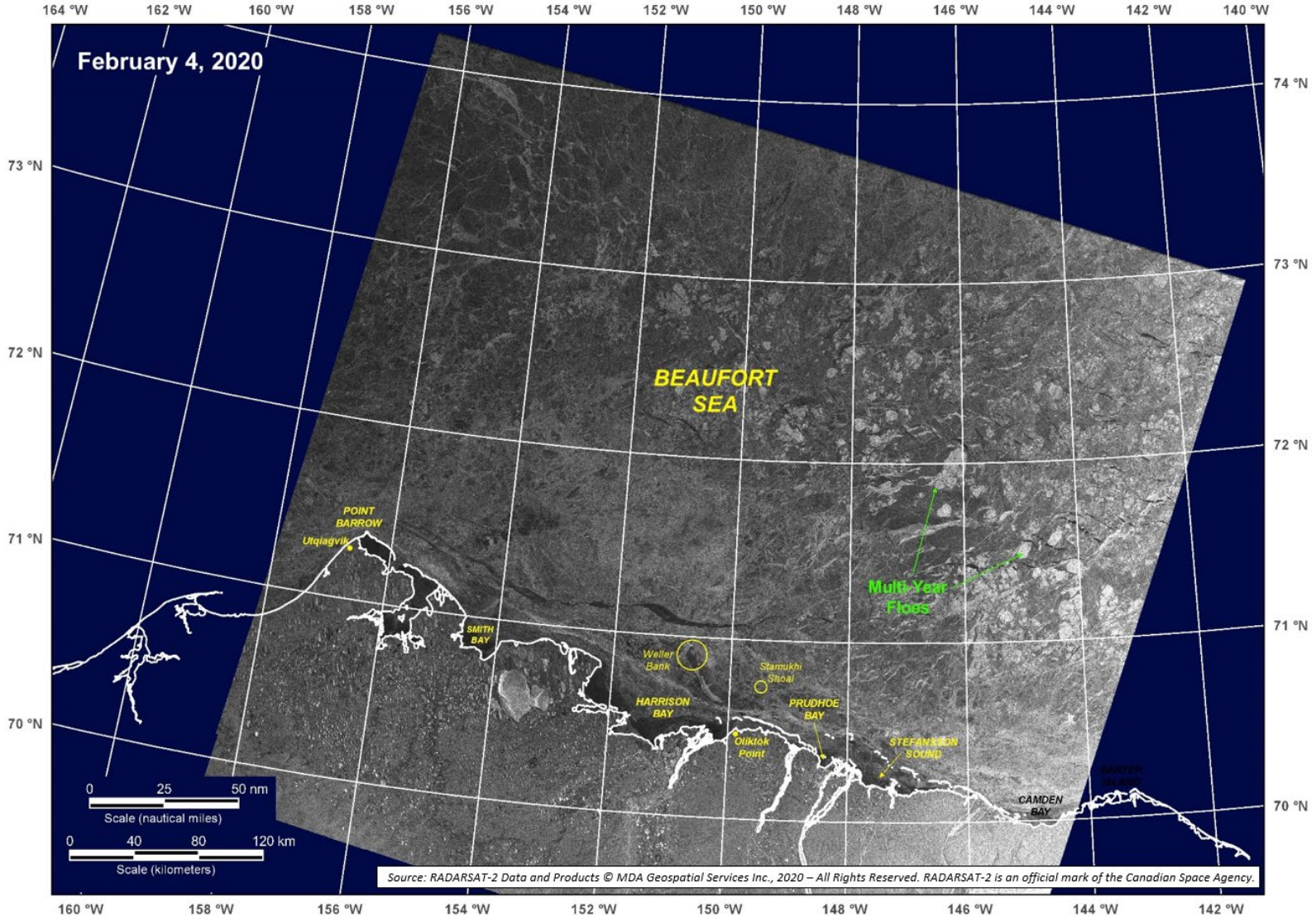

Figure 1. RADARSAT-2 Image of Beaufort Sea

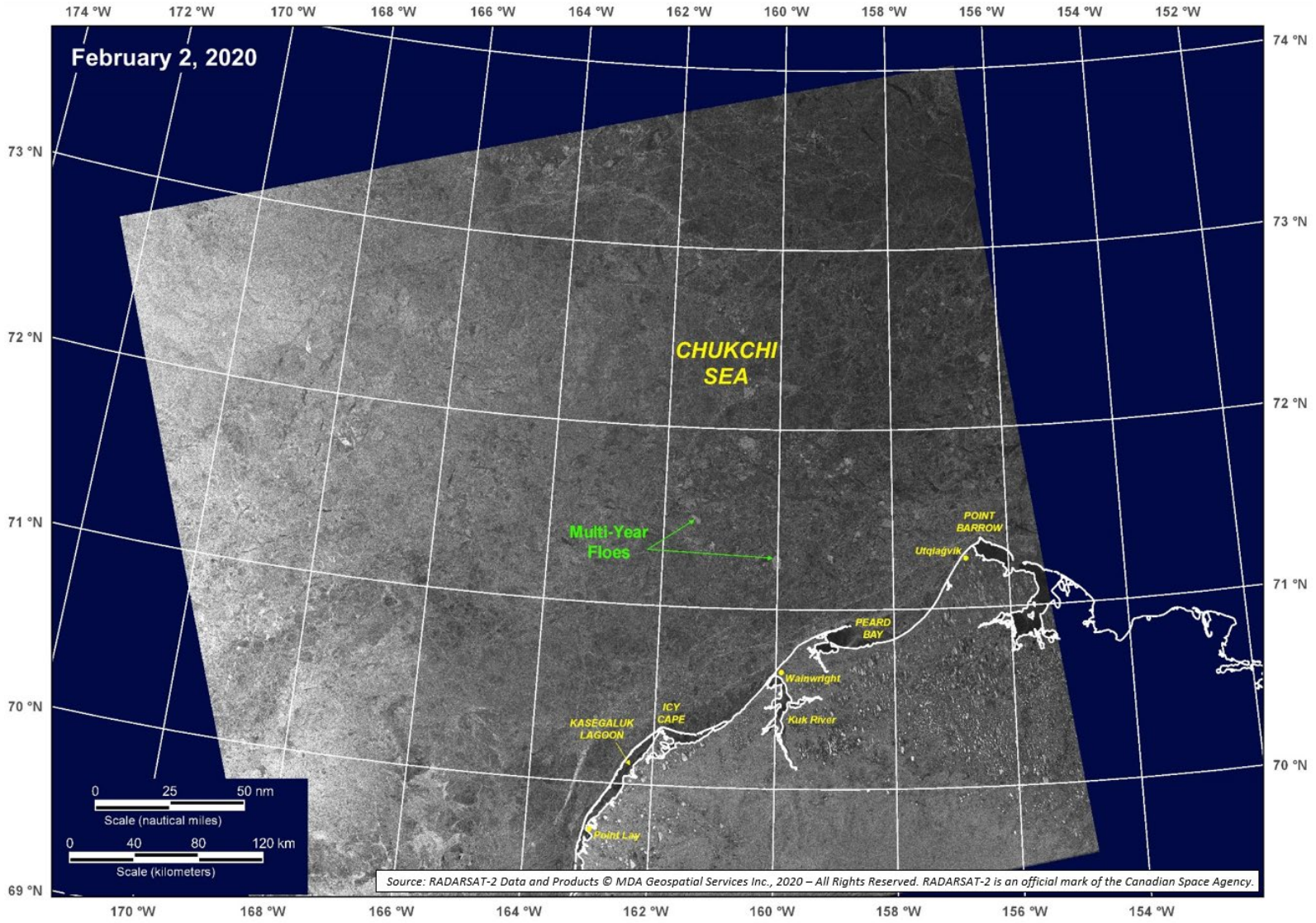

Figure 2. RADARSAT-2 Image of Chukchi Sea

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Remote Imaging Acquisition Progress Report No. 9

March 4, 2020

This report describes the ninth pair of RADARSAT-2 images obtained from MDA in support of the 2019-20 Freeze-Up Study of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas under Contract 140E0119C0011. Processed versions of the images, representing derivative products that may be transmitted to BSEE in accordance with MDA's End User License Agreement, are attached as Figures 1 and 2. A description and assessment of each image is provided below.

Image of Beaufort Sea

Date of Acquisition: February 21, 2020

Area of Observation: Alaskan Beaufort Sea extending from central Camden Bay to west of Point Barrow, and north of the 74°N parallel.

Principal Objective: Document the extent of landfast ice, the condition of the pack ice, and the absence or presence of multi-year ice.

Findings: The landfast ice edge moved seaward during the first half of February. The pack ice remained compact, with no significant leads or polynyas (linear and areal expanses of open water, respectively). Multi-year ice floes were present in the pack ice, with the highest concentrations and largest floe sizes located in the eastern portion of the study area (as noted in the prior two RADARSAT images).

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images along with two reconnaissance flights will be used to provide supplemental information on the ice canopy until the next RADARSAT-2 image acquisition covering the Beaufort Sea, which is scheduled for February 28, 2020.

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Image of Chukchi Sea

Date of Acquisition: February 19, 2020

Area of Observation: Alaskan Chukchi Sea extending from Point Barrow to west of the 172°W meridian, and from south of Point Lay to north of the 73°30'N parallel.

Principal Objective: Document the extent of landfast ice, the condition of the pack ice, and the absence or presence of multi-year ice.

Findings: The landfast ice zone expanded during the first half of February. Small leads and polynyas were scattered along its seaward edge when the image was acquired on February 19th. Farther offshore, the pack ice was relatively compact. As in the case of the RADARSAT images obtained on January 16th and February 2nd, multi-year ice floes were present to the northwest of Point Barrow. The highest concentrations and largest floe sizes were located north of the 71°N parallel and east of the 163°W meridian.

Assessment: The image is of good quality and suitable for its intended purpose. Publicly available ice charts and satellite images along with two reconnaissance flights will be used to provide supplemental information on the ice canopy until the next RADARSAT-2 image acquisition covering the Chukchi Sea, which is scheduled for February 26, 2020.

