Homeland Security

United States Coast Guard

Report of the International Ice Patrol in the North Atlantic

2021 Season
Bulletin No. 107
CG-188-76

INTERNATIONAL
ICE PATROL

USCG
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Season of 2021
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Forwarded herewith is Bulletin No. 107 of the International Ice Patrol (IIP) describing the Patrol's services and ice conditions during the 2021 Ice Year. With only a single iceberg drifting into the transatlantic shipping lanes, the 2021 season was designated as a “Light” Ice Season – the lightest year since 2013, when 13 icebergs crossed into the shipping lanes. Similar to 2020, which saw 169 icebergs entering the shipping lanes, slow formation of sea ice and warm temperatures at the end of 2020 created environmental conditions favoring a light season. By contrast, IIP classified 2019 as “Extreme” with 1,515 icebergs entering the shipping lanes, highlighting the dramatic inter-annual variability in iceberg season severity observed by IIP. The Ice and Environmental Conditions section presents a discussion of the meteorological and oceanographic conditions that resulted in this year’s very light season.

In 2021, the majority of icebergs were detected by satellite, as opposed to C-130 aircraft, continuing the trend begun in 2020. IIP’s first operational use of satellite iceberg reconnaissance occurred in 2017, which is considered the beginning of the “satellite era” of IIP reconnaissance, and follows the “aircraft radar,” “aircraft visual,” and “cutter” eras of our patrol operations. IIP continues to move toward eliminating the need for costly aircraft reconnaissance flights in the coming years. In order to achieve this goal, during the summer of 2021, IIP permanently relocated from New London, CT, to the NOAA Satellite Operations Facility in Suitland, MD in the National Capital Region.

Continuing progress made in satellite reconnaissance techniques enabled IIP to support increased Coast Guard and partner activity in the Arctic. IIP provided tailored iceberg warning products to five Coast Guard cutters operating off Greenland, including three non-ice-strengthened ships unfamiliar with iceberg risk.

Following cancellations in 2020, IIP was once again able to host events honoring sacrifices linked to our history. IIP personnel conducted memorial and wreath dedication ceremonies for RMS TITANIC in New London, CT, followed by a commemoration of the sacrifices of the Greenland Patrol during World War II.

This report was prepared by all members of the IIP team, who made additional sacrifices this year. During a pandemic which forced our ice observers into dozens of COVID tests and many weeks of mandated isolation in Canada, the women and men of IIP cheerfully executed a challenging relocation of both their unit and their families, and I will be forever grateful for their dedication to our mission. On behalf of the women and men of IIP, I hope that you enjoy reading this report of the 2021 season.

M. T. Hirschberg
Commander, U. S. Coast Guard
Commander, International Ice Patrol

International Ice Patrol
2021 Annual Report
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Previous IIP Annual Reports may be obtained from the IIP website:
http://www.navcen.uscg.gov/?pageName=IIPAnnualReports

Cover art: A collection of several images highlighting different operations throughout the 2021 Ice Season. The top image is the IRD 4 team walking out to their HC-130J in March prior to the first reconnaissance flight out of St. John's, NL in over a year. The bottom left image is an ice island located by IRD 8 in May. Second from the left is the aerial deployment of a wreath memorializing the lives lost from RMS TITANIC in April. Third is USCGC ESCANABA nearing pinnacled iceberg AMNY-21 in August. The last image is the sun setting on the USCG Research and Development Center prior to IIP moving to their new office in Suitland, Maryland.

INTERNATIONAL ICE PATROL

1. Introduction

This is the 107th annual report of the International Ice Patrol (IIP) describing the 2021 Ice Year. It contains information on IIP operations, along with environmental and iceberg conditions in the North Atlantic from October 2020 to September 2021; focusing on the Ice Season (February to August 2021). To conduct aerial reconnaissance, IIP deployed nine Ice Reconnaissance Detachments (IRDs) to detect icebergs in the North Atlantic and Labrador Sea. The IRDs used HC-130J aircraft from U.S. Coast Guard (USCG) Air Station Elizabeth City (ASEC). Due to COVID-19 pandemic travel restrictions, the first three IRD's operated from USCG Air Station Cape Cod (ASCC) on board ASEC aircraft. IRD 4 saw the return to St. John's, Newfoundland, with more effective aerial reconnaissance operations resulting from the proximity to the operating area. In addition to this reconnaissance data, IIP received iceberg reports from commercial aircraft and mariners in the North Atlantic. Further, IIP continued the progression toward incorporating satellite data into standard reconnaissance operations. IIP personnel analyzed iceberg and environmental data, using iceberg drift and deterioration models within the iceBerg Analysis and Prediction System (BAPS) at the IIP Operations Center (OPCEN) in New London, Connecticut. In accordance with the North American Ice Service (NAIS) Collaborative Arrangement, IIP used BAPS to produce a daily iceberg chart and a text bulletin from the model output. These iceberg warning products were then distributed to the maritime community. IIP also responded to individual requests for iceberg information in addition to these routine broadcasts.

While aviation missions will continue in 2022, IIP remains committed to transitioning all reconnaissance to space-based systems in the near future. Following the 2021 Ice Season, IIP relocated to the NOAA Satellite Operations Facility in the National Capital Region, facilitating access to additional space-based reconnaissance systems. While aircraft remain the most accurate method of sighting small icebergs, developments in commercial imagery and extensive coordination with interagency partners make satellite-only reconnaissance a viable option for IIP. Part of these efforts include the deployment of an automatic correlator for vessels' Automated Identification Systems beacons. Differentiating icebergs from ships is one of IIP's principal challenges with respect to satellites, and this system will automatically associate radar targets with vessel tracks, freeing up analysts to focus on oceanographic challenges.

IIP was formed after the RMS TITANIC sank on 15 April 1912. Ever since 1913, with the exception of periods of World War, IIP has monitored the iceberg danger in the North Atlantic and broadcast iceberg warnings to the maritime community. The activities and responsibilities of IIP are delineated in U.S. Code, Title 46, Section 80302 and the International Convention for the Safety of Life at Sea (SOLAS), 1974.

For the 2021 Ice Season, IIP was under the operational control of the Director of Marine Transportation (CG-5PW), Mr. Michael D. Emerson. CDR Marcus T. Hirschberg was Commander, IIP (CIIP).

For more information about IIP, including historical and current iceberg bulletins and charts, visit our website at www.navcen.uscg.gov/IIP.

2. Ice and Environmental Conditions

Operational Area

This section describes the ice and environmental conditions throughout IIP's Operational Area (OPAREA) during the 2021 Ice Year. The Ice Year spans the period between 01 October of the previous year and 30 September of the current year. IIP is responsible for guarding the southeastern, southern, and southwestern Iceberg Limits in the vicinity of the Grand Banks of Newfoundland. In conjunction with IIP's North American Ice Service (NAIS) partners, the Canadian Ice Service (CIS), the United States National Ice Center (USNIC), and the Danish Meteorological Institute (DMI), IIP monitors environmental, meteorological, and climatological data to develop accurate iceberg warning products in the OPAREA (**Figure 2-1**). This section documents the atmospheric, oceanographic and sea ice conditions that influenced iceberg conditions during the 2021 Ice Year.

Ice Year Summary
Season Severity

In 2021, sea ice extent along the Canadian East Coast was one of the lowest on record. The positive correlation between sea ice extent and the number of icebergs crossing south of 48°N is well

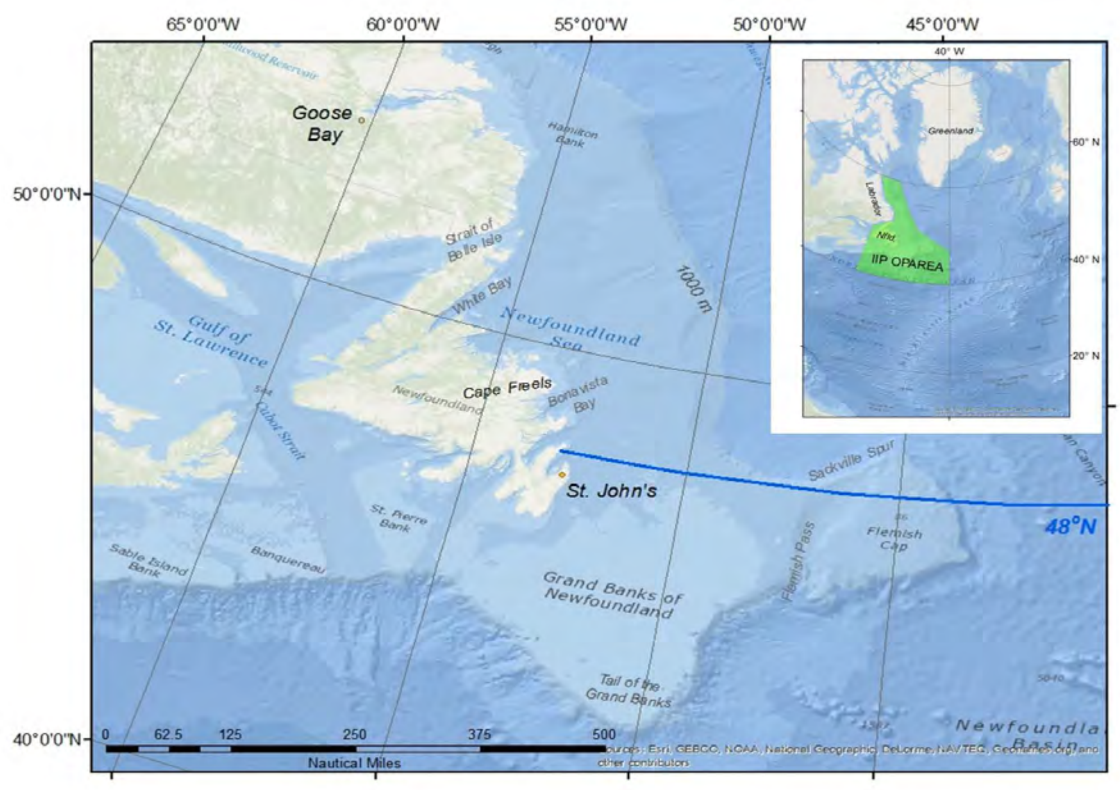

Figure 2-1. International Ice Patrol Operational Area (OPAREA) in green (inset). The latitude of 48°N is typically considered the northern boundary of the transatlantic shipping lanes. IIP measures season severity based on this line.

understood (Marko et al., 1994). This relationship held true in 2021 and was a key factor for 2021 iceberg observations. IIP recognizes 48˚N as the latitude where icebergs intersect the great circle route between Europe and North America, making them particularly hazardous to transatlantic shipping. With only one iceberg crossing south of 48˚N, IIP classified 2021 as a "Light" year.

IIP recently revised season severity classifications to account for varying observational methods and the use of iceberg modeling (IIP, 2018). Using these revised normalized metrics, the 2021 Ice Year ranks as 116th out of 117 in terms of icebergs crossing south of 48˚N. The 2021 Ice Year tied with three other years having only one iceberg crossing 48˚N (1940, 1958, and 2010) for this rank. Two Ice Years share the rank of 117th with zero icebergs crossing 48˚N (1966 and 2006). The 2021 Ice Year was the lightest year on record since 2010.

From 1900 to present, IIP has documented significant inter-annual variability in the number of icebergs drifting south of 48°N. This variability is caused both by variation in environmental conditions and by modifications to sighting methods **(Figure 2-2)**. The mean number of icebergs south of 48°N throughout IIP's entire iceberg data record prior to 2021 (1900-2020) is 491. The average number of icebergs crossing 48°N for the modern reconnaissance era (1983-2020) is 778. The modern era is characterized by IIP's use of aircraft with sophisticated airborne radar systems, ship reports, and satellite reconnaissance. The use of iceberg drift and deterioration modeling also allowed inclusion of drifting icebergs into the data record during the modern era. In 2017, IIP began incorporating satellite imagery into routine operations. While

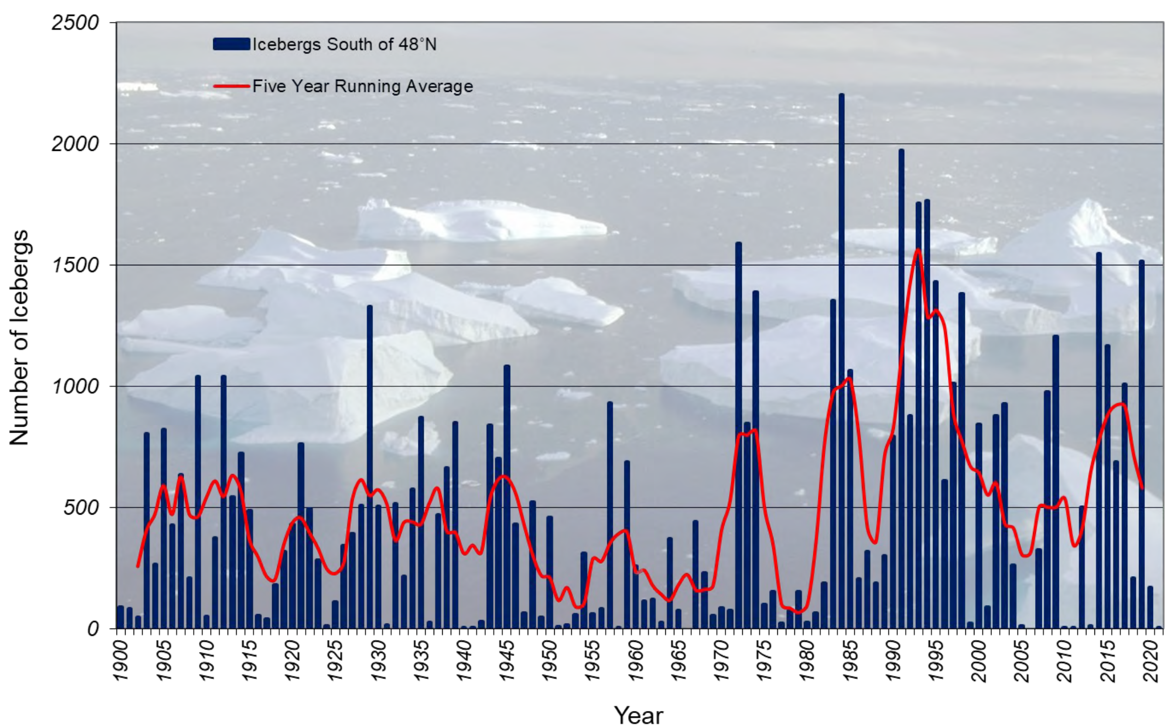

Figure 2-2. Icebergs crossing 48°N by year (blue bars) and five-year running average for 1903-2019 (red line). The five-year running average is calculated using a sliding window with year 3 as its center (2019).

this was a significant milestone, its impact on the number of icebergs crossing south of 48°N remains unclear. IIP will continue to report this year and subsequent years under the modern reconnaissance era but acknowledges 2017 as the potential start of a fourth reconnaissance era.

During the season, IIP tracked iceberg severity daily, by using normalized statistics to compare current-year severity to statistical benchmark “Light”, “Moderate”, “Heavy”, and “Extreme” years during the modern reconnaissance era (IIP, 2018). IIP established these benchmarks using the cumulative monthly mean number of icebergs for each severity class. **Figure 2-3** shows the results of this calculation with the observed monthly total of icebergs drifting south of 48°N during the 2021 Ice Year. The single iceberg drifting south of 48˚N, is shown as a solid black line, marked with dots along the horizontal axis in **Figure 2-3**. The 2019 and 2020 Ice Years are also plotted in gray for reference. Light iceberg conditions relative to other more severe years contributed to the CIIP’s decision to suspend aerial reconnaissance flights on 03 June 2021.

Ice Year Environmental Conditions Overview

Forecasts for positive North Atlantic Oscillation Index (NAOI) and near normal air and sea surface temperatures in Newfoundland prompted an ‘above normal’ outlook for iceberg activity in 2021 (CIS, 2020). A positive NAOI typically promotes offshore winds and colder air temperatures along the Newfoundland and Labrador (NL) coasts, ultimately creating conditions favorable for sea ice growth. However, the NAOI forecast did

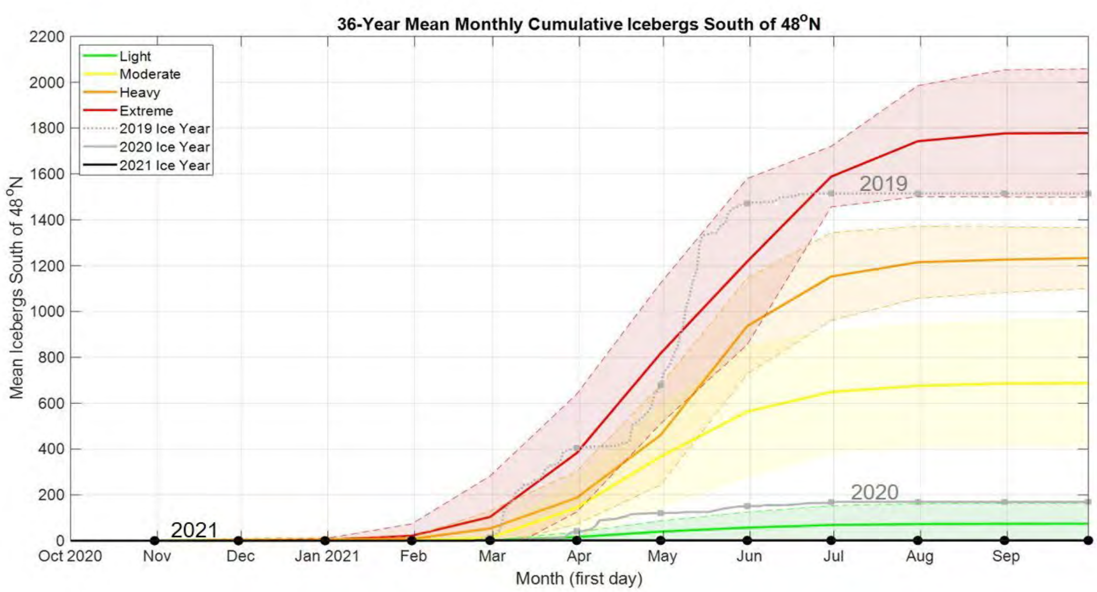

Figure 2-3. Icebergs crossing south of 48°N for the 2021 Ice Year plotted over the 36-year mean of monthly cumulative icebergs south of 48˚N from 1983 - 2018. The 2019 and 2020 Ice Years are shown in gray for comparison. Solid lines indicate the mean number of icebergs that have passed south of 48˚N throughout the iceberg season in "Light" (Green), "Moderate" (Yellow), “Heavy” (Orange), and "Extreme" (Red) seasons. The dashed lines and shading indicate ±1 standard deviation from the mean. Season types are defined using the normalized iceberg count and the 50% standard deviation method developed in 2018 (IIP, 2018).

not hold for the entire year. Several factors caused below median sea ice growth and a correspondingly small number of icebergs to drift into the transatlantic shipping lanes this year.

Although the NAOI at the start of the Ice Year (through 01 December) remained strongly positive, it reversed to slightly negative from early December through mid-February. This fact, coupled with significantly above normal air temperatures along the NL coasts inhibited sea ice growth throughout the winter. These conditions yielded "record low ice coverage" throughout the east coast of Canada (CIS, 2021a). Sea ice coverage and extent remained well below median for the entire year, peaking in early March, around three weeks earlier than normal.

The correlation between sea ice coverage and iceberg season severity is well established. Icebergs locked into sea ice are protected from exposure to the open seas, thereby slowing their melt. The extent of sea ice from the NL coasts can also impede the shoreward movement of icebergs, keeping them in the offshore branch of the Labrador Current. With below median sea ice coverage in 2021, the number of icebergs available to drift into the shipping lanes was well below normal.

With record low sea ice coverage, iceberg conditions during the 2021 Ice Year proved even less severe than the previous year (also classified by IIP as "Light"), both in terms of icebergs crossing south of 48°N and areal extent of the Iceberg Limit at its furthest south and east. Remarkably, the Iceberg Limit reached both its southernmost latitude and easternmost longitude on the same date on 27 February. Based on data collected since 2012, these milestones normally occur in mid-May. The maximum Iceberg Limits for 2021 were well inside of the climatological Iceberg Limit median **(Figure 2-4)**. **Appendix C** provides additional details on the development of Iceberg Limit climatology. For comparison, in 2020 the Iceberg Limit reached its southernmost latitude of 43°05'N on 01 May (**Figure 2-5**, **left panel**) and the easternmost longitude of 41°00'W on 28 April 2020 (**Figure 2-5, right panel)**. The 2021 Iceberg Limit is estimated (depicted as a dotted magenta-colored line) because of aerial reconnaissance limitations due to COVID-19 flight restrictions. Flights resumed from St. John's, NL in March.

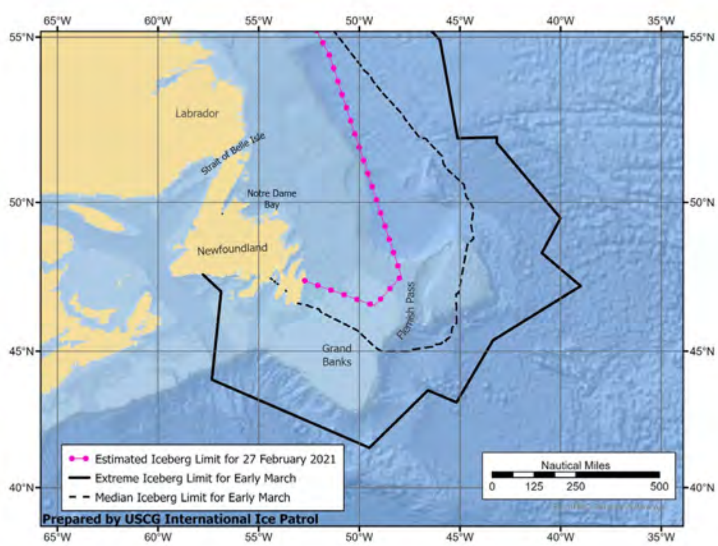

Figure 2-4. Southernmost and Easternmost Iceberg Limit extent for 2021. Median and Extreme Iceberg Limits for early March are based on IIP's 30-year Iceberg Limit Climatology from 1991-2020.

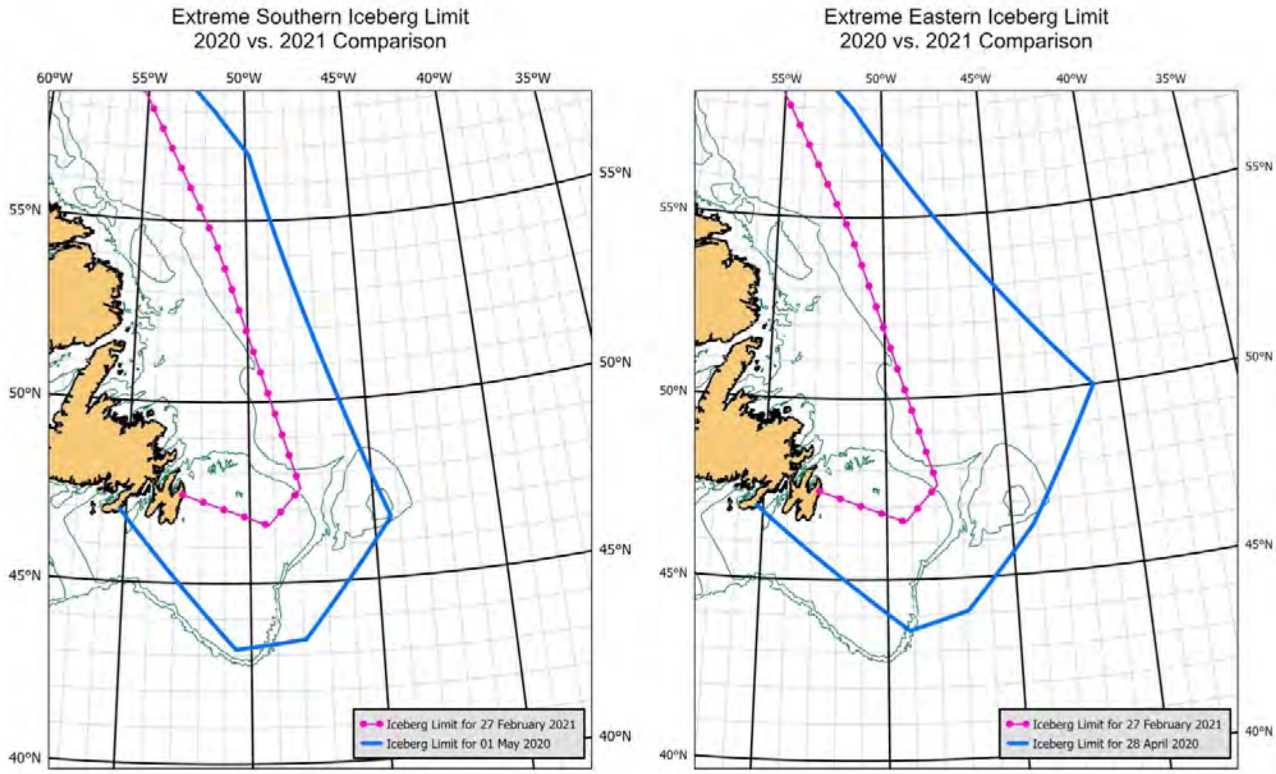

Figure 2-5. Southern and eastern maximum Iceberg Limit extent for 2020 (magenta) and 2019 (blue). Note: IIP considered 2020 and early 2021 Iceberg Limits as 'Estimated' due to degraded aerial reconnaissance with COVID-19 travel restrictions. Normal aerial reconnaissance resumed in March 2021.

Quarterly Environmental Summaries October – December 2020

At the beginning of the Ice Year, CIS had primary responsibility for issuing the NAIS daily Iceberg Limit warnings and were monitoring 32 icebergs in the iceBerg Analysis and Prediction System (BAPS). All icebergs were north of 52°N and most were within 120 NM of the Labrador coast. The majority of these icebergs were detected by satellite reconnaissance. The quantity, location, and density of the iceberg population remained at around 30 through mid-November. Isolated icebergs drifted towards 50°N and within 200 NM of the southern Labrador coast. An isolated iceberg caused the Iceberg Limit to extend south of 50°N and east of 50°W on 15 November but was removed the following day causing a significant reduction in the Iceberg Limit. For the rest of the period, the main iceberg population declined in quantity, remained north of 52°N and was confined to within 100 NM of the Labrador coast. Section 7 of this report contains IIP and CIS semi-monthly iceberg charts that were issued on the 1st and the 15th of each month. These charts depict the Iceberg and Sea Ice Limits, along with an estimate of the number of icebergs contained in a one-degree-by-one-degree latitude/longitude grid cell.

Normal to slightly below normal air temperatures throughout November initiated sea ice development in the bays along the Labrador coast. However, above normal air temperatures in December, kept sea ice growth below the median, a trend that persisted throughout the remainder of the Ice Year (CIS, 2021a).

As sea ice developed, satellite reconnaissance focused on areas outside of the sea ice edge which likely resulted in a decrease in the number of icebergs appearing on the daily warning product. By the end of December, nine icebergs remained, and the Iceberg Limit receded northward to approximately 53°N. No icebergs were sighted or drifted south of 48°N during the first quarter of the Ice Year.

January-March 2021

Sea Ice Development

Air temperatures remained well above normal along the NL coasts. During January and February. Air temperature anomalies ranged from 3°C above normal along the northern Newfoundland coast to more than 8°C above normal along the northern Labrador coast (**Figure 2-6**). During the third week of March, a brief period of below normal air temperatures caused a brief increase in sea ice growth.

Throughout January and February, the NAOI remained negative promoting onshore winds throughout the period (**Figure 2-7**). The sea level pressure (SLP) anomaly during the same period showed higher than normal air pressure over southern Greenland accompanied by correspondingly below normal SLP further south over the central Atlantic (**Figure 2-8**), again supporting predominantly onshore winds and inhibiting significant sea ice growth during these critical months. Further, periodic low-pressure systems, moving through the NL region accelerated sea ice destruction and kept the Total Accumulated Ice Coverage (TAC) well below median for the entire Ice Year.

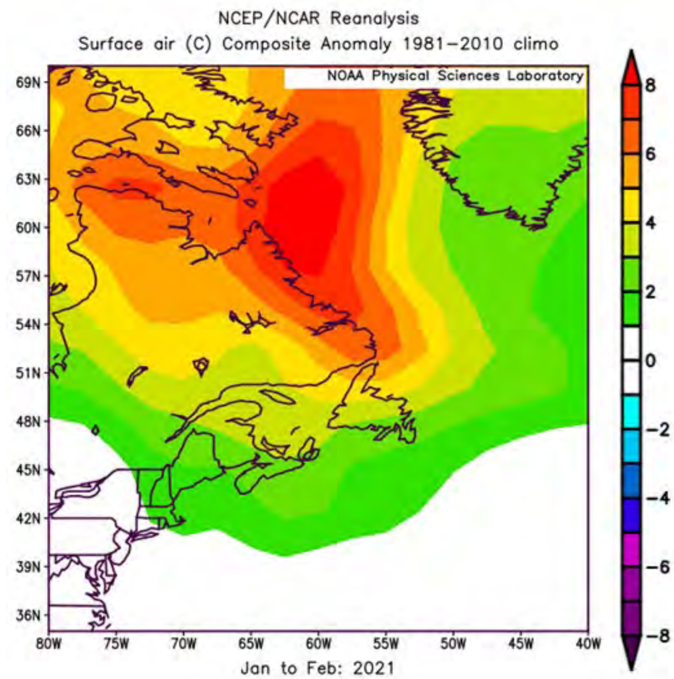

Figure 2-6. National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Surface Air Temperature Composite Anomaly for January through February 2021. (NOAA/ESRL PSD, 2021a)

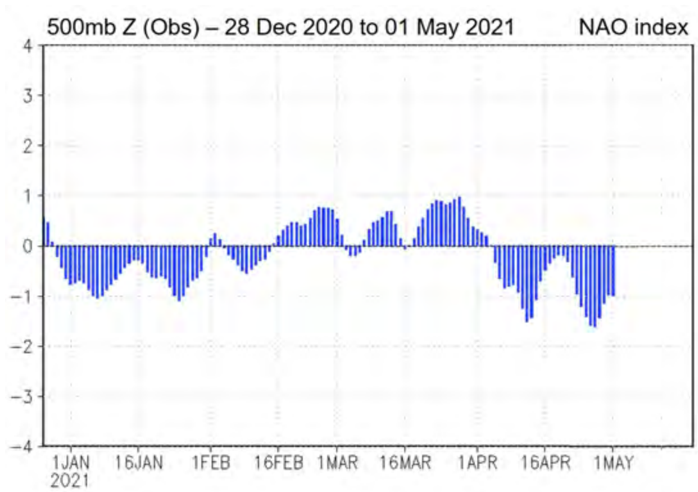

Figure 2-7. NAO Index from 28 December to 01 May 2021. (NOAA/NWS, 2021)

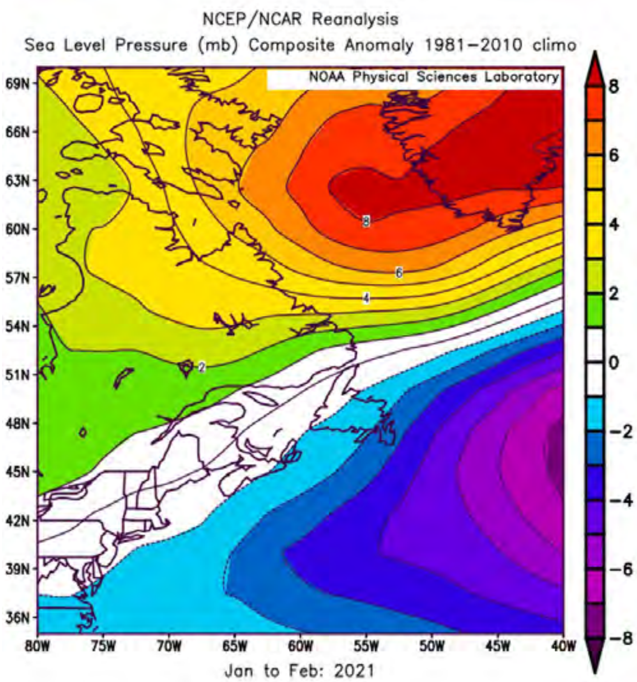

Figure 2-8. National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Sea Level Pressure Anomaly for January through February 2021. (NOAA/ESRL PSD, 2021b)

Predominantly offshore winds and below normal air temperatures during the last two weeks of March caused a peak in ice growth on 19 March. Sea ice reached its maximum southern extent on 22 March but began to decline steadily throughout the rest of March (**Figure 2-9, left panel**). Viewing the Departure from Normal Concentration alongside the Regional Sea Ice Concentration graphic for the same date highlights the unusually low sea ice coverage for the 2021 Ice Year (**Figure 2-9, right panel**) (CIS, 2021b).