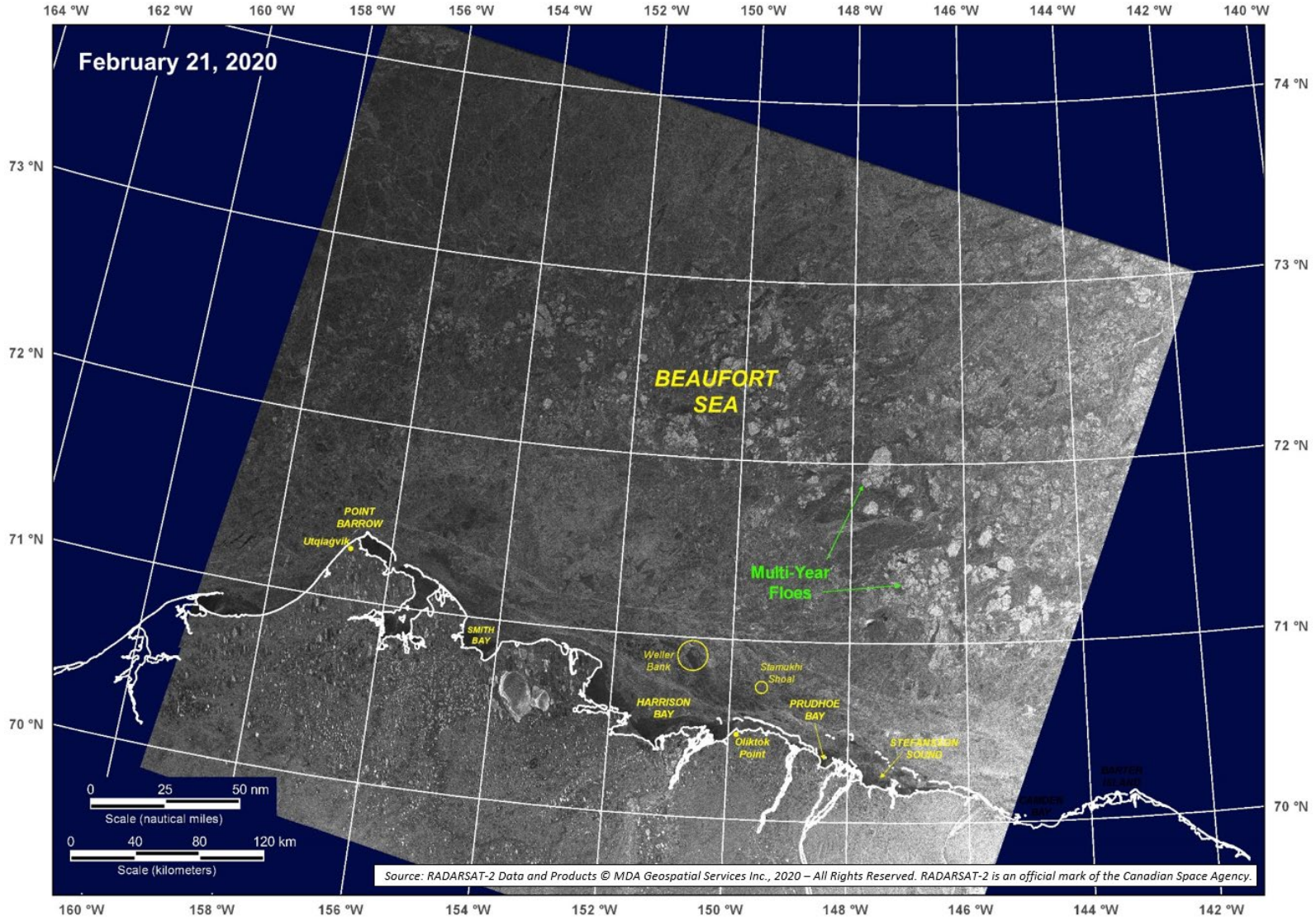

Figure 1. RADARSAT-2 Image of Beaufort Sea

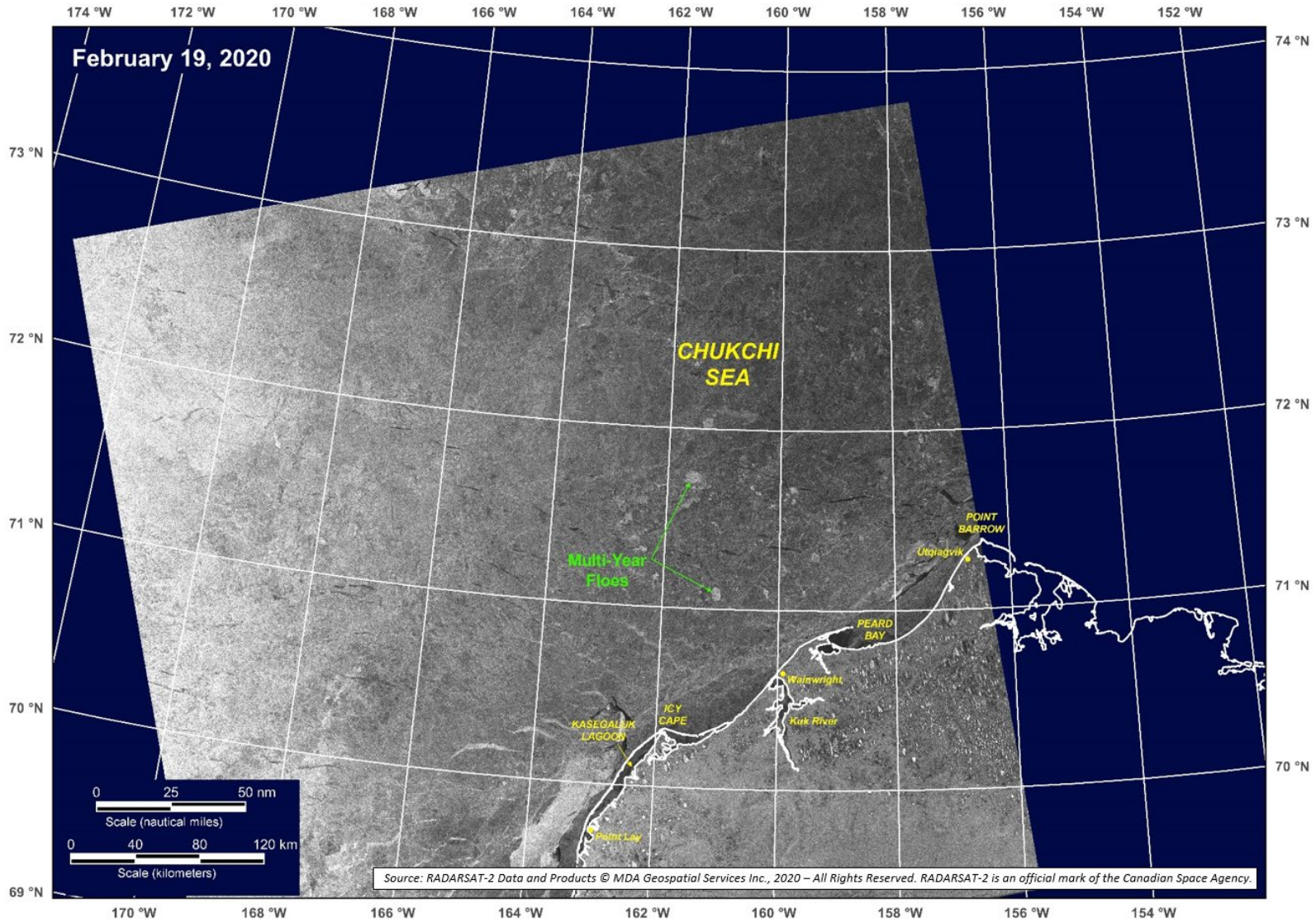

Figure 2. RADARSAT-2 Image of Chukchi Sea

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Remote Imaging Acquisition Progress Report No. 10

March 13, 2020

This report describes the tenth pair of RADARSAT-2 images obtained from MDA in support of the 2019-20 Freeze-Up Study of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas under Contract 140E0119C0011. Processed versions of the images, representing derivative products that may be transmitted to BSEE in accordance with MDA's End User License Agreement, are attached as Figures 1 and 2. A description and assessment of each image is provided below.

Image of Beaufort Sea

Date of Acquisition: February 28, 2020

Area of Observation: Alaskan Beaufort Sea extending from eastern Camden Bay to west of Point Barrow, and north of the 74°N parallel.

Principal Objective: Document the extent of landfast ice, the condition of the pack ice, and the absence or presence of multi-year ice.

Findings: During the one-week period that followed the acquisition of the prior RADARDAT-2 image on February 21st, the landfast ice zone contracted in response to westerly winds. Numerous leads trending southeast-northwest were present in the pack ice on February 28th. Most of these were small, but a flaw lead (a lead located at the seaward edge of the landfast ice) that typically ranged from 1 to 2 nm wide extended 65 nautical miles (nm) from Point Barrow to east of Smith Bay. Multi-year ice was present in the pack ice, with the highest concentrations and largest floe sizes located in the eastern portion of the study area (as was the case on February 21st).

Assessment: The image, which represents the final RADARSAT-2 image of the Beaufort Sea acquired in support of the 2019-20 freeze-up study, is of good quality and suitable for its intended purpose.

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Image of Chukchi Sea

Date of Acquisition: February 26, 2020

Area of Observation: Alaskan Chukchi Sea extending from Point Barrow to west of the 172°W meridian, and from south of Point Lay to the vicinity of the 74°N parallel.

Principal Objective: Document the extent of landfast ice, the condition of the pack ice, and the absence or presence of multi-year ice.

Findings: The landfast ice zone experienced minor changes between February 19th and 26th, a period dominated by light westerly winds. On February 26th, the pack ice was compact with only a small number of small, refreezing leads. As in the case of the RADARSAT-2 images obtained on January 16th, February 2nd, and February 19th, large multi-year ice floes with diameters exceeding 1 km were evident in the region to the north and west of Point Barrow. The floes had experienced only modest displacements since the previous image was acquired on February 19th.

Assessment: The image, which represents the final RADARSAT-2 image of the Chukchi Sea acquired in support of the 2019-20 freeze-up study, is of good quality and suitable for its intended purpose.

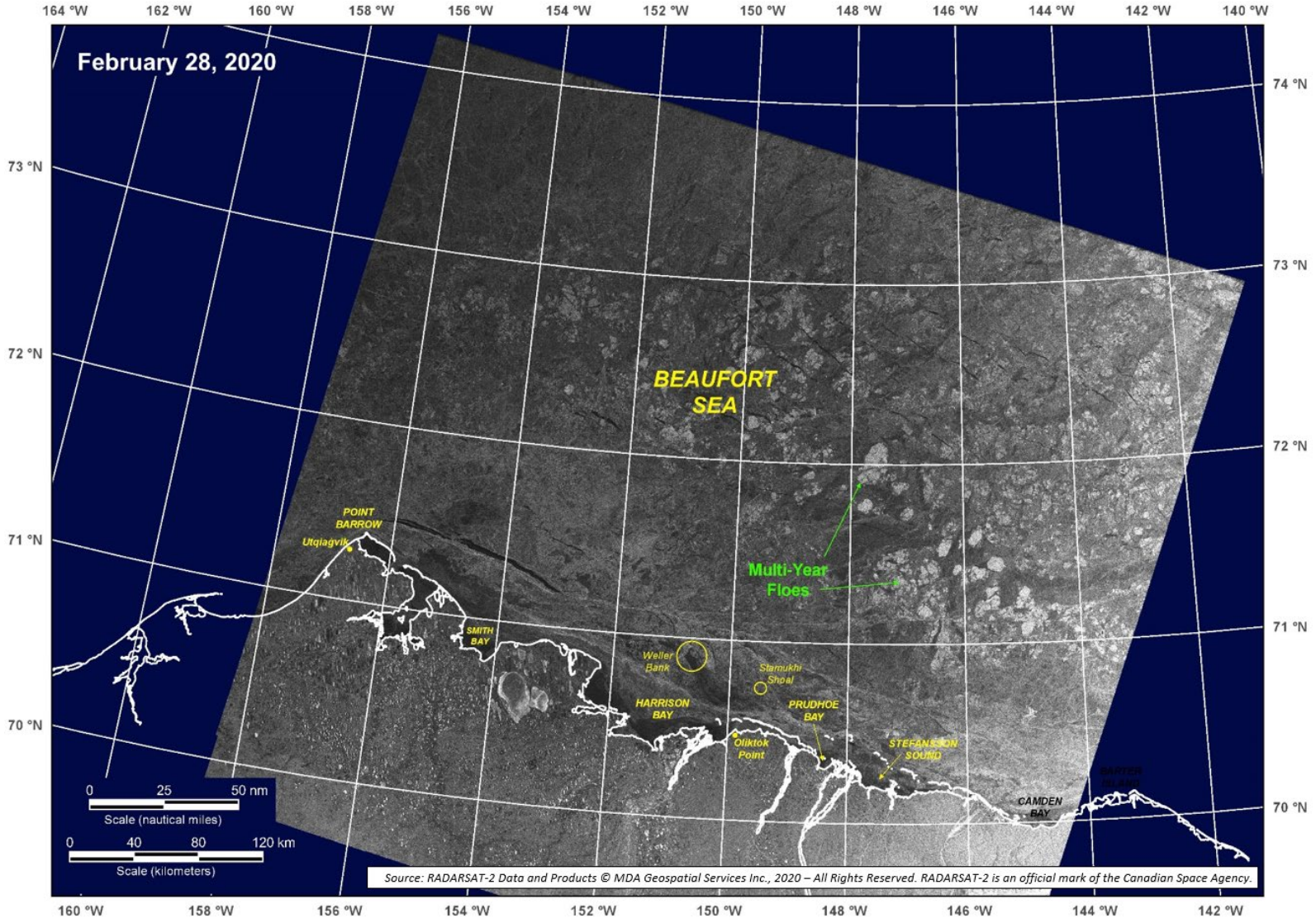

Figure 1. RADARSAT-2 Image of Beaufort Sea

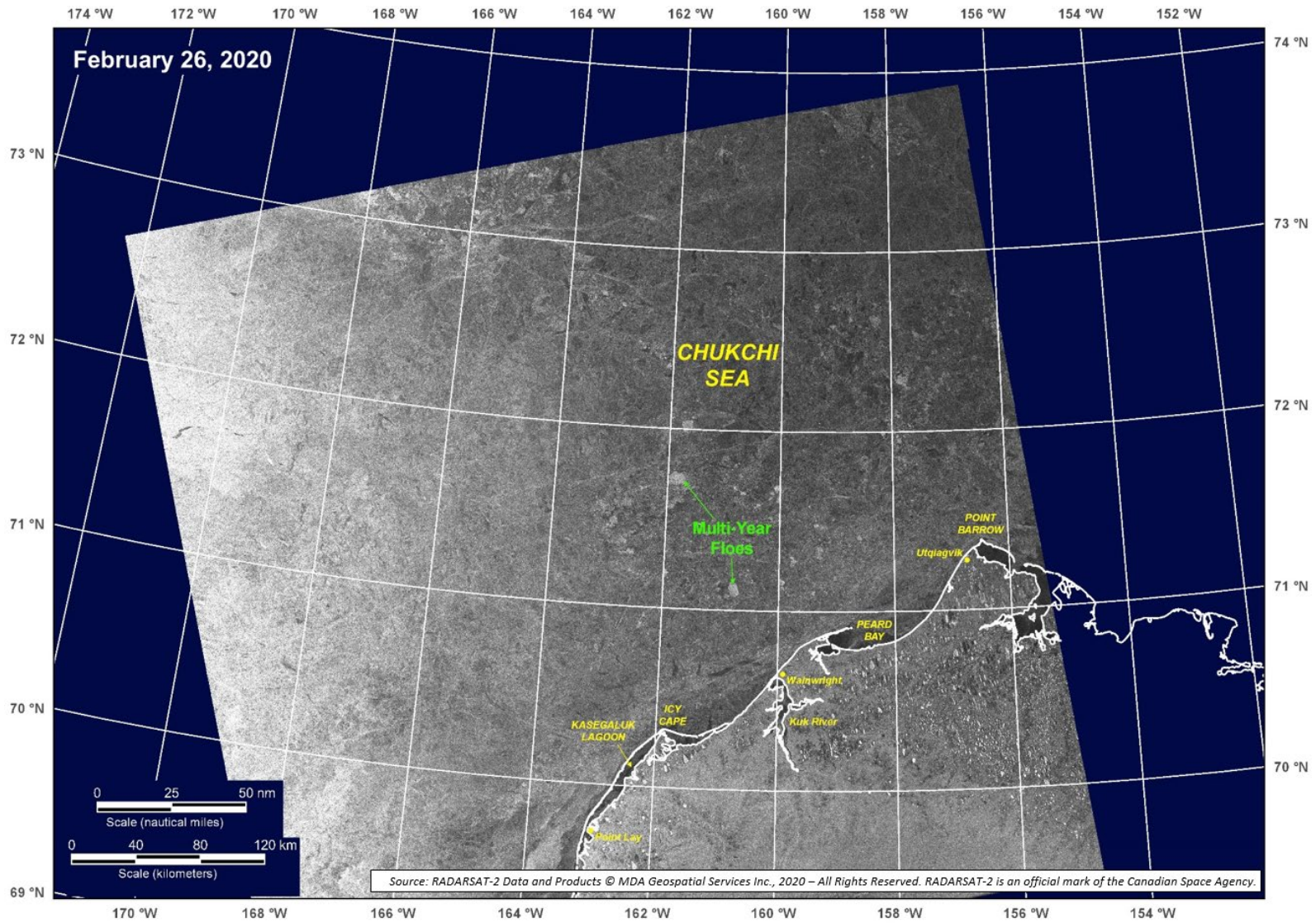

Figure 2. RADARSAT-2 Image of Chukchi Sea

APPENDIX C

POST-OBSERVATION FREEZE-UP PROGRESS REPORT

COASTAL FRONTIERS

2019-20 Freeze-Up and 2020 Break-Up Studies of Arctic Sea Ice in the Alaskan Beaufort and Chukchi Seas

Contract 140E0119C0011

Post-Observation Freeze-Up Progress Report

March 12, 2020

Objectives

Four aerial reconnaissance missions were conducted in late February 2020 to document the ice conditions that prevailed at the end of the 2019-20 Freeze-Up study period. The specific objectives of the flights were as follows:

1. Obtain ground truth information to confirm and expand upon the conclusions drawn from satellite imagery;
2. Investigate large-scale features identified in the satellite imagery, including multi-year ice floes, the landfast ice zone, and well-developed shear lines;
3. Detect, investigate, and document small-scale ice features that were beneath the resolution of the satellite imagery, including shoreline pile-ups, offshore ridges and rubble piles, and multi-year ice fragments.

Area of Observation

The first two flights took place in the Alaskan Beaufort Sea while the third and fourth took place in the Alaskan Chukchi Sea. Each was conducted using a twin-engine Aero Commander 690 with two pilots. The flight paths are shown in Figures 1 and 2, while details are provided below:

Central Beaufort Sea (February 22; Figure 1): The flight covering the Central Beaufort Sea originated at Deadhorse Airport under low-light conditions produced by complete cloud cover. The aircraft proceeded in an easterly direction along the barrier island chain and across Camden Bay to Barter Island, and then turned back toward the west at distances that typically ranged from 5 to 25 nautical miles (nm) off the barrier islands. When the aircraft approached Northstar Production Island, the visibility was severely reduced by falling snow. As a result, the mission was terminated at this location and the aircraft returned to Deadhorse.

Western Beaufort Sea (February 23; Figure 1): Cloud cover at the beginning of the flight over the Western Beaufort Sea gave way to clear skies and excellent visibility during the remainder. The flight originated at Deadhorse Airport and proceeded in a westerly direction along the barrier island chain and into the southern portion of Harrison Bay. It then turned north to Stamukhi Shoal and west to Weller Bank, the two customary anchor points for landfast ice in Harrison Bay.