Iceberg Conditions

The iceberg population remained light throughout January with distribution scattered along the Labrador coast. An isolated iceberg drifting southeastward caused the Iceberg Limit to expand to the south of 51°N for one day. Otherwise, icebergs were confined to within 80 NM of the coast. By the end of the month, IIP estimated that 25 icebergs were scattered along the NL coasts. IIP resumed primary responsibility for creating and distributing Iceberg Limit products on 21 January. No icebergs crossed south of 48°N in January.

PAL Aerospace began conducting aerial ice reconnaissance on behalf of CIS and the oil and gas industry on 13 January. Six reconnaissance flights, generally south of 55°N, confirmed the low iceberg population along the NL coasts, detecting zero icebergs in January and February.

Satellite reconnaissance continued throughout the quarter. Using Sentinel-1 satellite imagery, IIP detected an isolated iceberg on 04 February approximately 50 NM northeast of Fogo Island off of the Newfoundland coast. This iceberg continued drifting towards the east and then southward in the offshore branch of the Labrador Current (**Figure 2-10**), eventually becoming the only iceberg of the year to cross south of 48°N on 24 February. Forecasted drift of this iceberg resulted in both the southernmost and easternmost expansion of the Iceberg Limit of the year on 27 February (**Figure 2-10**). Although another iceberg drifted slightly further east on 11 April, IIP established the 27 February more conservatively due to aerial reconnaissance restrictions in place in February.

Still operating under COVID-19 flight restrictions at the beginning of the year, an IIP Ice Reconnaissance Detachment (IRD) attempted to deploy to the

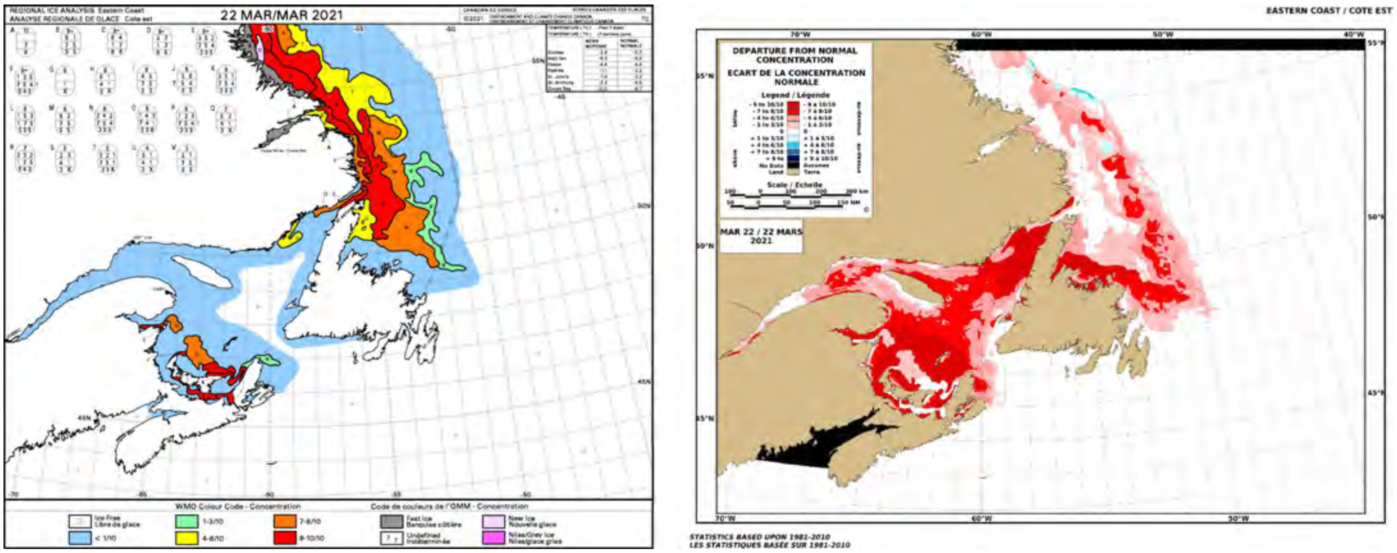

Figure 2-9. CIS Regional Ice Analysis Eastern Coast for maximum southern sea ice extent (22 March) (left panel) with Departures from Normal for 22 March (right panel). (CIS, 2021b, c)

OPAREA from Cape Cod, MA on 06 February but terminated the mission after several days without conducting any patrols due to OPAREA weather. The Iceberg Reconnaissance Operations section of this report (Section 4) provides a detailed narrative of each deployment for the year. Later in February, IIP reconnaissance conducted two flights between 56°N and 60°N offshore along the Labrador coast to determine the iceberg population in the Labrador Current. The first of these flights also checked the Strait of Belle Isle to confirm that there were no icebergs in this region. These flights located 50 icebergs. IIP estimated that the majority (47) of these icebergs were 'Small' or 'Medium' (less than 120 m in length) and only three 'Large' icebergs greater than 120 m. Due to the overall small iceberg sizes and the rapid retreat of sea ice in March, none of these icebergs survived the journey to 48°N into the shipping lanes. During February, one iceberg drifted south of 48°N.

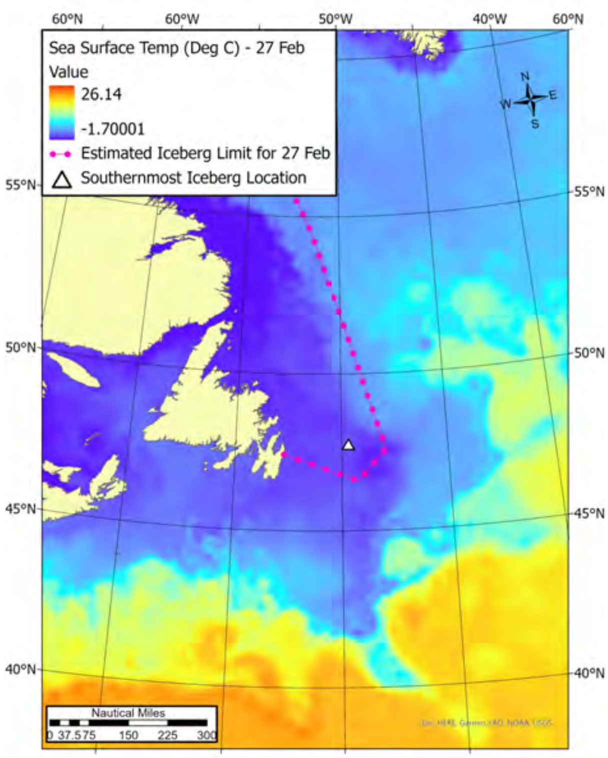

Figure 2-10. Southernmost iceberg location for the year overlaid on Group for High Resolution SST (GHRSST) image. The dotted magenta line represents the Estimated Iceberg Limit. (UKMO, 2021)

Satellite and aerial reconnaissance continued through March. PAL Aerospace reported 56 icebergs from two flights on 15 and 23 March, off the southern Labrador coast to 55°N and all within the sea ice edge. On 24 March, IIP resumed flights out of St. John's, NL for the first time in more than a year. This IRD focused on the iceberg population in the Newfoundland Sea out to the 1,000 m depth contour to determine the presence of icebergs in the offshore branch of the Labrador Current. IIP located three 'Small' and two 'Medium' icebergs in this area. To date, only three 'Large' icebergs (greater than 120 m in length) had been observed, all north of 57°N.

By the end of March, IIP was tracking 247 icebergs, 12 'Large' or 'Very-Large' (estimated size greater than 120 m). All others were 'Small' or 'Medium' (estimated length less than 120 m). The Iceberg Limit remained north of 48°N and extended eastward to 49°30'W, well within the climatological median Iceberg Limit. No new icebergs were sighted or drifted south of 48°N during the month of March.

April - June 2021

Sea Ice Development

Following two weeks of offshore winds during the end of March, wind direction shifted to predominantly onshore for the month of April (**Figure 2-11**). This corresponded with a reversal in the NAOI from 04 April through most of May. This observed wind pattern, coupled with continued above normal air temperatures hastened the decline of sea ice along the Canadian east coast. By 03 May, all medium first-year sea ice was to the north of 55°N. By 20 June, the Labrador coast was completely ice-free, leaving the iceberg population exposed to the open sea. Weekly ice coverage along the NL coasts remained well below median levels for the entire Ice Year (**Figure 2-12**).

The 2021 Ice Year, while unusual, was not unprecedented. In fact, as recently as 2010, IIP observed only a single iceberg in the shipping lanes for the entire year. To highlight the strong correlation between sea ice TAC and iceberg season severity, the number of icebergs drifting south of 48°N are plotted against TAC during the modern era of iceberg reconnaissance (1983-2021) (**Figure 2-13**). With exception of 1986-1989, the correlation between these two metrics is visually striking. Statistically, the correlation coefficient between TAC in this region and icebergs south of 48°N is 0.75.

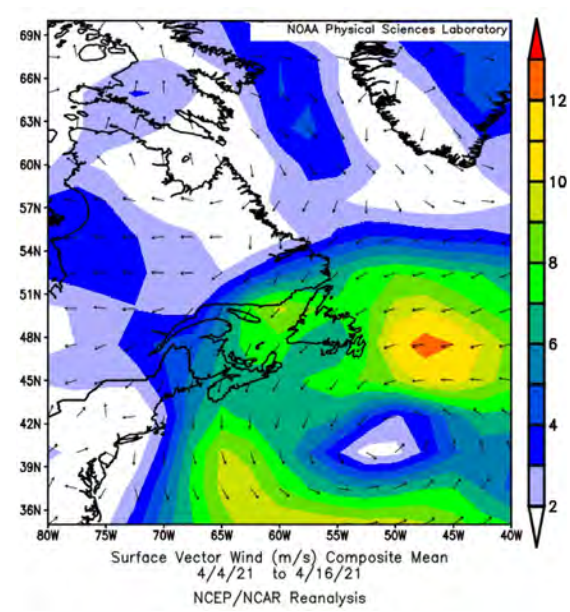

Figure 2-11. Surface Vector Winds Composite Mean for 04 through 16 April 2021. Color shading represents wind speed in meters per second and arrows show the mean wind direction during the time period. Wind estimates are based on the NCEP/NCAR Reanalysis. (NOAA/ESRL PSD, 2021c).

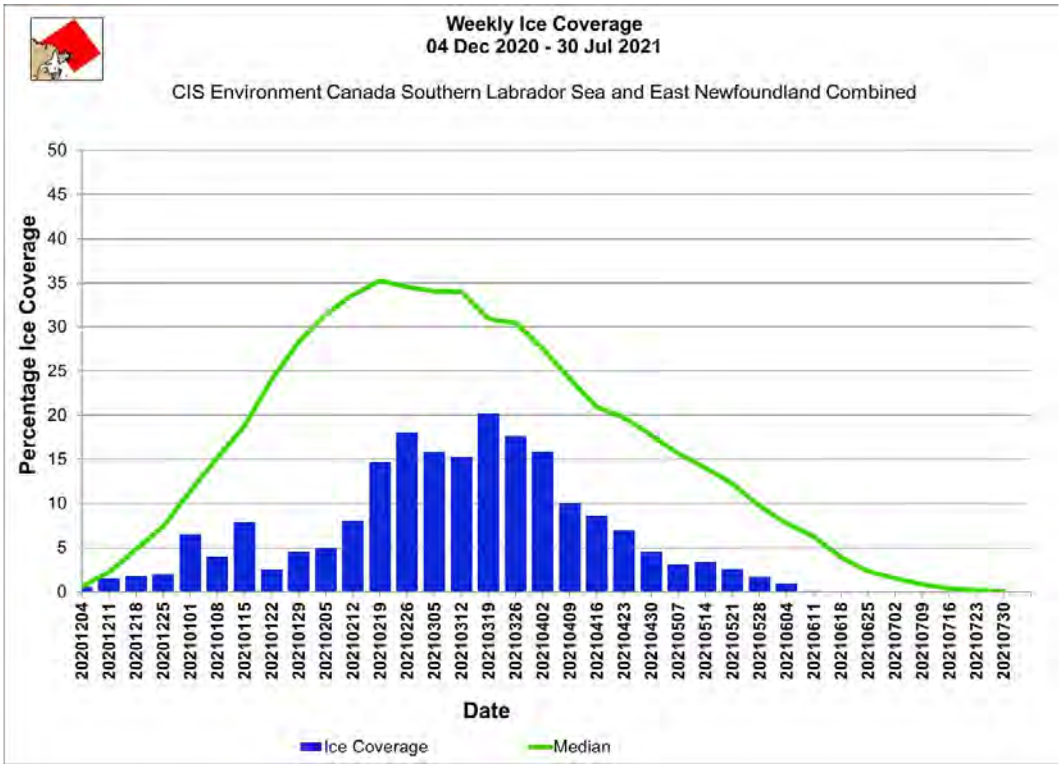

Figure 2-12. Weekly ice coverage for East Newfoundland and Southern Labrador Sea waters for 2020-2021. The percent coverage is relative to the area shaded in red in the upper left map of this figure (CIS, 2021d).

IIP will continue to carefully observe sea ice growth during the 2022 Ice Year to get an early indicator for next year's season severity.

Iceberg Conditions

The southern Iceberg Limit for 01 April was near 48°N and well north of the median Iceberg Limit for early April. The Iceberg Limit extended to near 47°N on 16 April but steadily retreated northward through the remainder of the quarter, being established by isolated icebergs. Throughout May and June, the southern Iceberg Limit remained north of 50°N and the eastern Iceberg Limit remained west of 50°W. The western Iceberg Limit in the Gulf of St. Lawrence made its maximum westward extent on 21 April. Much like the southern and eastern limit maxima (occurring on 27 February), the western Iceberg Limit reached its maximum around four weeks before normal.

Now operating out of St. John's, NL, IIP flight coverage increased significantly and focused on three general areas: (1) the 1,000 m depth contour, (2) the eastern Gulf of St. Lawrence/Strait of Belle Isle and (3) the mid- to northern Labrador coast. These flights determined the extent of the Iceberg Limits and assessed the iceberg population and distribution. Aerial and satellite reconnaissance both confirmed a steady decline in the iceberg population. At the end of April, IIP tracked 297 icebergs around the NL coasts with 27 adrift in the Gulf of St. Lawrence and only four remaining south

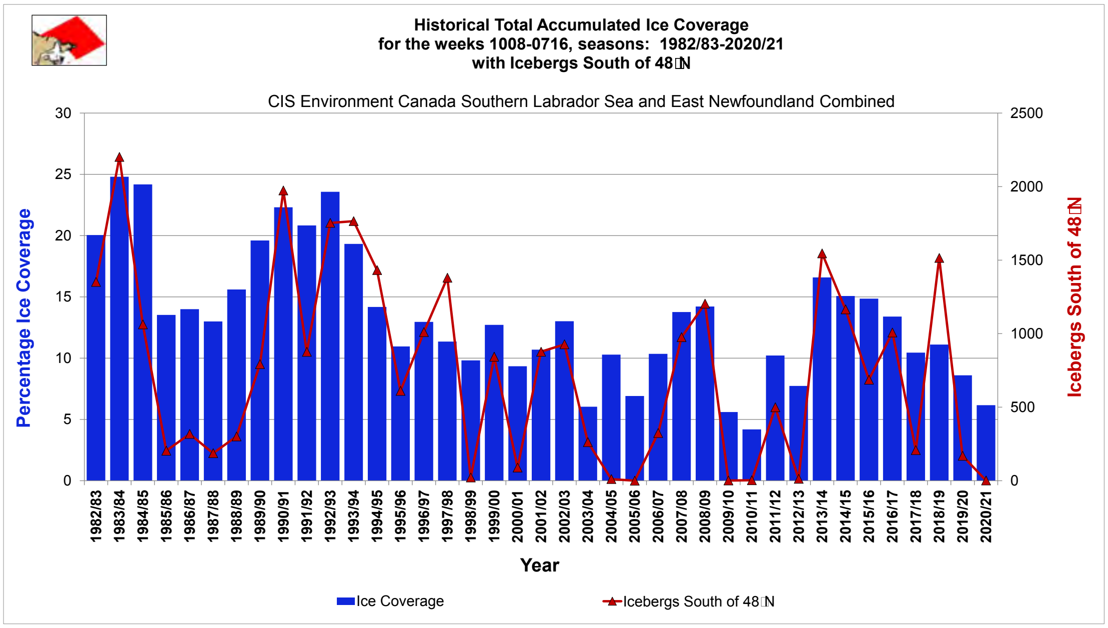

Figure 2-13. Historical Total Accumulated Ice Coverage with Icebergs South of 48°N during the modern reconnaissance era (1983-2021). The percent coverage is relative to the area shaded in red in the upper left map of this figure. Datasets showed 0.75 correlation coefficient (CIS, 2021d).

of 50°N. All other icebergs were located in Notre Dame Bay, the Strait of Belle Isle and along the Labrador coast. A group of 20 icebergs were located approximately 100 NM off of the Labrador coast along the 1,000 m depth contour at 54°N. Although these icebergs were near the core of the offshore branch of the Labrador Current they were in open water and deteriorated prior to arrival into the shipping lanes. No additional icebergs drifted south of 48°N for the remainder of the year.