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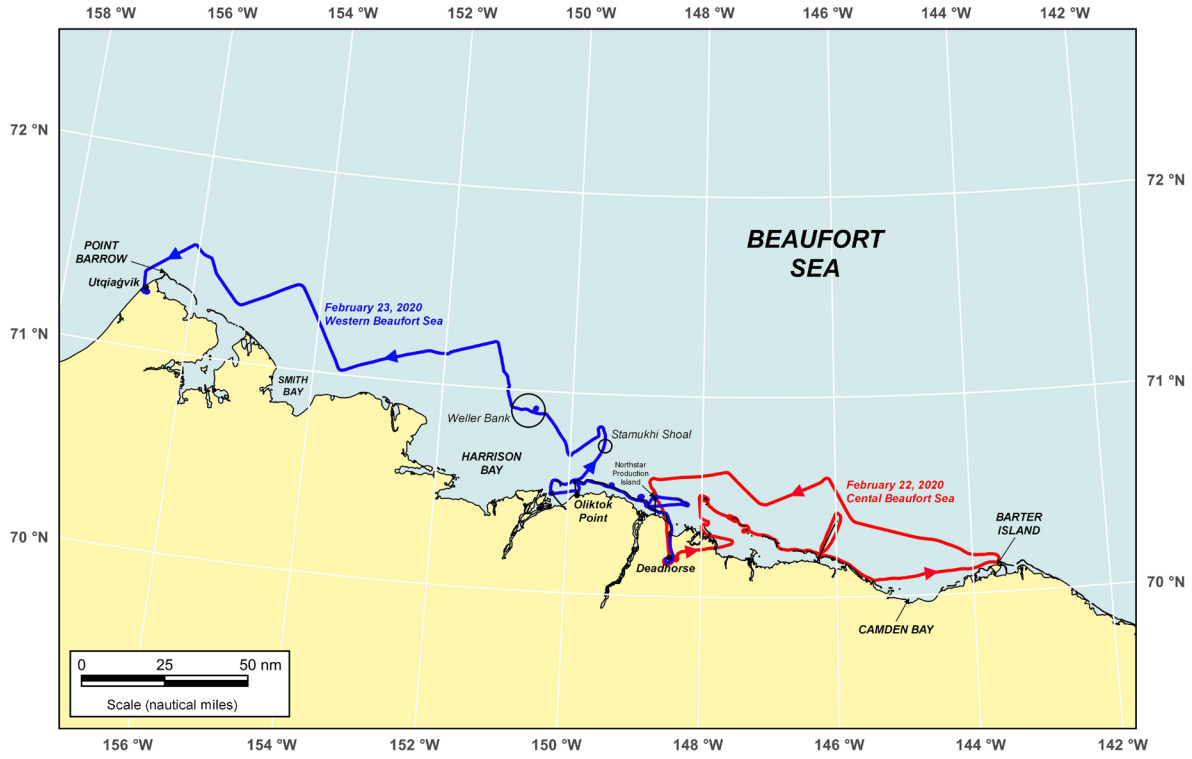

Figure 1. Flight Paths in Alaskan Beaufort Sea

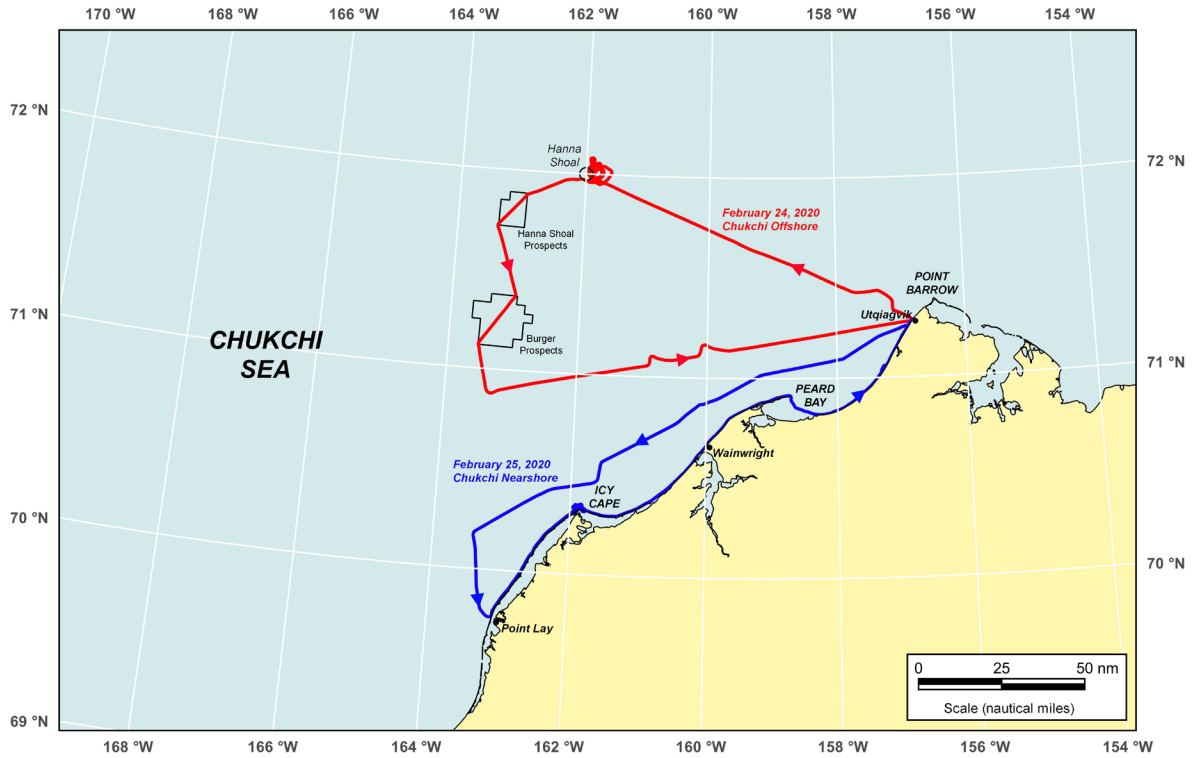

Figure 2. Flight Paths in Alaskan Chukchi Sea

The final portion of the flight consisted of six legs that zigzagged toward the west at distances of 5 to 30 nm offshore, followed by landing at Utqiagvik.

Offshore Chukchi Sea (February 24; Figure 2): The flight over the offshore portion of the Alaskan Chukchi Sea was conducted under clear skies that afforded excellent visibility. The flight path consisted of a counterclockwise loop that began and ended at Utqiagvik and included Hanna Shoal, the Hanna Shoal Prospects, and the Burger Prospects along with several small deviations to confirm the presence of large multi-year ice floes noted in the RADARSAT image of the Chukchi acquired on February 19th.

Nearshore Chukchi Sea (February 25; Figure 2): The flight over the nearshore portion of the Alaskan Chukchi Sea, like that over the offshore portion, was conducted under clear skies with excellent visibility. After departing from Utqiagvik, the aircraft headed southwest at distances of 5 to 15 nm off the coast. It turned back to the northwest at Point Lay, returning to Utqiagvik along the coastline to facilitate the observation of shoreline pile-ups.

Significant Findings in Beaufort Sea

Lagoon Ice: The ice in the semi-protected lagoons behind the barrier islands was primarily flat and undeformed (Plate 1). The primary relief consisted of widely-scattered ridges and rubble with heights to 1 m, and thermal cracks with associated ridge heights to 2 m. Thermal cracks tend to form when a rapid drop in air temperature is followed by a rapid rise. The drop causes contraction and cracking of the ice sheet, while the ensuing rise causes compression and extrusion of the refreezing slush in the crack, creating a ridge. The 2-m ridge associated with the thermal crack shown in Plate 1 was the highest such feature observed since the current series of freeze-up studies began in 2009-10.

Landfast Ice: The landfast ice zone in the Beaufort Sea was found to be narrow and poorly-developed at the time of the flight. Although the ice appeared to be grounded on Weller Bank (Plate 2), which constitutes one of its two customary anchor points, an open lead discovered to the southwest of Stamukhi Shoal (Plate 3) indicated that it was not firmly grounded on this second customary anchor point. The modest size of the landfast ice zone is consistent with the relatively low frequencies of easterly winds and easterly storms that occurred during the 2019-20 freeze-up season. As discussed in prior freeze-up reports, easterly winds tend to promote the formation of landfast ice whereas westerlies tend to have the opposite effect.

Pile-Ups: Thirty-two ice pile-ups were observed in the Central Beaufort Sea, consisting of six on man-made facilities and 26 on natural barrier islands and shoals. Representative examples are provided in Plate 4, which shows a 4-m high pile-up that encroached 10 m onto the north side of Northstar Production Island and a 5-m pile-up that did not encroach on the south side. The pile-up heights, which ranged from 1 to 7 m above sea level, the encroachment distances, which ranged from negligible to 20 m onto the subaerial beach, and the encroachment lengths, which ranged from 50 to 2,000 m alongshore, were unexceptional by historical standards.

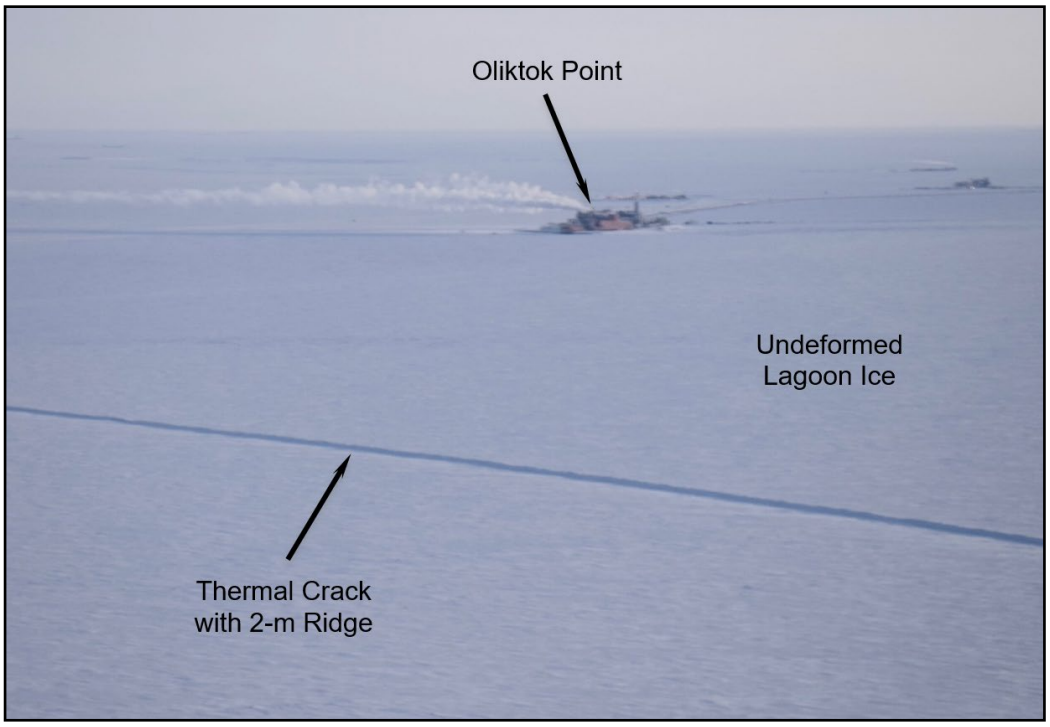

Plate 1. Undeformed Lagoon Ice off Oliktok Point Containing Thermal Crack with 2-m Ridge (February 23, 2020)

Plate 2. Grounded Rubble with Heights to 7 m on Eastern Side of Weller Bank (February 23, 2017)

Plate 3. Open Lead Located 6 nm Southwest of Stamukhi Shoal (February 23, 2020)

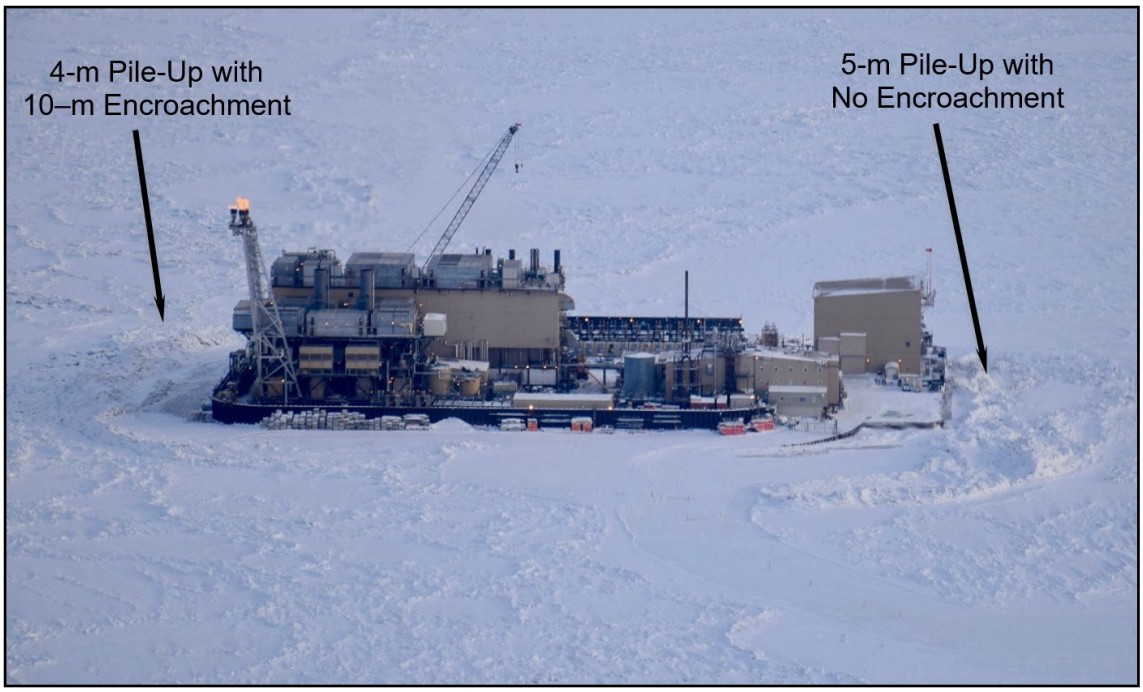

Plate 4. Two Ice Pile-Ups on Northstar Production Island (February 23, 2020)

Multi-Year Ice: Multi-year ice (MYI), defined for the present purpose as ice that has survived at least one melt season, was difficult to identify due to snow cover that often obscured its characteristic gray, leathery surface. Nevertheless, fragments and small floes of MYI were observed sporadically in the region between Camden and Harrison Bays. The highest concentrations, which peaked at 90% in localized areas, were found in the southern portion of Camden Bay (Plate 5), while the largest floes, with horizontal dimensions peaking at 300 m, were found outside the barrier islands to the west of Prudhoe Bay (Plate 6). The last occasion on which MYI floes were observed the nearshore region of the Alaskan Beaufort Sea was ten years ago, in 2009-2010.

Significant Findings in Chukchi Sea

Lagoon Ice: Although most of the ice in the protected waters of Kasegaluk Lagoon, the Kuk River Entrance, and Peard Bay was flat and undeformed (Plate 7), patches of 0.5-m rubble were evident in Kasegaluk Lagoon and Peard Bay (Plate 8).

Landfast Ice: During the month that preceded the reconnaissance flights, westerly winds predominated in the Chukchi Sea, pushing the pack ice against the coast. As a result, the landfast ice zone was robust by historical standards, with the width estimated to be 3 nm off Utqiagvik, 9 nm off Icy Cape (Plate 7), and 2 nm off Point Lay. The ice was anchored by grounded ridges and rubble piles with heights that typically ranged from 2 to 5 m and occasionally reached 7 m. At Blossom Shoals, however, anchoring was provided by a massive rubble pile that extended 25–m above the surrounding sea ice (Plates 7 and 9). (Blossom Shoals are located approximately 1 nm north-northwest of Icy Cape.)

Flaw Lead: The flaw lead that tends to develop at the seaward edge of the landfast ice in response to easterly winds was absent at the time of the reconnaissance flights, reflecting the occurrence of westerly winds prior to and during the flights.

Ice Pile-Ups: Fifty-seven ice pile-ups were observed on the coast between Point Lay and Utqiagvik, including forty-two in the southern half of this region. The dimensions were large by historical standards, with heights ranging from 1 ϕ 20 m, encroachment distances from negligible to 30 m, and alongshore lengths from 50 m to 7.9 km. The tallest pile-up, which was located on Icy Cape, is shown in Plates 7 and 10. The second largest encroachment, which extended 25 m onshore and overtopped Skull Cliff approximately halfway between Peard Bay and Utqiagvik, is shown in Plate 11.

Katie's Floeberg: Katie's Floeberg, which forms each winter when ice rubble accumulates on Hanna Shoal (Figure 2), had not developed at the time of the offshore reconnaissance flight on February 24th. Instead, an agglomeration of MYI floes with a combined diameter of 6.5 km appeared to have become grounded on the shoal (Plate 12). Ridges with heights to 5 m were present in the interior of the feature, along with rubble with an identical height of 5 m on its southwest side.

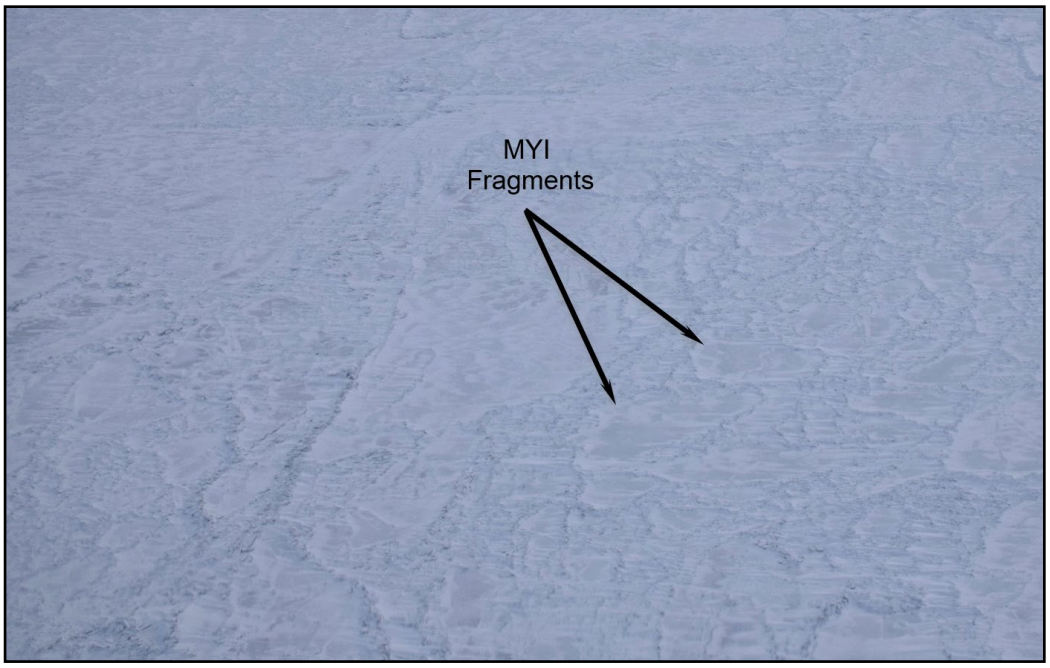

Plate 5. Dense Concentration of MYI Fragments in South Camden Bay (February 22, 2020)