Throughout May, the Iceberg Limit fluctuated between 50°N and 52°N. The iceberg population continued to decline throughout the month. By the end of May, IIP estimated that 192 icebergs remained along the Labrador coast. With exception of one iceberg in the Strait of Belle Isle (at 52°N), all other icebergs were north of 53°N. With the exception of two small groups of 9 and 10 icebergs near 57°N and 60°N, respectively, persistent onshore winds confined the iceberg population to within 75 NM of the Labrador coast and shoreward of the main flow of the Labrador Current.

In the absence of sea ice, aerial and satellite reconnaissance found a substantially larger population of icebergs during June than previously estimated. Beginning with its final reconnaissance flight of the year on 02 June, IIP detected 194 icebergs while on a northern survey flight along the Labrador coast, with over 75% confirmed by visual observation. IIP classified 153 of these (78%) as ‘Medium’ or smaller (lengths less than 120 m). All icebergs on this flight were observed north of 55°N with the majority located within 50 NM of the coast. Sentinel-1 and -2 imagery along with Canadian Coast Guard vessels continued to report icebergs along the coast. At the end of June IIP estimated that 384 icebergs remained along the Labrador coast. While the number of icebergs was much larger than originally thought, most of these icebergs remained inshore, were relatively small-sized and continued to deteriorate in open water. The southern extent of the Iceberg Limit remained near 50°N due to an isolated iceberg, 10 NM east of the Northern Arm of Newfoundland. Two icebergs in the Strait of Belle Isle established the western Iceberg Limit.

July – September 2021

Iceberg Conditions

The iceberg population steadily declined throughout July and the Iceberg Limit contracted, correspondingly. Predominantly offshore winds throughout the month forced numerous icebergs offshore towards the 1,000 m contour so that the iceberg population was more evenly distributed over the continental shelf of Labrador. By the end of the month, 79 icebergs remained, all north of 53°30'N latitude. Since the iceberg distribution did not pose a significant threat to the transatlantic shipping lanes, CIS agreed to resume primary responsibility for issuing the NAIS daily Iceberg Limit much earlier than normal on 29 July. This decision also greatly facilitated IIP's relocation from New London, CT to the NOAA Satellite Operations Facility in Suitland, MD.

During August, CIS contracted PAL Aerospace to assess the southern extent of the iceberg population near 52°N. These flights confirmed that no icebergs were in position to drift southward towards the transatlantic shipping lanes. CIS also significantly increased the use of Radarsat Constellation Mission (RCM) satellite imagery to monitor iceberg danger along the Labrador coast. While RCM continued to find a large population of icebergs distributed across the Labrador shelf, mostly north of 57°N, only few icebergs drifted southward. On 26 August, one iceberg detected by RCM, drifted into White Bay, just east of the Northern Arm of Newfoundland, causing the Iceberg Limit to reach 50°N. By 30 August, CIS estimated that 170 icebergs remained along the northern Labrador coast.

In September, the Iceberg Limit continued to contract and recede northward. The number of icebergs steadily declined with an estimate of 100 remaining on 30 September to end the Ice Year.

Oceanographic Observations

During the 2021 Ice Year, seven Surface Velocity Program drifting (SVP) buoys provided input to modify ocean currents used to drive the IIP iceberg drift model. Four of these SVP buoys were originally deployed by USCGC CAMPBELL for research purposes during the summer of 2020. Three out of four of the CAMPBELL buoys drifted into IIP's OPAREA and were used operationally for iceberg drift modeling during the 2021 Ice Year (**Figure 2-14**). IIP also deployed three SVP buoys aerially in March, April, and May (**Figure 2-15**). Per standard procedure, IIP OPCEN watchstanders downloaded and incorporated hourly buoy data each day to modify current historical vectors with near real-time current data from SVP buoy drift. All buoys were deployed with a 50 m drogue length to best represent current beneath the wind-

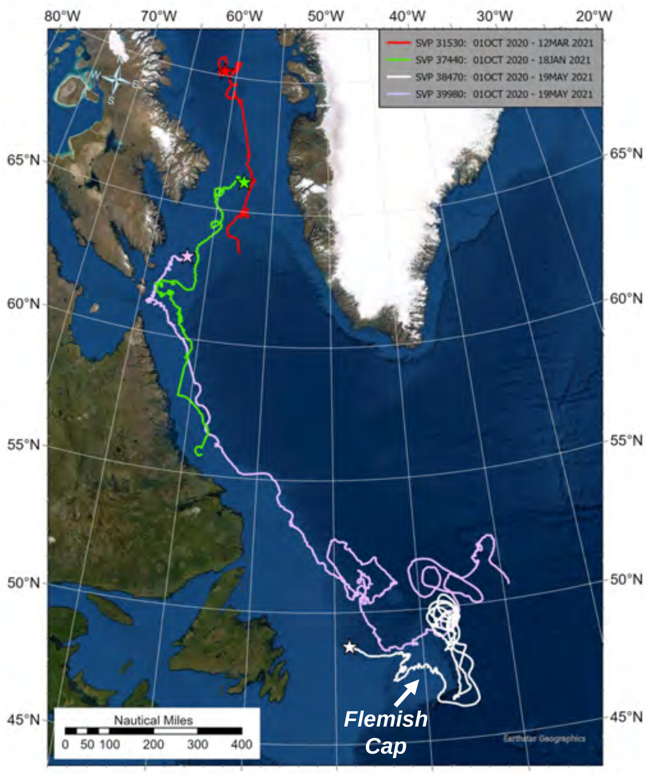

Figure 2-14. SVP buoy tracks for four buoys deployed by USCGC CAMPBELL in summer 2020. Violet- and white-colored tracks show current flow north and across Flemish Cap. Note that only data from the 2021 Ice Year (from 01 October 2020) are shown.

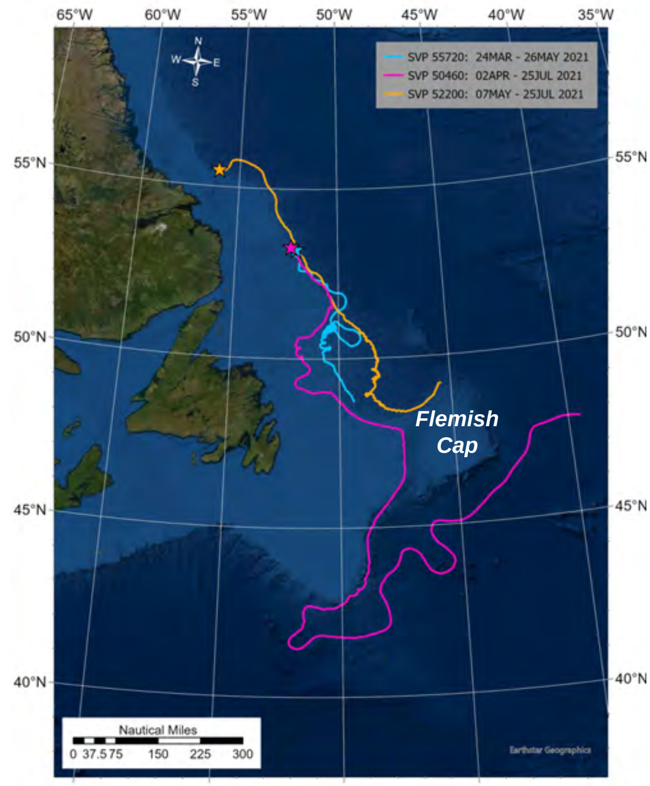

Figure 2-15. SVP drift buoy tracks for three buoys deployed aerially by IIP in March (cyan-colored), April (magenta-colored) and May (orange-colored). Buoy tracks show current flow both north of Flemish Cap and through Flemish Pass.

influenced layer. Of note, IIP supplied USCGC HEALY nine SVP buoys for deployment in Baffin Bay and the Labrador Sea. IIP will monitor these buoys and incorporate into its operations for 2022 as appropriate.

Four SVP buoys drifted south of 48°N, showing the presence of typical current flow around the Grand Banks and Flemish Cap. Three of the four, drifted north of Flemish Cap and continued eastward into the warm North Atlantic Current. This current pattern can bring icebergs, and the Iceberg Limit, well to the east and cause a challenging reconnaissance situation due to the long transit time to the search area. One SVP buoy turned southward through the Flemish Pass and along the eastern edge of the Grand Banks. This flow is normally responsible for transporting icebergs southward causing expansion of the Iceberg Limit and therefore having the greatest impact on transatlantic shipping. The absence of any significant iceberg population south of 48°N reduced the role of the Labrador Current system and considerably reduced the risk of transatlantic vessels encountering icebergs.

In summary, **Figure 2-16** graphically shows the number of icebergs estimated to have drifted south of 48°N by month for the 2021 Ice Year. A solid red line depicts the monthly averages for the entire 121-year record from 1900 through 2020. The monthly average for the modern reconnaissance era (1983-2020) is also included as a solid green line. All 2021 monthly totals were significantly lower than the monthly averages for both periods. **Table 2-1** summarizes extreme iceberg positions, both sighted and drifted by modeling, along with the sighting source. As noted previously, the easternmost sighted and modeled iceberg position occurred on the same date, 11 April. Due to flight restrictions in place during February, IIP established the 27 February Estimated Iceberg Limit slightly further east than the Iceberg Limit established by the 11 April sighting.

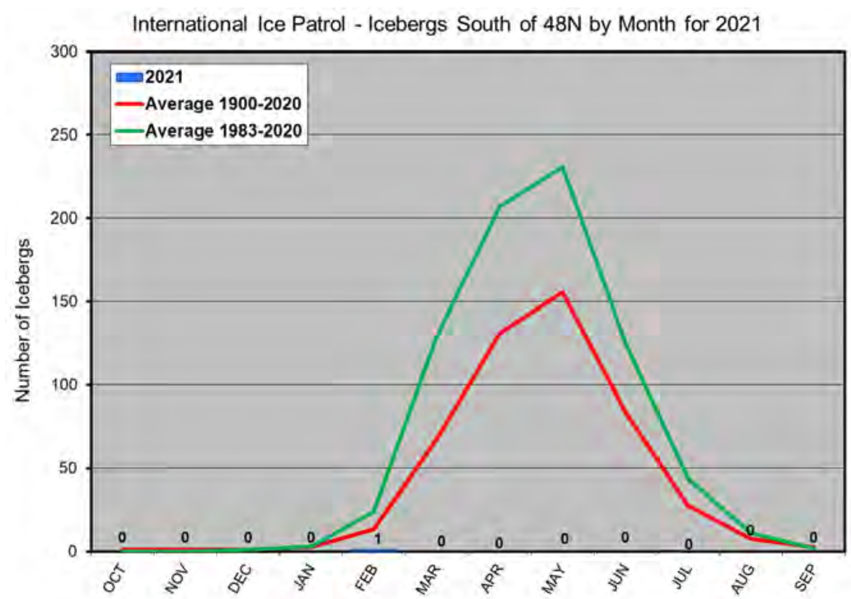

Figure 2-16. Icebergs south of 48°N by month for 2021 (1 total). Red and green solid lines show the monthly averages for the entire historical dataset through the preceding Ice Year (1900-2020) and for the modern reconnaissance era (1983-2020), respectively.

2021 Extreme Icebergs	Sighted				Drifted			
	Source	Date	Latitude	Longitude	Source	Date	Latitude	Longitude
Southern	Satellite (Sentinel-1b)	4-Feb-21	48-45.9N	51-39.9W	Satellite (Sentinel-1b)	27-Feb-21	47-46.9N	49-41.0W
Eastern	Satellite (RCM-3)	11-Apr-21	51-18.7N	49-26.4W	Satellite (RCM-3)	11-Apr-21	51-18.7N	49-26.4W
Western	IIP HC-130J	17-Apr-21	51-02.4N	58-12.0W	IIP HC-130J	21-Apr-21	50-35.9N	58-39.7W

Table 2-1. 2021 extreme sighted and drifted (modeled) iceberg positions by original sighting source and date. Note: western icebergs listed were those used to set the Iceberg Limit in the Gulf of St. Lawrence.

3. Operations Center Summary

The IIP Operations Center (OPCEN) is the hub of IIP's information processing and dissemination. IIP OPCEN watchstanders receive iceberg reports from a variety of sources, process the information, and create daily iceberg warning products that are distributed to mariners. Iceberg reports are received from IRD flights, commercial reconnaissance flights, satellite imagery, and vessel sighting reports. After these reports are received, icebergs are added to IIP's iceberg database and processed through the drift and deterioration models on BAPS. Iceberg Limits are then defined to contain the modeled iceberg positions and daily NAIS warning products are created and distributed to mariners via numerous means.

Products and Broadcasts

IIP and CIS partner to create and distribute two versions of the daily Iceberg Limit in a text and graphic format. IIP's defined Ice Season encompasses the time IIP is actively conducting aerial reconnaissance and generating products; when icebergs typically threaten the transatlantic shipping lanes. This year, the Ice Season ran from 21 January to 28 July (while the deployment period was 03 February – 03 June). CIS published products during the remainder of the 2021 Ice Year, termed "out of season," when the iceberg population is typically found farther north along the Canadian coast. CIS also assumed responsibility for products generation over one month before the typical changeover date of 01 September. This was done to reduce IIP's responsibilities while executing the unit relocation from New London, CT to Suitland, MD.

The first product released daily by IIP is the NAIS-10 bulletin, which is a text bulletin that lists the latitude and longitude points along the Iceberg Limit and sea ice limits. The second product is the NAIS-65, which is a chart that shows the forecasted Iceberg Limit and estimated concentrations of icebergs in 1˚x 1˚ latitude x longitude gridded bins. Examples of the NAIS-65 iceberg charts can be found in Section 7 of this report. Both products include information regarding the most recent reconnaissance, including the date, type, and coverage area. These two products are released between 1830Z and 2130Z and are valid for 0000Z the following day. During the 2021 Ice Season, 100% of iceberg warning products were released on time.

IIP publicly distributes the NAIS iceberg warning products via a variety of methods. The NAIS-10 iceberg bulletin is broadcast over SafetyNET, Navigational Telex (NAVTEX), Simplex Teletype Over Radio (SITOR), and posted online. The NAIS-65 iceberg chart is broadcast over radio facsimile (Radiofax) and posted online. Both products are available on IIP's website:

https://www.navcen.uscg.gov/?pageName=iipProducts.

Additionally, the NAIS-65 iceberg chart is available on the National Weather Service (NWS) Marine Forecast and NOAA Ocean Prediction Center (OPC) sites:

http://tgftp.nws.noaa.gov/fax/marsh.shtml

https://ocean.weather.gov/Atl_tab.php

Keyhole Markup Language (KML) files and ArcGIS shapefiles of the Iceberg Limit and sea ice limit are available on the IIP website for use with compatible charting software. The daily Iceberg Limit is also a displayable layer within NOAA's Arctic Environmental Response Management Application (ERMA) mapping tool:

https://erma.noaa.gov/arctic

Product Changes for 2021

Each year, IIP, in conjunction with CIS and the Danish Meteorological Institute (DMI), reviews products, procedures, and processes to improve content, delivery, and value to the mariner. For 2021, the partners discussed context-based approaches for classifying ambiguous Synthetic Aperture Radar (SAR) targets. Ambiguous targets in satellite images are encountered by analysts on a daily basis, and they must make a decision on whether or not the target is an iceberg or not. Context clues like the general size, distribution, and location of the main iceberg population can help analysts decide if an ambiguous target, especially targets far from the main iceberg population, may be, in fact, an iceberg, a ship, or an anomalous feature in the frame. For example, classifying a target as an iceberg 100 miles south of the Iceberg Limit towards the end of the season while the Iceberg Limit is receding north should stick out as a questionable decision to an analyst. One hundred miles of unnoticed movement (especially in areas where repeat satellite coverage or flights have covered), and an iceberg surviving significantly farther south as the general population melts and recedes are all indications that the target is less likely an iceberg.

Ideas for prototype iceberg warning products were also discussed and were implemented to support the operations of several Coast Guard Cutters, Canadian Coast Guard Ships, and Royal Danish Navy ships (discussed in more detail in **Appendix B**.) The continued challenges imposed by the COVID-19 pandemic did not hinder the daily release of iceberg warning products. COVID-19-related depictions of uncertainty on the product were included at the onset of the pandemic, and are described by IIP (2020). These measures included displaying the Iceberg Limit as "estimated" because of the reduction in aerial reconnaissance attributed to travel restrictions between the U.S. and Canada. This measure was again employed at the beginning of the season before IRDs were based out of St. John's beginning in March of 2021. After IRDs began staging out of St. John's, IIP was again able to source and provide reliable aerial reconnaissance. The Iceberg Limit was therefore depicted without the "estimated" qualifier, and remained so for the balance of the Ice Season.

Iceberg Reports

The IIP OPCEN received reports of icebergs from a variety of sources including IRD flights, commercial flights, ship reports, and satellite reconnaissance from IIP, CIS, and commercial sources (**Figure 3-1**). Collecting and processing iceberg reports from this wide array of sources bolsters IIP's reconnaissance mission. An important source contributing to IIP's successful safety record are the reports received from mariners transiting through the OPAREA. A list of the individual ships that made voluntary iceberg reports during the 2021 Ice Season is compiled in **Appendix A**.

Iceberg reports are received in various formats and are converted into a Standard Iceberg Message (SIM) that contains information on the reported iceberg's time of sighting, position, size, shape, and any other amplifying information. Depending on the reporting source and time of year, SIMs may report zero icebergs or hundreds of icebergs. Overall, during the 2021 Ice Season, IIP received, analyzed, and processed 540 SIMs, 298 of which included iceberg sightings, approximately a 38% decrease in total SIMs from the 2020 Ice Season. In 2020, 77% of SIMs contained iceberg

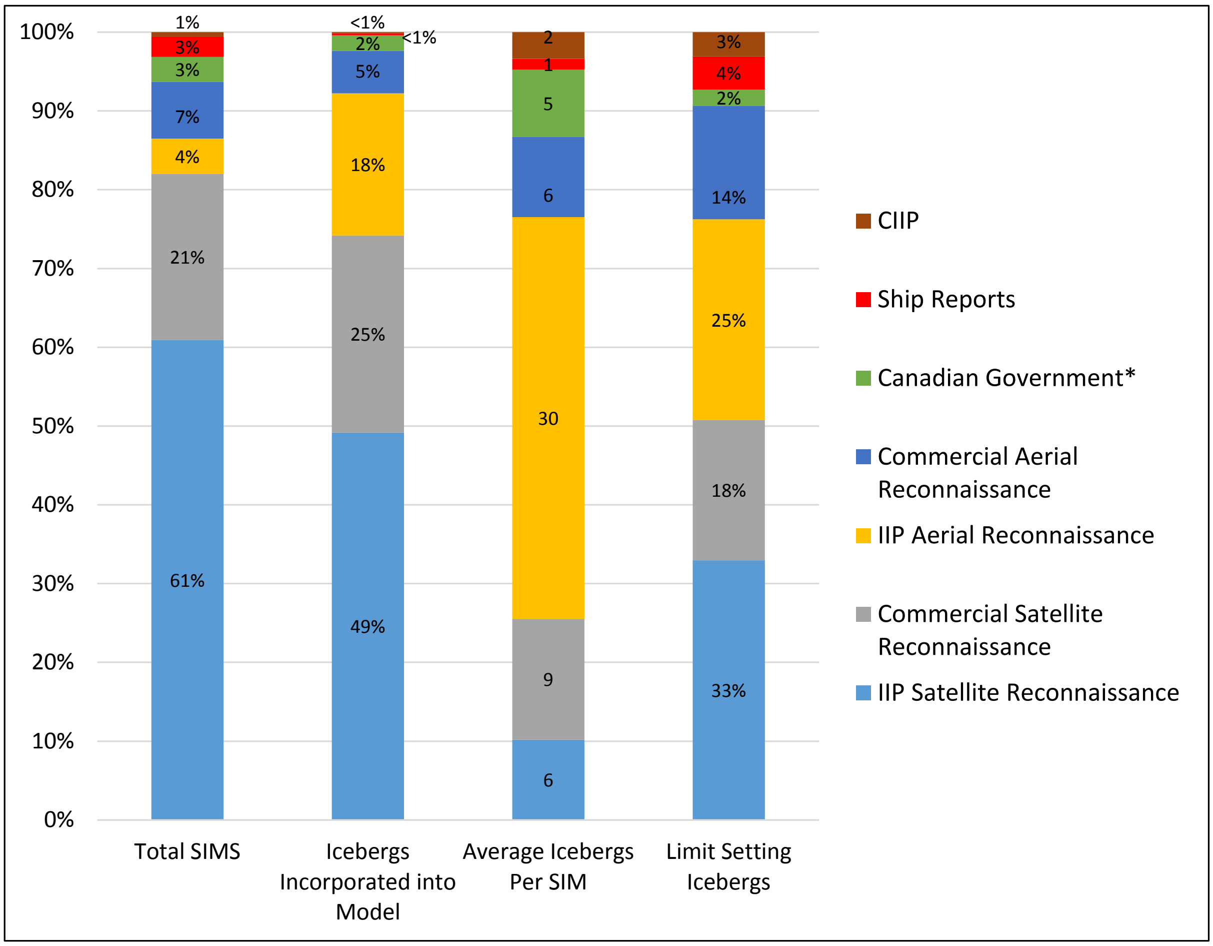

Figure 3-1. 2021 Standard Iceberg Message (SIM) information. The first bar (left) shows the percentage of SIMs received from each source. The second bar shows the percent contribution from each source to the total number of iceberg observations that were included into the model database. The third bar depicts the average number of icebergs per SIM. The fourth bar (right) shows the percentage of limit-setting icebergs reported by each SIM source. Here, the Canadian Government data does not include government-funded commercial reconnaissance which is included in the Commercial Aerial Recon category.

sightings, while only 55% of SIMs contained iceberg sightings in 2021. The significant decrease in iceberg messages (fewest since 2013) is likely attributed to the exceptionally light season. Fewer IIP and commercial flights were needed to monitor the sparse iceberg population (224 combined flights in 2020 vs. 63 in 2021), and ship reports dropped by 71% (down to 14 reports from 49 in 2020). Furthermore, IIP satellite reconnaissance decreased by 28% from 2020. During the height of the COVID-19 pandemic in 2020, IIP's flight activities were severely degraded because of international travel regulations, so more analysts were assigned to interpret satellite imagery on a daily basis to attempt to make up for the reduced aerial reconnaissance. With full crews deploying on aircraft in 2021, that practice was not feasible during the 2021 season, partially explaining the significant drop in IIP satellite SIMs. **Table 3-1** summarizes the number of iceberg reports received by reporting source and **Figure 3-2** shows the number of SIMs received compared with the number of icebergs that drifted south of 48°N for each year since 2012.

At times when manual changes to the Active iceBerg File (ABF) are needed outside of a reconnaissance SIM, icebergs can be added, deleted, or modified using a "CIIP SIM". This is an iceberg message drafted manually by the

Source	Total SIMS	Icebergs Incorporated into Model	Average Icebergs Per SIM	Limit Setting Icebergs
IIP Satellite Reconnaissance	329	1960	6	172
Canadian Government Satellite	0	0	0	0
Commercial Satellite Reconnaissance	114	996	9	93
IIP Aerial Reconnaissance	24	718	30	133
Commercial Aerial Reconnaissance	39	216	6	75
Canadian Government*	17	77	5	11
Ship Reports	14	11	1	22
CIIP	3	6	2	16
Total	**540**	**3984**	**7**	**522**

Table 3-1. Detailed information of 2021 icebergs received from each Standard Iceberg Message (SIM) source. "CIIP SIMs" are those created by IIP watchstanders to correct or modify the iceberg database. * The Canadian Government row does not include Government-funded Commercial Aerial Reconnaissance (which are included in the Commercial Aerial Reconnaissance source) and mostly is made up of Canadian Coast Guard reports.

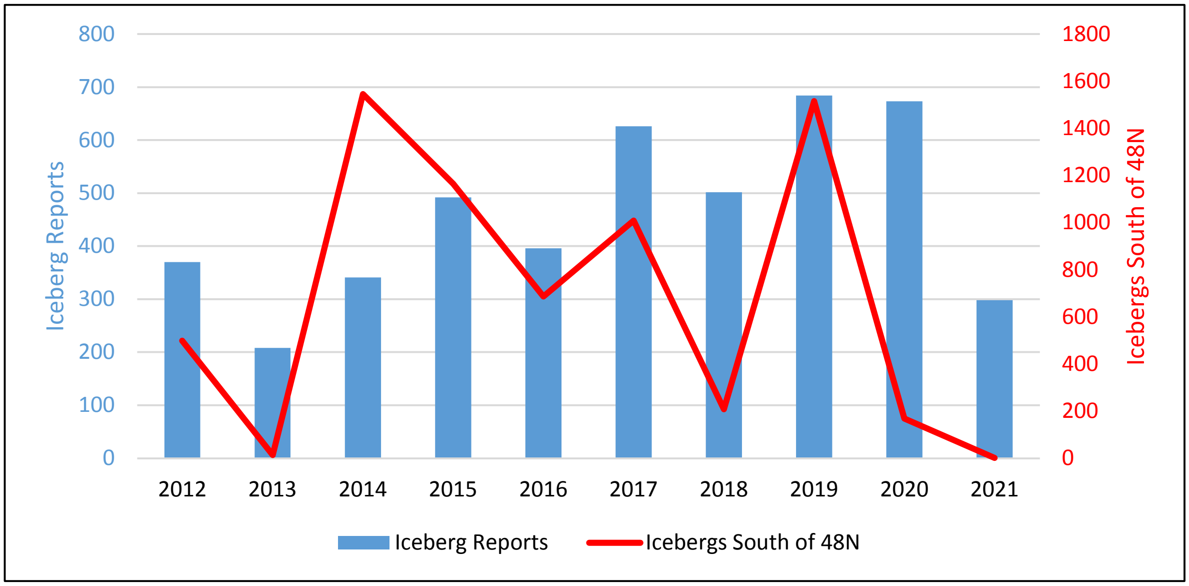

Figure 3-2. Record of the number of Standard Iceberg Messages (SIMs) received that contained iceberg sightings (blue bars) and the number of icebergs observed south of 48˚N (red line) from 2012 to 2021.

watchstander that is input into BAPS as if it was a routine sighting. Examples of scenarios that might warrant a CIIP SIM include extending the life of an iceberg on plot past 30 days, correcting discrepancies in the ABF between IIP and CIS, or if an iceberg was accidentally deleted during the editing process.

A total of 4,517 icebergs, growlers, and radar targets were reported to IIP during the 2021 Ice Season (a 65% decrease from 2020). Of these, 3,984 (88%) were incorporated into the model. IIP watchstanders reviewed each received report for accuracy and validity before the data were entered into BAPS. This included reviewing environmental conditions, other recent reconnaissance, and the detection method of each report. Observed icebergs that can be correlated with already modeled icebergs are "re-sighted" to the model. If they cannot be resighted, they are added to the model. The number of additions corresponds to the number of unique iceberg sightings in a season. This season there were 1,396 additions to the model, which was 31% of all actions taken (add, delete, re-sight) for icebergs in SIMs received throughout the season.

The 12% of reported icebergs that were not incorporated in the model included many that were coincident sightings where the OPCEN received reports of the same iceberg(s) from numerous sources at approximately the same time. In these circumstances, the OPCEN will only ingest the most recent position with the most complete size information and take no action on older or less complete reports. This also includes instances in which multiple agencies analyzed the same satellite frame. In these cases, IIP added all unique icebergs from the two reports but took care to not add the same iceberg twice.

Satellite Reconnaissance

Table 3-1 and **Figure 3-1** show that the majority of icebergs, growlers, and radar targets incorporated into the model were from satellite reconnaissance (Commercial and IIP satellite reconnaissance combined for a total of 2,956 icebergs, growlers, and radar targets added into the model from 443 SIMs). IIP staff processed and analyzed 329 SIMs with 2,105 total icebergs, and C-CORE, a St. John's based company that conducts satellite reconnaissance for icebergs in support of the oil and gas industry, processed 114 SIMs with 996 total icebergs. Both satellite sources together accounted for 82% of the additions to the model, compared to 85% of the additions in 2020. IIP continued to analyze Sentinel-2 multispectral imagery after incorporating the imagery source for the first time operationally in 2020. In conditions when the ocean surface is not obscured by significant cloud, Sentinel-2 is an incredibly useful resource for IIP satellite reconnaissance as it has higher resolution (10 m) than Sentinel-1 (20 m) and results in very high confidence iceberg classifications, especially for icebergs greater than 30 m in length.

Aerial Reconnaissance

This season, IIP conducted 24 reconnaissance flights, which accounted for 718 icebergs, growlers, and radar targets added or resighted into the BAPS model. On average, 30 icebergs were observed per IRD flight (compared to seven icebergs per IRD flight in 2020). The increase in icebergs per flight is due to the return to normal flying operations out of St. John's after resorting to contingency operations out of Cape Cod, MA in 2020.

Commercial aerial reconnaissance accounted for 216 icebergs added to the model; an average of six icebergs observed per flight. It should be noted that IRD flights have a primary mission of iceberg reconnaissance on every sortie; this is not necessarily the case for commercial flights. The commercial aerial reconnaissance data in **Table 3-1** and **Figure 3-1** are from SIM reports made by PAL Aerospace, which was contracted by multiple sources. **Figure 3-3** shows the percentage of PAL Aerospace flights that were dedicated ice flights (funded by CIS or by the oil and gas industry) and other flights that reported icebergs as a by-product of various other missions. More than half (56%) of the total PAL Aerospace flights which reported icebergs were flown for primary missions other

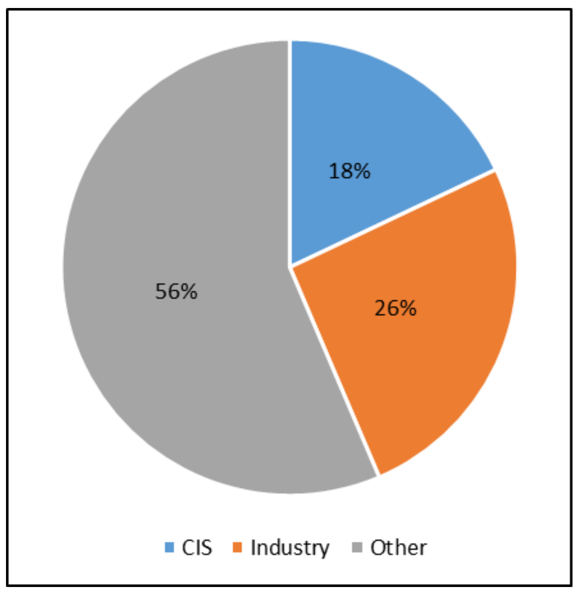

Figure 3-3. The percentage of PAL Aerospace flights by primary mission type that reported icebergs. The "Other" category includes flights that reported icebergs but with a primary mission other than iceberg reconnaissance.

than iceberg reconnaissance. Of note, 26% of flights that reported icebergs were funded by the oil and gas companies concerned with icebergs in the vicinity of the offshore oil rigs (compared to 41% in the 2019 “Extreme” season). The smallest portion, 18%, of PAL Aerospace flights that reported icebergs were funded by CIS specifically for iceberg reconnaissance in areas designated by either IIP or CIS. This was increased from 9% in the 2020 season. The willingness of PAL Aerospace to identify and share iceberg reconnaissance information regardless of funding source demonstrates a notable and significant commitment to maritime safety across the region.