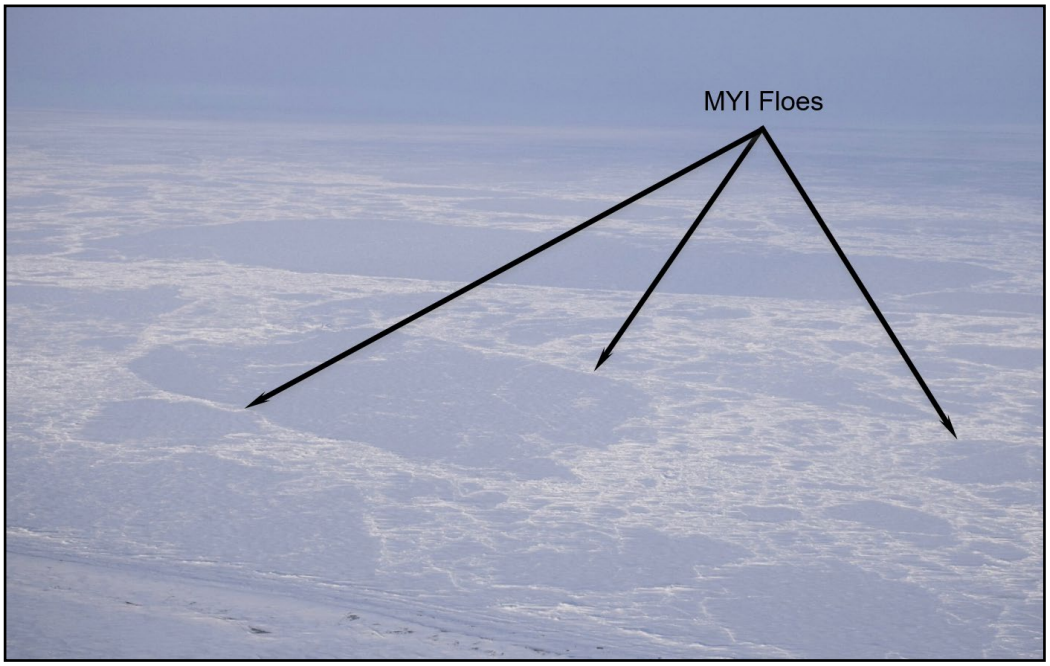

Plate 6. MYI Floes off Barrier Islands 10 nm West of Prudhoe Bay (Februry 23, 2020)

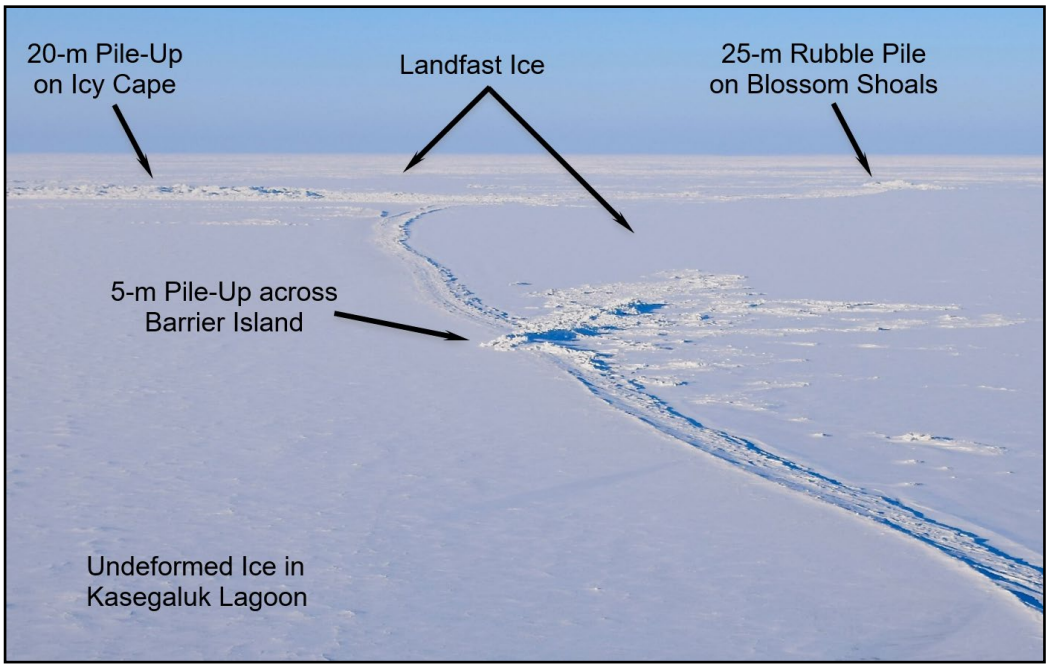

Plate 7. Landfast Ice off Icy Cape, Undeformed Ice in Kasegaluk Lagoon, and 5-m Pile-Up that Encroached 10 m onto Barrier Island 1 nm East of Icy Cape (February 25, 2020)

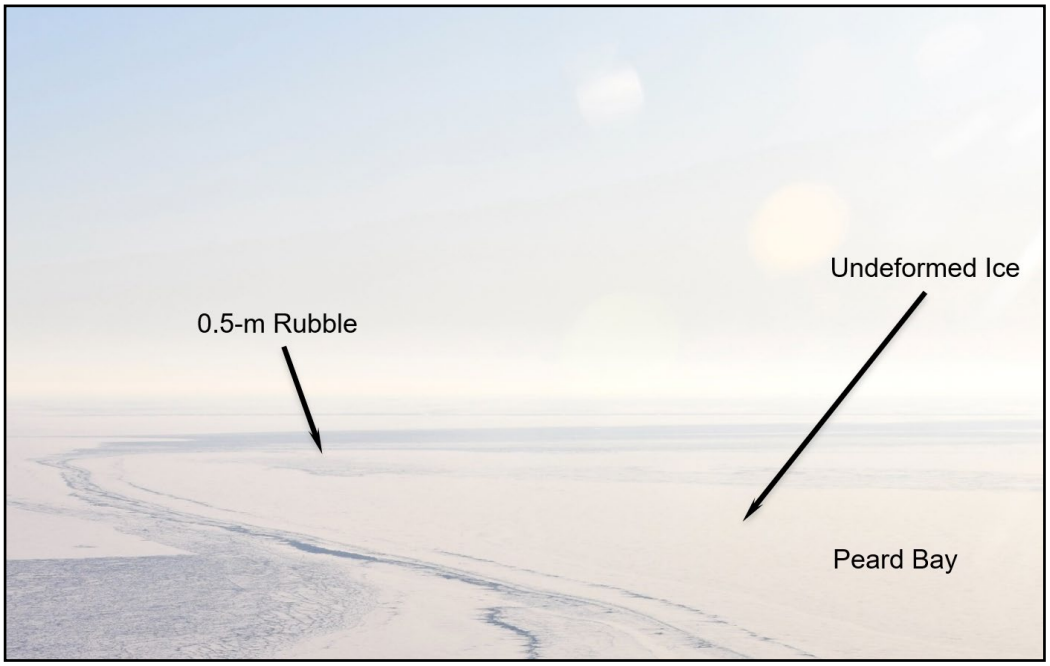

Plate 8. Undeformed Ice with Patch of 0.5-m Rubble in Peard Bay (February 25, 2020)

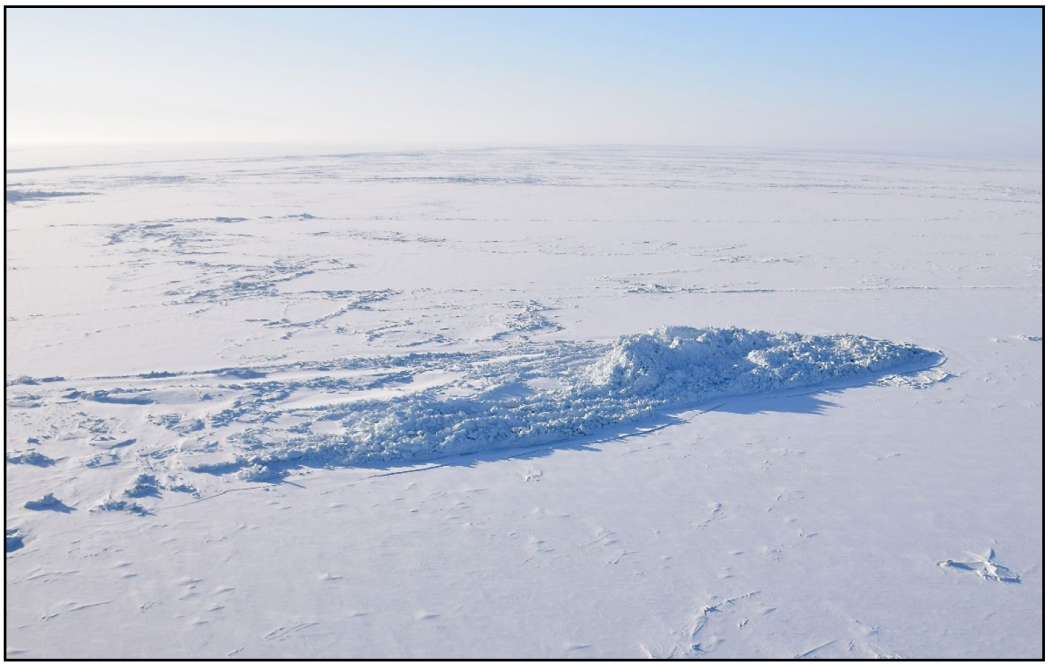

Plate 9. 25-m Rubble Pile on Blossom Shoals (February 25, 2020)

Plate 10. 20-m Pile-Up that Encroached 20 onto Icy Cape (February 25, 2020)

Plate 11. 15-m Pile-Up that Encroached 25 m Onshore and Overtopped Skull Cliff (February 25, 2020)