Iceberg Deletions

After they are sighted, icebergs are added or re-sighted in the active iceberg database, and are then drifted and deteriorated via numerical models in BAPS. Icebergs are deleted from the active iceberg database as a result of modeled deterioration, time since last sighting, or IIP aerial reconnaissance results. This season, 452 icebergs were deleted based upon the results of IIP aerial reconnaissance as no icebergs were present in the vicinity of the modeled position when the flight flew overhead. In general, most commercial aerial reconnaissance and satellite reconnaissance do not meet necessary probability of detection standards to meet IIP criteria for deleting icebergs from the database completely.

Given the high confidence associated with Sentinel-2 reconnaissance, IIP continued to rely on Sentinel-2 imagery to justify deletions of modeled icebergs greater than 30 m in length in imagery with no cloud or sea clutter. This practice was only applied to completely cloud-free and low-wind wave frames that provided little to no chance of missing icebergs. In 2021, 54 icebergs were deleted from Sentinel-2 imagery.

PAL Aerospace again flew CIS-funded iceberg reconnaissance flights using IIP-drawn flight plans. This allowed IIP to plan commercial flights based on internal criteria for deleting modeled icebergs from what are typically IRD flights. This season, only eight modeled icebergs were deleted from CIS-funded PAL flights. The remainder of the modeled icebergs were typically deleted due to predicted melting and deterioration.

Limit-Setting Icebergs

Of all the icebergs sighted and modeled by IIP, the most important were the ones that defined the Iceberg Limit. Typically, an average of four icebergs (minimum of one and maximum of seven) set the Iceberg Limit at any time. In the 2021 Ice Season the Iceberg Limit stretched approximately 195 NM east of St. John’s at its maximum extent of 47°55’W on 27 February, and approximately 155 NM south of St. John’s to 46°35’N on the same day.

Compared to 2020, PAL Aerospace flights decreased as a reporting source of limit-setting icebergs from 26% to 14%, and IIP aerial reconnaissance increased from 5% to 25%. Reconnaissance from satellite imagery accounted for 51% of limit-setting icebergs, compared to 64% in 2020.

Although a large number of icebergs incorporated into the model and setting the Iceberg Limit were observed by satellite, satellite reconnaissance using SAR is unable to reliably determine ice-free conditions due to low confidence in the ability to avoid false positives and false negatives. A false positive result is one in which a target is determined to be an iceberg where, in fact, there is not one. This can result in the needless expansion of the Iceberg Limit, negatively impacting shipping without a corresponding increase in safety. Of greater concern, are false-negatives; for which it is determined there are no icebergs where, in fact, icebergs exist. This situation is especially dangerous and can result in the Iceberg Limit not encapsulating the iceberg hazard, placing ships in harm's way. Continued development of satellite imagery analysis is aimed at reducing these errors through increased understanding of the impact of satellite parameters, image quality, and environmental conditions on valid positive detection and classification of targets. Though there is much higher confidence associated with visible imagery, such as Sentinel-2, the Iceberg Limit is typically located offshore, outside of Sentinel-2 coverage.

Given these considerations, the more reliable method for monitoring the Iceberg Limit remains aerial reconnaissance. Observing the exact location of limit-setting icebergs, especially those in the vicinity of the transatlantic shipping lanes, continues to be a critical part of completing IIP's mission.

IIP Protocol for Icebergs Reported Outside of the Iceberg Limit

A total of one report of an iceberg or radar target outside of the published Iceberg Limit was received throughout the 2021 Ice Year. This report was received while IIP was not producing products.

In the event that an iceberg or radar target is reported outside the published Iceberg Limit, the OPCEN Duty Watchstander (DWS) takes prompt action to ensure that the maritime community is quickly notified and the NAIS products are updated.

Typically, the first step is for the DWS to notify the Canadian Coast Guard Maritime Communication and Traffic Service (MCTS) Port aux Basques. In turn, MCTS issues a Navigational Warning (NAVWARN) which is the primary means of relaying critical iceberg information to the transatlantic shipping community and provides the IIP watchstanders with time to transmit revised products. The NAVWARN is sent via NAVTEX and forwarded to the U.S. National Geospatial-Intelligence Agency (NGA). NGA broadcasts the message as a Navigational Area (NAVAREA) IV warning message over SafetyNET and posts it to their website. NAVAREA IV is one of 21 Navigational Areas, designated by the World Wide Navigational Warning Service (WWNWS); the United States is the co-ordinator for NAVAREA IV.

If the report of an iceberg or radar target outside the Iceberg Limit is received by IIP during office hours (1200Z – 0000Z), products will be immediately revised by the OPCEN valid for 1200Z or 0000Z depending on the time received. If the report reaches IIP after office hours, products will be revised no later than 1400Z the following morning valid for 1200Z.

While SAR satellites have proven to be able to detect icebergs, classifying targets as an iceberg, vessel, or another item such as marine life, fishing gear, or weather feature remains a challenge. SAR returns are quite open to interpretation. IIP takes a conservative approach to ensure that the maritime community receives a timely warning of any possible target outside of the Iceberg Limit and keeps the target plotted in the model until subsequent reconnaissance could verify its status. IIP relies on coordination with other data sources such as vessel Automatic Identification System (AIS) and a collaborative exchange with Coast Guard Intelligence to help classify ambiguous targets as icebergs or ships. Access to this data and partnerships will continue to be key factors in space-borne reconnaissance efforts.

In past seasons, several cases of icebergs outside the Iceberg Limit were closely linked with the sea ice limit, where icebergs had been undetected within the sea ice limit, but outside the Iceberg Limit in "open drift" sea ice concentrations or greater (four-tenths sea ice concentration or more) of gray or gray-white ice. In response to this, IIP and CIS worked closely together from December to February tracking the leading edge of the gray and gray-white sea ice drifting south from Baffin Bay. This sea ice makes identification of icebergs from satellite challenging though it is very likely to include icebergs. Therefore, this leading edge was included within the Iceberg Limit as if it contained icebergs. IIP attributes this reduction in the number of icebergs reported outside of the Iceberg Limit early in the Ice Year to the close cooperation with CIS.

Out of Season Icebergs and Radar Targets outside the Iceberg Limit

On September 9, 2021, a PAL Aerospace flight reported an iceberg outside the Iceberg Limit. The target was observed 265 NM outside of the Iceberg Limit as seen in **Figure 3-4**. A NAVWARN was issued and revised products were published which resulted in a significant expansion of the Iceberg Limit. The following morning, the original products were republished as the iceberg was discovered to be an iceberg message coding error.

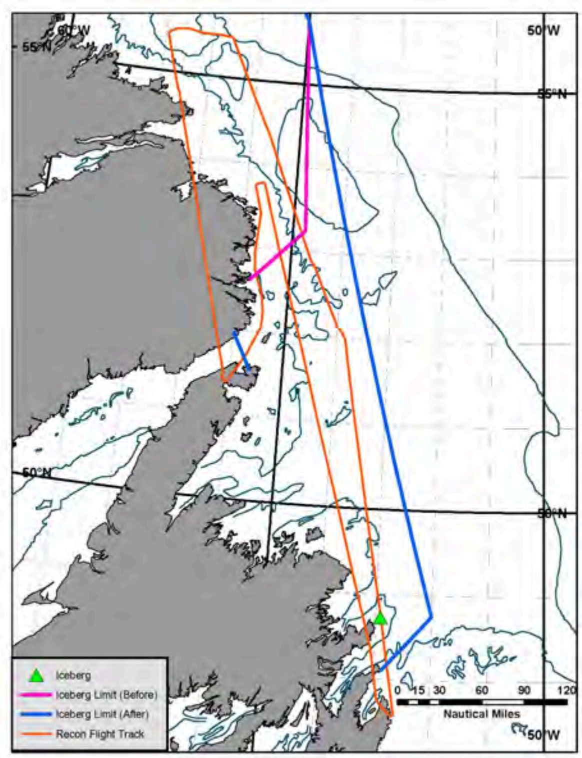

Figure 3-4. On September 9, 2021, a PAL Aerospace flight reported an iceberg outside the limit (green triangle). The following morning, the radar target was discovered to be an iceberg message coding error.

4. Iceberg Reconnaissance Operations

Ice Reconnaissance Detachment

The IRD, a sub-unit under CIIP, partners with ASEC to conduct aerial iceberg reconnaissance. During the 2021 Ice Season, nine IRDs deployed to observe and report icebergs, sea ice, and oceanographic conditions in the North Atlantic Ocean. All observations from the IRDs were transmitted to the IIP OPCEN in New London, CT for processing and entry into BAPS. These observations provide critical Iceberg Limit information used by the IIP OPCEN to create the NAIS iceberg warning products that are distributed to the maritime community on a daily basis.

Over the 2021 Ice Season, IIP and ASEC crews deployed for 69 days, conducting 24 iceberg reconnaissance sorties on HC-130J aircraft. The 2021 flight season spanned 121 days; 23 days shorter than the five-year (2016-2020) average of 144 days. The first IRD departed on 03 February, with the last IRD returning on 03 June. The number of sorties flown this season increased from 17 to 24, a 41% increase. This was due to travel restrictions imposed in response to the COVID-19 pandemic during the 2020 Ice Season. In 2021, only the first three IRDs of the season were conducted out of Coast Guard Air Station Cape Cod (ASCC). The remaining six were based out of St. John's, Newfoundland. This allowed IIP to increase the amount of time it spent conducting aerial reconnaissance due to the reduced transit hours spent flying from ASCC. As a result of this change, 60% of all flight hours flown out of St. John's were patrol hours. In comparison, the flights out of ASCC last season were 59% transit hours to and from the OPAREA. **Table 4-1** contains a summary of operations for each IRD.

IRD	Deployed Days	Iceberg Patrols	Transit Flights	Patrols en Route	Logistics Flights	Flight Hours
1	6	0	2	0	0	3.8
2	8	2	2	0	2	35.0
3	6	3	2	0	0	30.0
4	9	2	2	0	0	26.8
5	4	2	2	0	0	25.4
6	9	4	2	0	0	41.4
7	9	4	2	0	1	46.8
8	9	5	2	0	0	48.3
9	9	2	2	0	1	35.8
10	0	0	0	0	0	0.0
11	0	0	0	0	0	0.0
12	0	0	0	0	0	0.0
Total	**69**	**24**	**18**	**0**	**4**	**293.3**

Table 4-1. An overview of Ice Reconnaissance Detachment (IRD) days and flight hours used during the scheduled IRD's for the 2021 Ice Season.

Aerial Iceberg Reconnaissance

HC-130J aircraft equipped with two radars and an Automatic Identification System (AIS) integrated into the mission system suite were used to conduct aerial iceberg reconnaissance. The ELTA-2022 360° X-Band (ELTA) surface search radar is capable of detecting and discriminating surface targets. The HC-130J Tactical Transport Weather Radar (APN-241) is capable of detecting surface targets, but cannot discriminate or classify targets as an iceberg, ship, or other object. The AIS receives information transmitted by AIS-equipped ships for positive identification, and is used to differentiate vessels from icebergs on the radar.

The ability to employ ELTA radar significantly enhances reconnaissance capabilities. The 360° coverage provided by the ELTA radar supports the use of up to 30 NM track spacing for patrol planning. Historically, 25 NM was used for standard flight planning and 30 NM track spacing was reserved for flying in ideal conditions with calm sea states. In the 2021 season, IIP planned all flights at 30 NM while still maintaining a 95% probability of detection (POD) of small icebergs (15 to 60m). Planning flights at 30 NM track spacing began as a method to maximize coverage on the shorter IRD flights based out of Cape Cod, but was maintained after the return to St. John's in absence of any data that suggested the sensors (camera and radar) were any less effective at the increased track spacing.

If the ELTA radar is inoperable, the IRD must fly patrols under "visual-only" specifications using 10 NM track spacing, covering 40% less area in a given time period. Further, visual-only patrols require areas with pristine environmental conditions; clear skies and visibility to the surface, which rarely occur in IIP's meteorologically active OPAREA.

During the 2021 Ice Season, all IRDs were flown with Minotaur Mission System (MMS)-equipped aircraft. The MMS is a software and hardware suite that allows for onboard networking of cameras, radar sensors, navigational instruments, and communications.

IRD crews also utilize the Inverse Synthetic Aperture Radar (ISAR) onboard the HC-130J. This technique generates a high-resolution image of a target using the movement of the target to create an image frame. ISAR imagery is analogous to the SAR imagery IIP receives from satellites in that it is a still image created from radar energy pulses. The key difference between the two technologies is that SAR sensors onboard orbiting satellites rely on the movement of the sensor in orbit to create a "synthetic" image, while the ISAR uses the movement of the target to generate the image. This technology has proven extremely useful for identifying icebergs and distinguishing between icebergs and non-AIS ships in poor visibility.

IRD Operational Summary

The first IRD of 2021 began on 03 February out of Air Station Cape Cod (airport code KFMH). Due to delays in the required COVID testing, the aircrew from Air Station Elizabeth City (airport code KECG) did not arrive at KFMH until 05 February. On 06 February, IRD 1 was grounded at KFMH due to icing and freezing precipitation in the patrol area. Forecasted snow of 5-8" at KFMH on 07 February caused the aircrew to return to KECG later that day. IIP and ASEC personnel planned to return to KFMH on 08

February. This return was delayed again due to forecasted weather that would impact the IRD returning to KFMH. The initial weather system that brought the snowfall to the northeast was now a stationary low-pressure system to the east of Newfoundland. Due to the negative impact to large portions of the operational area through 11 February, IIP decided to terminate IRD 1.

IRD 2 was scheduled to begin on 17 February but was delayed again due to the wait for COVID testing results. The IIP crew traveled to KFMH on 18 February but the aircrew was grounded at KECG due forecasted snow at Cape Cod and the inability to hangar the plane there. Snow continued through 19 February. The aircrew took off on 20 February with the intent to pick up the IIP crew en route to the patrol area. Shortly after takeoff the plane suffered an Automatic Thrust Control System issue and returned to KECG. Due to the expected lengthy repair, equipment was moved to another aircraft which departed for KFMH. The aircraft arrived at KFMH that afternoon, but due to the delay, the patrol scheduled for 20 February was cancelled. Furthermore, during transit, the aircraft noted a failure of the rudder trim but was able to land at KFMH. That evening, repair parts were flown to KFMH from KECG. Knowing that repairs would have to be effected the following day combined with the knowledge of the long transit times from KFMH to the patrol area led to the decision to cancel the patrol for the following day (21 February). On the afternoon of 21 February, during the repairs, a failure of an avionics computer component (Bus Adapter Unit) was identified, thus delaying the required post-repair test flight. On 22 February, the test flight was once again delayed due to icing on the aircraft. Once the successful test flight was completed, it was determined that it was too late to arrive in the operational area prior to sunset and conduct reconnaissance. On 23 February, a patrol of the 1,000 m bathymetric contour in the vicinity of Hamilton Bank and the western Iceberg Limit was conducted. The patrol had excellent visual and radar coverage throughout and identified a total of five icebergs. On 24 February, another patrol was conducted along the 1,000 m bathymetric contour between 60°N and 56°N. A total of 45 icebergs were identified. A patrol was scheduled for 25 February, but upon landing, post flight maintenance identified an issue with the #2 engine. Parts were flown up that night with repairs taking the following day. IIP crew returned to New London on 25 February with the ASEC crew returning to KECG on 26 February.