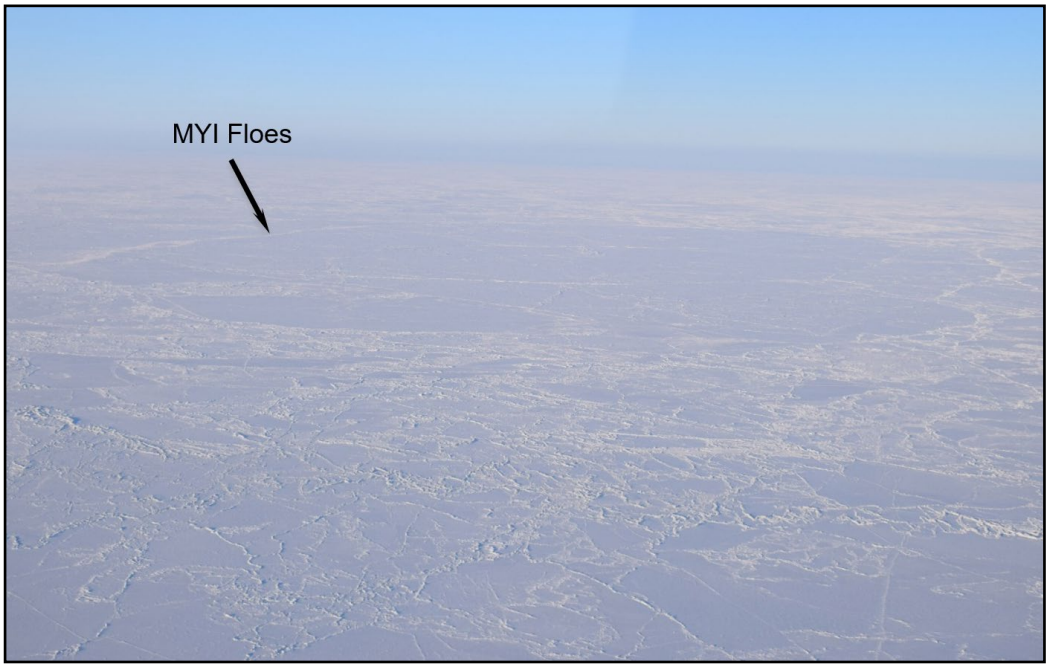

Plate 12. Agglomeration of MYI Floes Grounded on Hanna Shoal (February 24, 2020)

Multi-Year Ice: In addition to those grounded on Hanna Shoal, numerous MYI floes were observed in both the offshore and nearshore regions of the Chukchi. The concentrations ranged from negligible to 30% on the offshore flight path, and from negligible to 20% on the nearshore flight path. The largest floes were located to the north and west of Utqiagvik, including one with a maximum horizontal dimension approaching 9 km. Relatively small MYI floes, with diameters less than 100 m, were observed in the landfast ice zone. Plate 13 displays a MYI floe with an estimated diameter of 250 m and ridge height of 5 m that was observed 14 nm northwest of Utqiagvik.

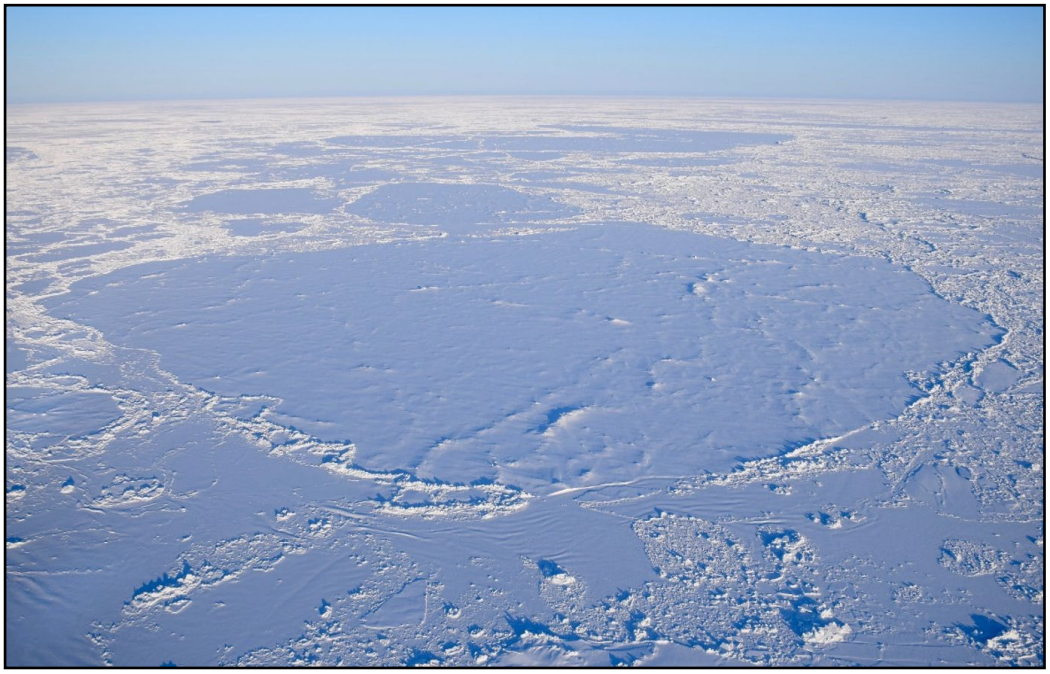

Plate 13. MYI Floe with Diameter of 250 m and Ridge Height of 5 m Located 14 nm Northwest of Utqiagvik (February 24, 2020)

Summary and Conclusions

The four aerial reconnaissance missions accomplished the objectives identified at the beginning of this report. No significant problems were encountered, and no data gaps have been identified.

The data acquired during the flights will be analyzed in greater detail in the months ahead, providing a valuable complement to the data acquired by remote sensing. Due to the limited nature of the analysis conducted to date, the findings presented in this report should be regarded as preliminary and subject to refinement.

APPENDIX D

TECHNICAL SUMMARY

2019-20 FREEZE-UP STUDY OF ARCTIC SEA ICE IN THE ALASKAN BEAUFORT AND CHUKCHI SEAS

TECHNICAL SUMMARY

Overview

This study characterizes the processes that occur during freeze-up in the Alaskan Beaufort and Chukchi Seas. It is based on annual research programs conducted from 2009-10 through 2016-17 as well as in 2019-20. Particular emphasis is to be placed on comparing and contrasting the freeze-up processes that occur today with those that prevailed in past decades.

Application

The information developed in this study is suitable for immediate application to the planning, design, construction, and operation of coastal and offshore facilities in the lease sale areas of the Alaskan Beaufort and Chukchi Seas. As an example, the timing and pace of freeze-up play a critical role in determining the length of the drilling season.

Methods

The study was conducted using a combination of remotely-sensed data and on-site observations. The remotely-sensed data consisted of meteorological data recorded at Deadhorse and Utqiagvik Airports, ice charts prepared by the Canadian Ice Center, National Ice Center, and National Weather Service, satellite imagery acquired using the RADARSAT-2, VIIRS, and MODIS platforms, and drift buoy data available through the International Arctic Buoy Programme. On-site observations were conducted during four aerial reconnaissance missions undertaken at the end of the freeze-up season in February 2020.

Observations and Conclusions

Air Temperatures: Since the 1970s, progressively warmer winter seasons have caused the number of accumulated freezing-degree days at Utqiagvik to decline at an average rate of 49 per year. The rate of warming has accelerated, with the greatest increase in temperature occurring during the early portion of freeze-up.

Winds: Since the early 1980s, the frequency of storm events during freeze-up has increased by about 50%. The frequency of mid-winter storms (January through April) appears to have remained stable.

Timing of Freeze-Up: Nearshore freeze-up currently tends to occur at the end of October in the Alaskan Beaufort Sea and during the fourth week in November in the northeastern Chukchi Sea. The former is more than three weeks later than in the 1980s, while the latter is more than one month later than in the 1970s. The rate of change has accelerated in recent years, with the date of freeze-up currently trending later by 2.3 days/yr in the Beaufort and 4.6 days/yr in the Chukchi.

Duration of Freeze-Up: The duration of freeze-up in the Alaskan Beaufort Sea, from first ice to complete freeze-up, currently averages 37 days with a standard deviation of 11 days. In the Chukchi, the duration is substantially longer, averaging 63 days with a standard deviation of ten days. The duration in the Beaufort is increasing at a rate of 1.0 days/yr, while that in the Chukchi is increasing at 1.9 days/yr.

First-Year Ice Growth: Based on air temperature alone, the thickness of undeformed first-year ice attained during an average winter has decreased by 25 cm (15%) since the early 1980s. However, a significant increase in snowfall may be causing an even greater reduction in the ice thickness due to its insulating effect.

Landfast Ice: In the Alaskan Beaufort Sea, the extent of the landfast ice zone to the west of Prudhoe Bay is similar to that observed in the 1980s but the landfast ice develops more slowly. To the east of Prudhoe Bay, a stable, well-grounded shear zone is less likely to develop during freeze-up and develops more slowly in those years when it does occur. In the Chukchi, the narrow, ephemeral nature of the landfast ice zone noted in the 1980s continues to prevail today.

Coastal Flaw Lead: Notwithstanding trends toward warmer air temperatures, increased storminess, and slower ice growth during freeze-up, the frequencies with which the flaw lead and extended flaw lead occur off the Chukchi Sea coast have remained unchanged since the 1990s.

Multi-Year Ice: The probability of large multi-year ice floes invading the nearshore portion of the Alaskan Beaufort Sea during freeze-up currently is about 20%, based on four such occurrences in the past 20 years. In the Chukchi, the probability is about 65%, based on 13 invasions in the past 20 years.

Ice Drift: The limited data acquired in recent years indicate that the drift rate for pack ice in the Alaskan Beaufort Sea averages about 6 nm/day (11 km/day) during the early stages of freeze-up. This value is comparable to that which prevailed in the 1980s

Detailed technical information specific to the 2019-20 freeze-up season is provided in Attachment A.

ATTACHMENT A

TECHNICAL INFORMATION FOR 2019-20 FREEZE-UP SEASON

Entire Study Area

1. ***Air Temperatures:*** The air temperatures during the 2019-20 winter season were warm by historical standards, but unexceptional compared to those in the recent past. Specifically, the temperatures at Utqiagvik Airport were the sixth warmest in past 50 winters, but also the sixth warmest in the 11 winters from 2009-11 through 2019-20. Those at Deadhorse Airport were the ninth warmest in this 11-winter period.

2. ***First-Year Ice Growth:*** The computed thickness of undeformed first-year ice at the end of the 2019-20 winter season was 162 cm in the Alaskan Beaufort Sea and 148 cm in the Chukchi Sea, based on accumulations of 7,143 and 6,122 FDD at Deadhorse and Utqiagvik Airports, respectively. The thickness in the Beaufort was the third highest in the past 11 winters, while that in the Chukchi was tied with that in 2014-15 as the sixth highest. The highest values in recent years, 176 cm in the Beaufort and 167 cm in the Chukchi, occurred in 2011-12.

Beaufort Sea

1. ***Late Summer:*** The ice cover in the Alaskan Beaufort Sea diminished rapidly in July and early August, reflecting the prevalence of warm air temperatures and clear skies. Subsequently, from mid-August through mid-September, the rate of loss slowed. The minimum ice extent, which occurred on September 18th, tied those in 2007 and 2016 as the second lowest since the acquisition of satellite-based data began in 1979.

2. ***Timing of Freeze-Up:*** Freeze-up began in mid-October with the formation of ice along the coast between Admiralty Bay and Point Brownlow. Nearshore freeze-up occurred on November 11th, followed by complete freeze-up on November 24th. During the nine years covered by recent freeze-up studies (2009-11 through 2016-17 and 2019-20), the average date for the occurrence of nearshore freeze-up was October 28th with a standard deviation of nine days. The average date for the occurrence of complete freeze-up was November 10th with a standard deviation of ten days.

3. ***Duration of Freeze-Up:*** The duration of freeze-up was 41 days, consisting of 28 days from first ice to nearshore freeze-up and an additional 13 days from nearshore freeze-up to complete freeze-up. During the nine years covered by recent freeze-up studies, the duration averaged 37 days with a standard deviation of 11 days.

4. ***Wind Regime:*** Based on the daily average wind directions recorded at Deadhorse Airport, westerlies predominated in each of the five months from October through February. The frequencies of occurrence ranged from 55% in December to 79% in February. Over the entire five-month study period, westerlies outnumbered easterlies by a margin of 64% to 36%. The average monthly speeds were tightly clustered and relatively low by historical standards, with values of 11 kt (6 m/s) recorded in October, November, and December, and 9 kt (5 m/s) in January and February.

5. ***Storm Events:*** Storm events with daily average wind speeds exceeding 15 kt (8 m/s) occurred on only nine occasions encompassing 18 days. Four of the events were easterlies, while five were westerlies. The numbers of easterly storms (4), easterly storm days (9), total storms (9), and total storm days (18) all represented historical minima relative to 2009-10 through 2016-17. Storm duration was low, averaging 2.3 days/event for easterlies and 1.8 days/event for westerlies.

6. ***Landfast Ice:*** Landfast ice began to develop in early November, with growth occurring first in the western portion of the study area and subsequently in the eastern portion. The ice continued to expand offshore through the first half of December, but the advance stalled during the second half of the month. Substantial expansion followed in January, causing the landfast ice edge to reach one of its customary anchor points, Weller Bank, by mid-month and a second, Stamukhi Shoal, by early February. A reversal occurred at the end of February when a brief westerly storm caused the ice edge to retreat by distances up to 20 nm (37 km). Although the ice remained grounded on Weller Bank, it was displaced from Stamukhi Shoal - a development that underscored the absence of a well-developed, firmly-grounded shear zone during the 2019-20 freeze-up season.

7. ***Ice Pile-Ups:*** Thirty-two ice pile-ups formed in the central portion of the Alaskan Beaufort Sea during the 2019-20 freeze-up season. Two were located on the Endicott Project's Endeavor Island, two on Northstar Production Island, one on the Oooguruk Offshore Drillsite (ODS), one on the Spy Island Drillsite (SID), and 26 on natural barrier islands and shoals. The dimensions of the pile-ups were unexceptional by historical standards, with heights ranging from 1 to 7 m above sea level, encroachment distances from negligible to 20 m onto the subaerial beach, and lengths from 50 m to 2 km alongshore. The thicknesses of the ice blocks comprising the piles ranged from 20 to 50 cm.

8. ***Multi-Year Ice:*** Multi-year ice began to drift west into the Alaskan Beaufort Sea study area during the second week in October. In the absence of a well-developed first-year ice canopy, the multi-year floes advanced rapidly to the west in November. Some of the ice at the southern boundary was incorporated into the landfast ice zone in late November and early December, and remained there through the end of the freeze-up study period in February. The concentrations typically were less than 10%. Farther offshore, where the multi-year floes tended to be larger, the concentrations ranged from less than 10% to 50% in December, less than

10% to 60% in January, and less than 10% to 70% in February. The only region lacking multi-year ice for an extended period of time was a tongue of first-year ice that developed between the U.S.-Canadian border and Harrison Bay in mid-December, and persisted through February just offshore of the landfast ice zone.

Chukchi Sea

1. ***Timing of Freeze-Up:*** Ice began to form in Kasegaluk Lagoon, the Kuk River Inlet, and Peard Bay in mid-October, but freeze-up proceeded slowly in the weeks that followed. Complete coverage of these semi-enclosed basins did not take place until the last week in November. Although ice appeared in the exposed waters adjacent to the coast during the first week in November, it failed to coalesce into a near-continuous strip spanning the entire length of the study area until the end of the month. Farther offshore, first-year pack ice began to stream west past Point Barrow during the second week of November but stalled in response to periods of westerly winds. As a result, most of the Chukchi Sea remained ice-free at the end of November. A strong predominance of easterly winds in December delayed the attainment of complete ice cover adjacent to the coast until December 26th. On that date, nearshore freeze-up and complete freeze-up occurred simultaneously. During the nine years covered by recent freeze-up studies (2009-11 through 2016-17 and 2019-20), the average date for the occurrence of nearshore freeze-up was November 26th with a standard deviation of 15 days. The average date for the occurrence of complete freeze-up was December 11th with a standard deviation of 11 days.

2. ***Duration of Freeze-Up:*** Nearshore freeze-up and complete freeze-up both occurred 72 days after first ice. During the nine years covered by recent freeze-up studies, the duration of freeze-up (from first ice to complete freeze-up) averaged 63 days with a standard deviation of ten days.

3. ***Wind Regime:*** Easterlies outnumbered westerlies in November, December, and January, while westerlies prevailed in October and February. Over the entire five-month study period, easterlies outpaced westerlies by a margin of 55% to 45%. The monthly average speeds declined over the course of freeze-up, decreasing from 13 kt (7 m/s) in October and November to 11 kt (6 m/s) in December, 9 kt (5 m/s) in January, and 7 kt (4 m/s) in February.

4. ***Storm Events:*** Thirteen storm events took place from October through February, consisting of nine easterlies and four westerlies. The easterlies produced 16 storm-days while the westerlies produced 7 storm-days. The numbers of easterly storm-days (16) and total storm days (23) represented historical minima relative to 2009-10 through 2016-17. As in the case of the Beaufort, storm duration was low, averaging 1.8 days/event for both easterlies and westerlies.

5. ***Landfast Ice:*** The first traces of landfast ice appeared in Kasegaluk Lagoon, the Kuk River Inlet, and Peard Bay in mid-November. Although several small patches

of landfast ice formed in the exposed waters adjacent to the coast during the first half of December, a continuous strip encompassing the entire length of the study area between Point Barrow and Point Lay did not develop until month-end. Most of the newly-formed landfast ice was lost during the first half of January, a period in which winds with a significant offshore component prevailed. A partial rebound occurred during the second half of January, when westerly winds resulted in the re-establishment of a continuous strip. Additional expansion followed in February, causing the landfast ice to reach Blossom Shoals, its customary anchor point, by mid-month. At the end of the month, the width of the landfast ice zone ranged from less than 1 nm (2 km) off South Kasegaluk Lagoon and Point Belcher to 21 nm (39 km) off North Kasegaluk Lagoon.

6. ***Coastal Flaw Lead:*** From December 2019 through February 2020, the distinctive flaw lead that forms off the Chukchi Sea coast in response to offshore winds opened on seven different occasions. The frequency of occurrence, which averaged 54% over the three-month period, increased from 23% in December to 65% in January and 76% in February. The maximum width, 75 nm (139 km) occurred in January, while the maximum length, 250 nm (463 km), occurred in both January and February. The lead persisted for periods that ranged from one to 20 days.

7. ***Pack Ice:*** When a reconnaissance flight was performed at the end of February, the pack ice on the west side of the flaw lead consisted primarily of first-year floes with diameters typically ranging from less than 500 m to 1 km and occasionally reaching 3 km. Deformation was moderate. Ridge and rubble heights of 2 to 3 m were common but heights to 5 m were observed in some areas, particularly in the vicinity of the flaw lead.

8. ***Ice Pile-Ups:*** Fifty-seven ice pile-ups occurred on the shoreline between Utqiagvik and Point Lay during the 2019-20 freeze-up season. Thirty-seven were located on the seaward side of the barrier islands fronting Kasegaluk Lagoon while one was located on the landward side. The remaining 19 were located between North Kasegaluk Lagoon and Utqiagvik. The dimensions were large by historical standards, with heights ranging from 1 to 20 m, encroachment distances from negligible to 30 m, and alongshore lengths from 50 m to 8 km. The block thicknesses varied from 30 to 60 cm.

9. ***Multi-Year Ice:*** Multi-year ice drifting west in the Alaskan Beaufort Sea reached the vicinity of Point Barrow at the end of November. It remained stalled at that location until mid-December, when multi-year floes began to move into the region northwest of the Point. On December 23rd, the ice drifted south of the Point after entering the first flaw lead of the freeze-up season. A larger flaw lead appeared at the end of December, allowing the ice to move within 2 nm (4 km) of Icy Cape by early January. The ice continued to advance to the south and west of Point Barrow during the remainder of January, reaching the Hanna Shoal and Burger Prospects in mid-month and the vicinity of Point Lay at month-end. Changes in the ice edge

were minimal in February, with the western boundary tending to follow the 163ºW meridian between the 70ºN and 72ºN parallels.