IRD 3 was scheduled to begin on 03 March but crews did not arrive at KFMH until 04 March due to delays in COVID testing. No patrol was done on 05 March due to freezing precipitation and low level jets in the primary and secondary patrol areas. An outer contour patrol was conducted on 06 March which included the southern Iceberg Limit as well as the Strait of Belle Isle. Zero icebergs were identified during the patrol. On 07 March, a patrol was conducted near the 1,000 m bathymetric contour near 55°N. A total of seven icebergs were identified by the IRD crew. On 08 March, a patrol of the eastern Iceberg Limit and interior was performed. Low visibility and changing icing levels were encountered through a majority of the flight. Zero icebergs were identified during the flight. Due to the low iceberg population and the three identified patrol areas having already been searched, IRD 3 returned early on 09 March.

IRD 4 marked the return of patrols out of St. John's, NL (CYYT) for the first time since March 2020. On 17 March, the ASEC crew picked up IIP in Groton, CT (KGON) and flew to St. John's. This also marked the first on-time departure for an IRD this season. The following day, 18 March, a patrol of the interior was completed including the area of Hamilton Bank. A total of 15 icebergs were identified. On 19 March, the flight was grounded due a 75 kt low-level jet over CYYT. A crew rest day was taken due to the weather. On 20 March, a planned patrol of the northern area was aborted when during takeoff a failure of an anti-icing valve was noticed. The repair part was sent via commercial air due to lack of available aircraft from KECG to deliver the part directly to CYYT. The part did not arrive until 23 March and repairs were immediately completed. A planned afternoon patrol was cancelled due to winds greater than 30 kts restricting the opening of the hangar doors. On 24 March, a patrol of the southern Iceberg Limit identified five icebergs. The first SVP buoy of the season was also deployed in position 53°14'N 052°02'W. IRD 4 returned the following day.

IRD 5 began on 31 March and ASEC and IIP personnel arrived in CYYT for the second time this season. On 01 April, a southern Iceberg Limit patrol proceeding into the interior found 18 icebergs. The next day's patrol on 02 April delayed takeoff until 1400Z to take advantage of a visibility window later in the day. The flight followed the 1,000 m contour up to 56°N, and recorded 16 icebergs. An SVP buoy was also deployed on this patrol in position 53°17'N 052°17'W. After completing this patrol, the Aircraft Commander and flight planners at the IIP OPCEN shared concerns that weather conditions in the area were deteriorating rapidly and the likelihood of being able to fly again during IRD 5 was low. This factor combined with the fact that the whole patrol area had been covered by two flights in two days led to the decision to cancel the remainder of the deployment and the IRD members transited back to KGON/KECG on 03 April. With the benefit of hindsight and a review of the actual weather conditions at CYYT this proved to be a good decision.

IRD 6 began on 14 April. After the transit to CYYT, a southeastern Iceberg Limit patrol on 15 April identified 52 targets, only eight of which were icebergs. Gusting winds over 30 kts at CYYT on 16 April persisted throughout the day and prevented the hangar doors from opening. Conditions on 17 April were favorable for a patrol of the western Iceberg Limit and Hamilton Bank. 40 icebergs were sighted. On 18 April, a low pressure system impacted CYYT throughout the day, bringing 200-ft ceilings and severe icing and turbulence. Maintenance was performed instead of a patrol. On 19 April, a Northern Search assessed the population density of icebergs flowing down the Labrador coast and found 39 Icebergs. The following day, 20 April, winds on the ground were gusting to 35 kts, which again prevented the hangar doors from opening. A crew rest day was taken. The final flight of the deployment was a patrol of the western Iceberg Limit and Hamilton Bank. 55 icebergs were sighted. IRD 6 concluded with the transit home on 22 April.

IRD 7 began on 28 April. A patrol on 29 April found two icebergs in the vicinity of the western Iceberg Limit. A patrol of the southeastern Iceberg Limit and interior on the following day did not observe any icebergs. On 01 May, an oil leak on the #3 propeller was discovered during routine maintenance. The plane was grounded and a logistics flight took off from Elizabeth City on the same day to bring a replacement prop. The following day, repairs were completed, but the required engine run-up could not be conducted because of high winds preventing the hangar door from being opened. After repairs were completed, all hands took a 24-hour rest period and returned to complete the required engine testing on 03 May. The engine testing was successful, however winds increased throughout the day to the point where the hangar was unlikely to be able to open later in the evening if a patrol were to be flown. The patrol was cancelled to avoid the potential of exposing the aircraft to freezing temperatures overnight. On 04 May, another patrol of the western Iceberg Limit and interior Newfoundland coast enjoyed excellent conditions and sighted eight icebergs. A Northern Survey on the next day spotted 39 icebergs and was the last patrol before the transit home on 06 May.

IRD 8 began on 12 May. A Northern Search up to 60°N on 13 May found 28 icebergs and included diverts for three very large icebergs. Low ceilings and moderate icing throughout the OPAREA grounded the aircraft on 14 May, and a routine maintenance day was taken in lieu of a patrol. A Northern Search patrol up to 57°N on 15 May found 71 icebergs. Patrols of the eastern Iceberg Limit and western Iceberg Limit on 16 and 17 May sighted 25 and 71 icebergs, respectively. 18 May was taken as a crew rest day since a cold front was approaching the area and the weather forecast for 19 May was highly favorable for a patrol. A unique patrol on 19 May flew from 60°N to 65°N to investigate a large ice island fragment. The patrol was unique in that it was planned outside of the normal IIP OPAREA, but ended up being critical for spotting an ice island fragment over one nautical mile in length that had previously gone undetected in satellite imagery. The flight path was drawn to investigate a completely different ice island fragment that had been successfully located in satellite imagery, and it wasn't confirmed until a day later that the sighted ice island fragment was, in fact, a different iceberg than the one the flight was drawn to investigate. IRD 8 ended with a transit home on 20 May.

26 May marked the start of IRD 9 and what would later be determined to be the last deployment of the season. High winds at CYYT prevented opening the hangar door on the first patrol day, so a crew rest day was taken. Conditions were favorable on 28 May, and the patrol covered the entirety of the limit south of 54°N spotting 54 icebergs. Winds at CYYT on 29 May were gusting above 40 kts, so a maintenance day was taken. A routine inspection during that maintenance day led to the discovery of a tear in the rubber de-icing boot. The casualty grounded the aircraft, and a replacement part could not be flown into CYYT until two days later. Repairs were affected, but winds again came to gust over 40 kts early on 01 June. After four days on the ground, a Northern Survey patrol up to 60°N was planned as the last patrol of season on 02 June. Between the two flights of the IRD, the entire Iceberg Limit Area was covered and the exceptionally light iceberg season combined with comprehensive

coverage of the area led to the decision to close the season early.

Figure 4-1 shows a breakdown of IIP's deployment days during the 2021 Ice Season in seven categories: Operations, Transit, Weather, Maintenance, Crew Rest, Training, and Other.

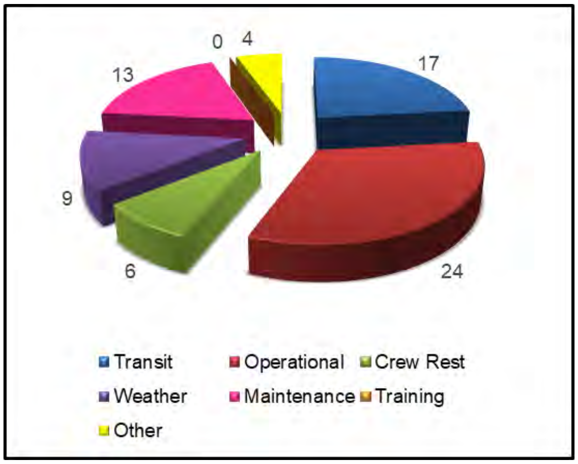

Figure 4-1. Utilization of days for the 2021 Ice Season.

Examples of days in the "Other" category include time taken for partner meetings, higher priority tasking of the aircraft (i.e. search and rescue) while on an IRD, and logistics flights. In 2021, the "Other" category was made up of four logistics flights to bring repair parts to the deployment location. In accordance with USCG regulations, the IRD normally takes one crew rest day as well as one maintenance day per nine day deployment; otherwise, the intent is to fly every day. Operational time took up the largest fraction of deployment days in 2021 (33%).

The prevailing OPAREA weather contributes significantly to the number and effectiveness of reconnaissance patrols. In 2021, weather conditions prevented patrols on 12% of the days deployed. When deployed to St. John's, the IRD crew capitalized on poor weather opportunities whenever possible to meet the required crew rest and maintenance days, in order to maximize operational iceberg reconnaissance on favorable weather days.

Unscheduled maintenance and mechanical issues proved to be the largest sink of lost patrol time. Ten out of the 73 days (which include the 69 deployment days and the four additional logistics that were required) were allotted to unscheduled maintenance or waiting for replacement parts to arrive at the deployment location. IRDs based out of both KFMH and CYYT experienced logistics challenges with transporting spare parts to the deployed aircraft.

Table 4-2 shows a further breakdown of the crew rest and maintenance days into days taken when the weather conditions did not permit flights (opportunity days), days taken when conditions permitted flights, but required crew rest or maintenance had to be taken (scheduled) or days taken because of crew or maintenance issues (unscheduled).

	Crew Rest	Aircraft Maintenance
Opportunity (Weather)	4	3
Scheduled	2	0
Unscheduled	0	10
Total	6	13

Table 4-2. Crew rest and aircraft maintenance days for the 2021 Ice Season.

IRD Iceberg Detections

IRD personnel detected 811 icebergs over the nine IRDs in the 2021 Ice Season. Twelve IRDs were initially scheduled, but the final three deployments were cancelled due to the lack of a need to continue flying in the exceptionally light season. Of the 811 icebergs sighted, 718 were incorporated into BAPS, which accounted for 18% of the total icebergs added during the 2021 Ice Season. No action was taken on a total of 93 icebergs. This was either due to the reconnaissance occurring outside the boundaries of the model or icebergs merged from another SIM the same day. The 18% of icebergs incorporated into BAPS from IRDs is significantly higher than the 1% in 2020, which was the season more significantly impacted by COVID-19 related international travel restrictions.

IIP classified 2021 a ‘Light’ season with respect to the number of icebergs crossing south of 48ºN (only one single iceberg), and also with respect to the total area encompassed by the iceberg limits. The first three IRDs were based out of Cape Cod, MA. This meant longer transit times to/from the OPAREA, and it also meant that the northern portion of the OPAREA (the area typically with the most icebergs) was less accessible. IRD flights proved they could reach up 60°N out of Cape Cod during IRD 2 of 2021, but the short on scene time reduced effectiveness. For flights out of ASCC, six-hour transit times to reach and return from the OPAREA meant on-scene patrol time was reduced significantly (approximately 2-3 hours per patrol). Consequently, individual patrols almost exclusively focused on verifying deletions in reconnaissance areas near the southern and eastern Iceberg Limits, IIP’s highest priority reconnaissance areas.

IRDs 1 through 3 accounted for five of the 24 patrols for the 2021 Ice Season. Three of these flights focused on the 1,000 m bathymetric contour, with the other two flights covering the western Iceberg Limit and a short Northern Survey. 57 icebergs were detected over these five flights, and the criticality of these iceberg reports remained high as they served to verify the accuracy of the Iceberg Limits.

Figure 2-4, in the Ice and Environmental Conditions Section (**Section 2**), depicts an example of a daily iceberg limit compared to a bi-weekly median and extreme limit from 1991-2020. For the 2021 Ice Season, daily limits below 50°N were consistently well contained by the corresponding median limits from the end of March through the end of the season. This, in conjunction with the limitations associated with operating from ASCC for IRDs 1 through 3, meant that most flights had longer transits, covered less patrol area, and flew primarily in areas where iceberg populations were expected to be low to verify the presence of one or two critical limit-setting icebergs.

During IRDs, icebergs are detected in one of three ways: (1) with both radar and visual, (2) radar only, or (3) visual only. This year, 69% of the icebergs were detected by both radar observations and visual sightings (67% in 2020). 8% of the remaining icebergs were detected by radar only (3% in 2020), and 23% were detected visually only (30% in 2020) **(Figure 4-2).**

These proportions closely mirrored the 2020 season, but in the context of the last 10 years the fraction of icebergs detected both by radar and visually is high (**Table 4-3).**

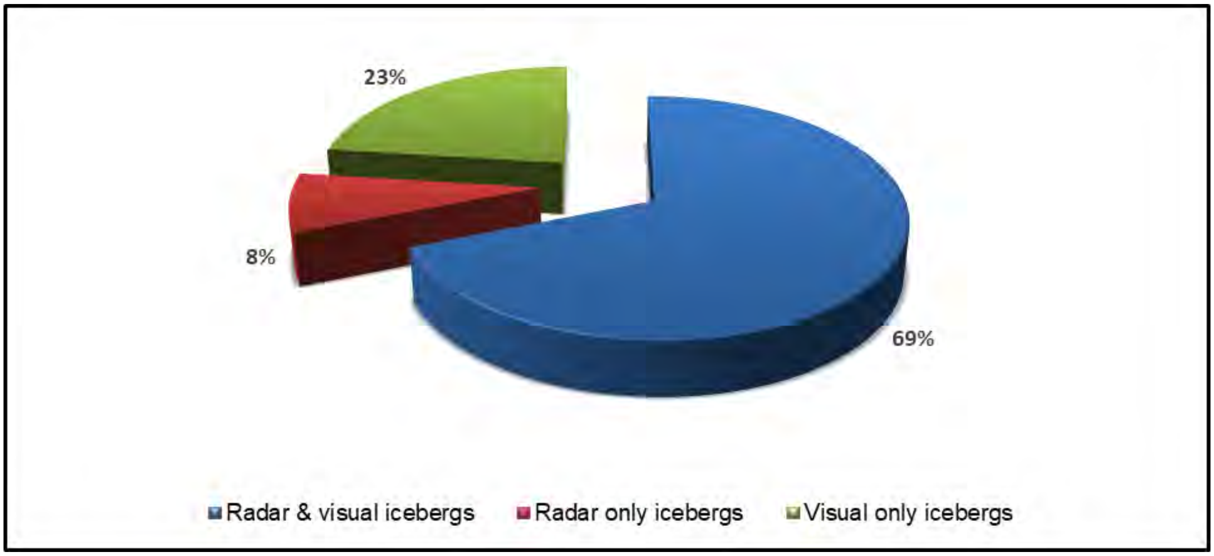

Figure 4-2. Ice Reconnaissance Detachment iceberg detection methods for the 2021 Reconnaissance Season.

Year	Radar & visual icebergs	Radar only icebergs	Visual only icebergs
2012	47%	10%	43%
2013	46%	17%	37%
2014	43%	5%	52%
2015	29%	45%	26%
2016	20%	32%	48%
2017	21%	39%	40%
2018	24%	31%	45%
2019	44%	26%	30%
2020	67%	3%	30%
2021	69%	8%	23%

Table 4-3. IRD iceberg detections by method from over the last ten years (2012-2021).

This is because icebergs identified via the aircraft's onboard Electro-Optical Infrared (EOIR) camera and via the ELTA radar are now categorized as radar and visual sightings. The camera's ability to detect targets from much farther ranges than typical human visual observation and high confidence with which icebergs are identified was the foundation for its reclassification as a visual reconnaissance source in 2020, while its ability to determine a high confidence position fit in the electronic source category.

Further contributing to the increase of radar-detected bergs over 2020 was the continued training for IRD personnel on inverse synthetic aperture radar (ISAR). This capability continues to serve as an exceptionally useful tool for finding and identifying iceberg targets within sea ice.

Visual-only detection still accounted for a significant portion of total icebergs sighted. IIP personnel employ a two-tiered approach in areas of favorable environmental conditions, focusing visual observations close to the aircraft and radar observations away from the flight path enabling maximum detection efficiency. This tactic often resulted in visual-only iceberg detections within the range of the radar (and even detected on radar), but in those scenarios observers were recording high volumes of icebergs and there was not a need to have the exact radar position or detection information recorded.

2021 Flight Hours

As in previous seasons, IIP was allotted 500 Maritime Patrol Aircraft flight hours for its operation during the 2021 Ice Season. IIP used 293.3 hours in 2021. This total includes patrol, transit, and logistics hours attributed to the IIP mission. **Figure 4-3** shows the breakdown of these hours for 2021 compared to the past five Ice Seasons into three categories: transit hours, patrol hours, and logistic hours.

Transit hours are the hours the aircraft is transiting to and from specific locations in support of the IIP mission, without conducting reconnaissance. These flights are generally between Elizabeth City, NC and St. John's, NL, with a brief stop in Groton, CT to onload IIP personnel and equipment. At the beginning of the season, when IRD's were flying out of Cape Cod, IIP personnel with IRD equipment drove to meet the aircraft in Sandwich, MA. There were 75.1 hours used this season for transits.

Patrol hours are those hours associated with iceberg reconnaissance including the flight time to and from the reconnaissance area. IIP flew 187.4 patrol hours this season. When a patrol is conducted during a regularly planned transit flight, such as a patrol while transiting back to Groton, CT, the hours are counted as patrol hours vice transit hours and the flight is termed a patrol en route. There were no patrols en route during this season. For operations out of Cape Cod, IIP personnel spent much longer times during a patrol flying to and from the OPAREA. In 2021, 80.7 hours out of the logged 187.4 patrol hours (43%) were used for flying to/from the OPAREA. On average, it took two hours to fly to/from the OPAREA when operating out of St. John's. When flying out of Cape Cod, it took an average of seven hours to reach and return from the OPAREA. This made the typical nine-hour endurance of the aircraft much less efficient. **Figure 4-4** depicts a breakdown of flight hours for the 2021 season by IRD.

Logistics hours are the hours used to support the IIP mission, but do

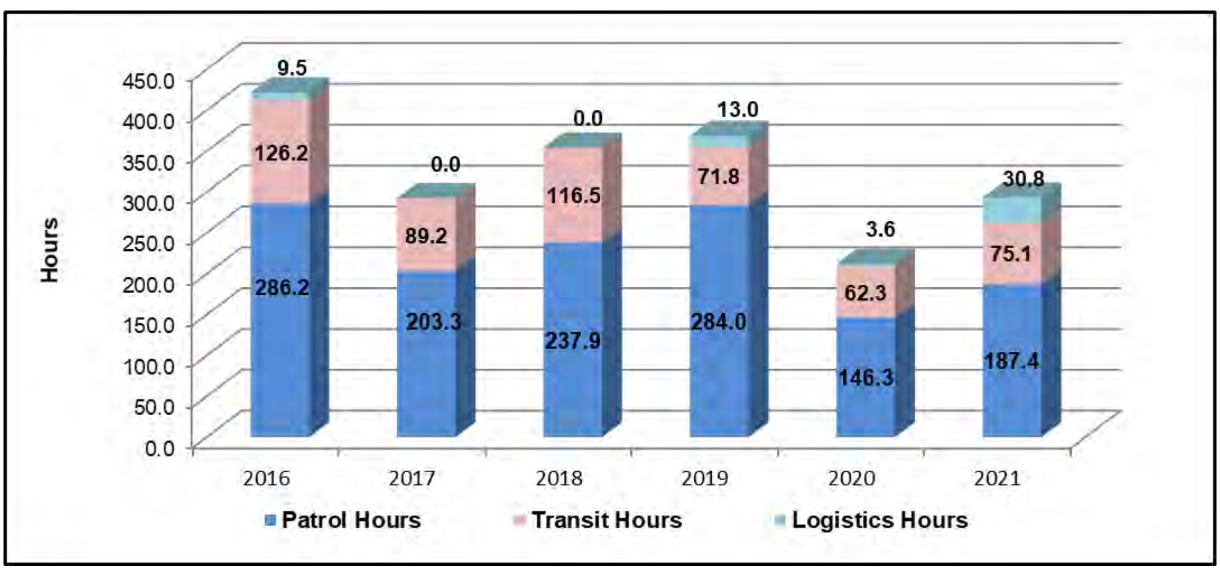

Figure 4-3. Flight hours broken down by patrol, transit, and logistics hours over the past six years.

not fall into the previous two categories. Logistic hours accrue when a Coast Guard aircraft is used to transport parts for an aircraft deployed on an IIP mission. This season there were four logistics flights. One benefit to deploying out of Cape Cod was the ease with which logistics flights could reach the Fixed Base of Operations (FBO) without major schedule changes. Conversely, a logistics flight needed for transporting parts to CYYT was flown on the Memorial Day holiday and required a significant alteration to ASEC's scheduled missions and ready crew roster.

The spatial and temporal distribution of icebergs, as well as the quantity of icebergs drifting south of 48ºN, all contribute to the amount of reconnais-

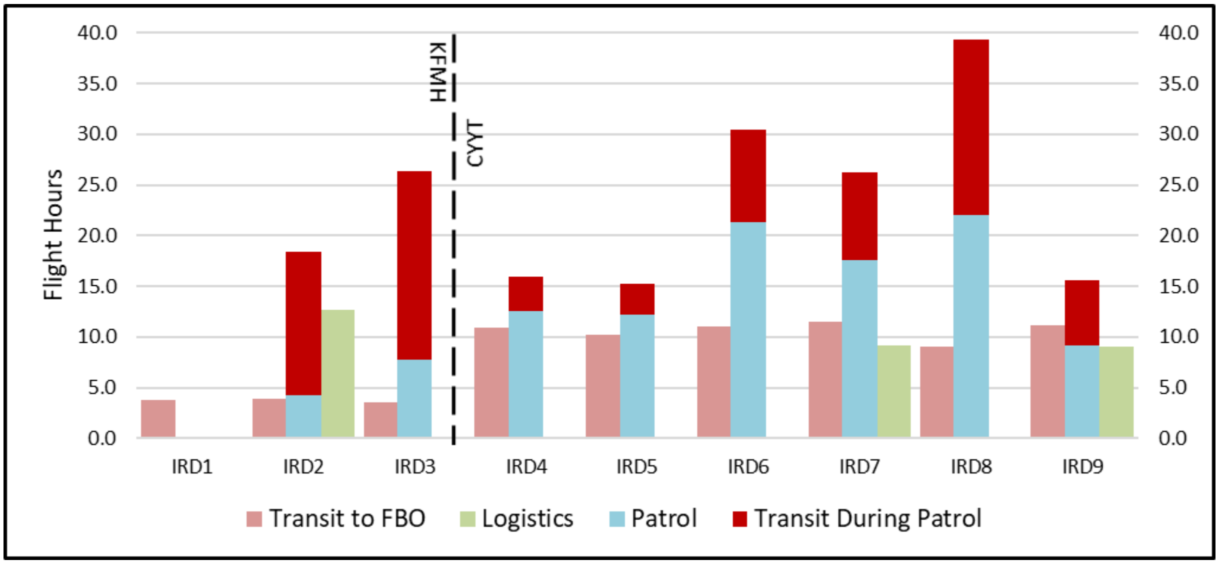

Figure 4-4. 2021 Flight hours broken down by IRD. The first three IRDs were based out of Cape Cod (KFMH), and all remaining IRDs were based out of St. John's (CYYT). FBO refers to a Fixed Base of Operations, the staging area for reconnaissance flights.

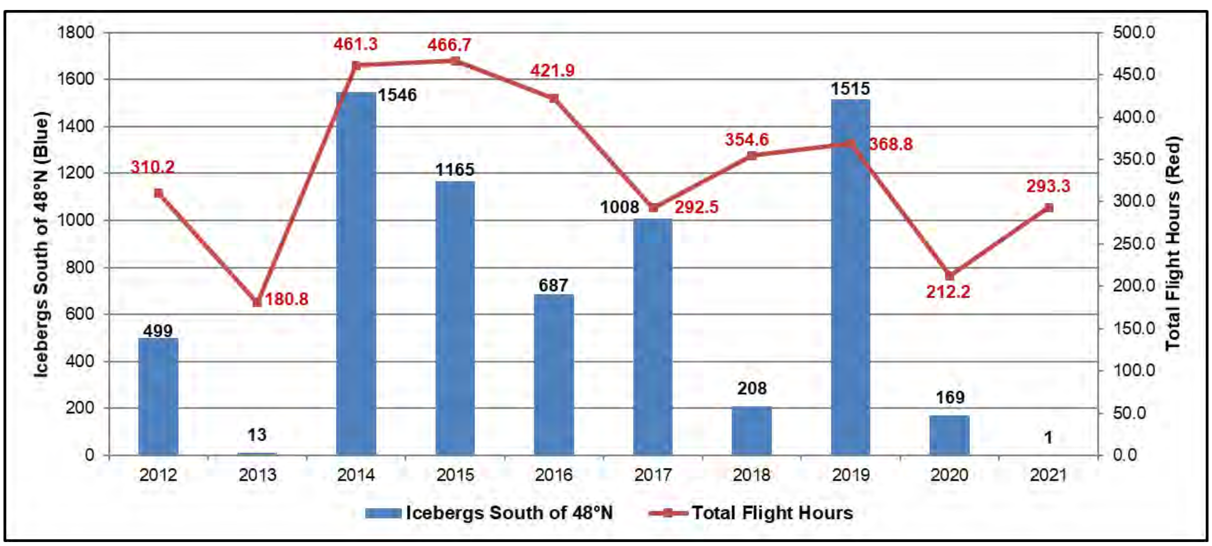

Figure 4-5. Comparison between total IRD flight hours per season and season severity, measured by number of icebergs sighted or drifted below 48ºN for the past 10 years.

sance needed to effectively monitor the iceberg danger and provide relevant warning products. **Figure 4-5** shows a comparison of flight hours to the number of icebergs that drifted south of 48ºN from 2012 to 2021. IIP flew 293.3 hours and saw only a single iceberg drift south of 48ºN. This was an outlier season, with one iceberg being well below the average for the modern reconnaissance era (1983 – 2020) of 778 icebergs.

Satellite Reconnaissance

IIP satellite reconnaissance during the 2021 Iceberg Season focused on the continued automation of processes, development of analysts, and pursuit of new capabilities. The majority of frames analyzed by IIP in 2021 remained to be from the European Commission's SAR satellites Sentinel-1A and -1B. IIP continues to rely on Sentinel-1A/B imagery due to their consistent collection schedule and open source, no-cost imagery availability online in near real-time. IIP continued to utilize Sentinel-2A/B multispectral imagery in 2021 as began in 2020. Of special note, this season saw the first operational use of imagery from the Canadian Space Agency's Radarsat Constellation Mission (RCM), a direct result of the important partnership between IIP and CIS.

IIP analyzed 410 individual satellite frames during the 2021 Ice Season. These 410 satellite frames were comprised of 243 Sentinel-1 frames, 0 RADARSAT-2 frames, 135 Sentinel-2 frames (from 54 SIMs), and 32 RCM frames. IIP's Satellite Dayworker (SDW) identified 2,105 icebergs in the 410 analyzed frames, of which 1,960 were added or resighted in BAPS. **Section 3** contains a further breakdown of satellite iceberg reports received from all sources and the total number of satellite icebergs entered into BAPS. The total number of frames analyzed in-house by IIP decreased from the 526 frames analyzed in 2020. The decrease is directly attributed to the increased flight hours in 2021 season. In 2020, IIP operated with reduced flight hours due to the COVID-19 pandemic enabling the employment of multiple satellite analysts per day. As operations returned toward normal in 2021, the increased number of IIP personnel deployed on aircraft thereby decreased the number available at the OPCEN to carryout satellite analysis. Further, the small number of icebergs within the IIP OPAREA and the constrained Iceberg Limit throughout the season reduced the number of satellite frames available and relevant for analysis over the Iceberg Limit region. This discussion is reflected in **Figure 4-6**, which shows that the total percentage of satellite-identified icebergs (from all sources) decreased in 2021, but remained higher than years prior to 2020.

As reported by IIP (2020), IIP made the first operational use of Sentinel-2 multispectral imagery for reconnaissance in March 2020. In July 2020, IIP created an automated iceberg detection script that utilized the spectral signature of each pixel in a multispectral image to identify potential icebergs for the SDW to classify. The script was revised in early 2021 and was used operationally throughout the 2021 Ice Season. A detailed description of the script and its accuracy is presented in **Appendix E** of this Report.

In December 2020, IIP's Satellite Reconnaissance Branch conducted a satellite Northern Survey between 55°N and 70°N along the coast of Labrador, east coast of Baffin Island, and southwestern Baffin Bay. The goal was to estimate the "upstream" iceberg popula-

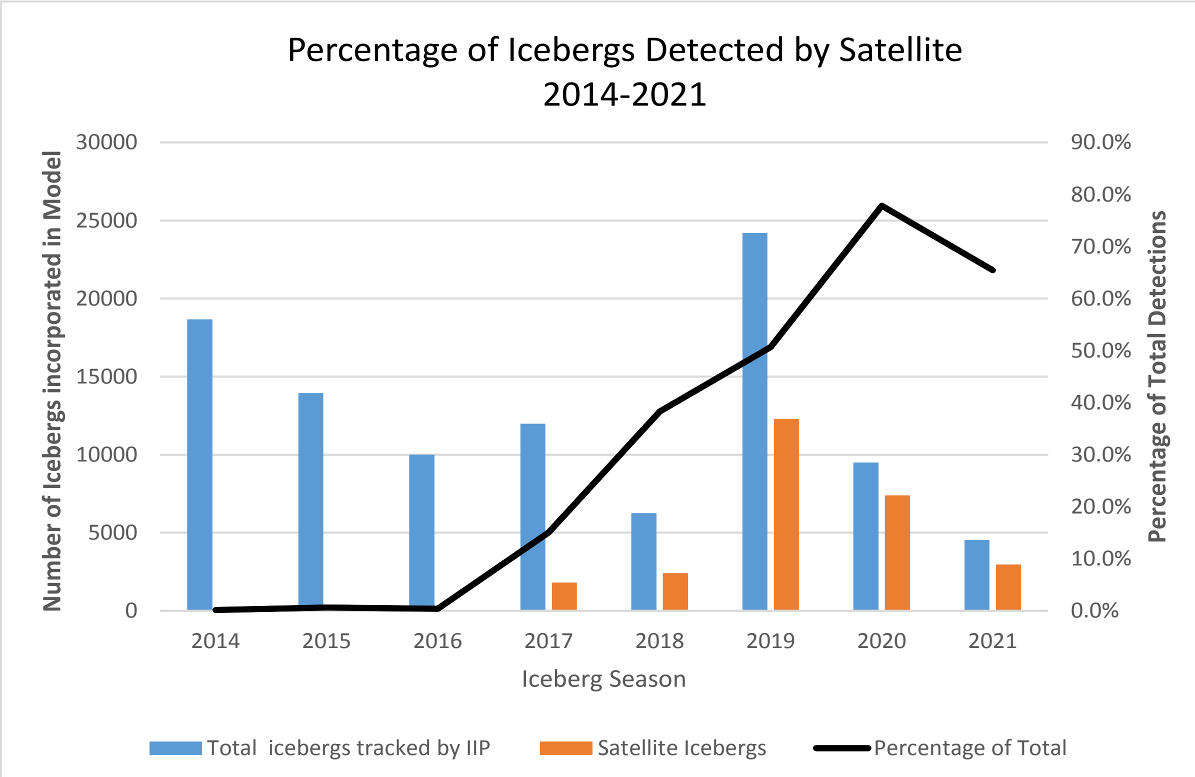

Figure 4-6. Comparison of the number of satellite iceberg detections (all sources) incorporated into the model at IIP and the total number of iceberg sightings from 2014-2021. The black line shows the percentage of total iceberg sightings merged to the model by IIP that were from satellite sources.

tion that could drive aerial reconnaissance decision-making in the early part of IIP's iceberg reconnaissance season. The survey found a relatively small population of icebergs in the currents that transport icebergs from Baffin Bay to the transatlantic shipping lanes. More than half of the population was still within Baffin Bay and 97% of it was contained within the first-year sea ice that was drifting south. The report recommended that the IIP Operations Center track the leading edge of the Gray/Gray-White sea ice and include it within the Iceberg Limit. The report was presented to IIP's command and partners and is included as **Enclosure (1)** of this Annual Report.

After the 2020 Ice Season, the IIP Satellite Reconnaissance Branch utilized coincident Sentinel-1 and Sentinel-2 imagery to identify a dataset of 203 verified icebergs in SAR imagery. Statistical analysis of this dataset demonstrated that IIP's Sentinel-1 2020 filtering process was 92% effective at presenting verified iceberg targets to the analyst. The filtering process was updated to capture the remaining 8% by employing a "dB catch": re-analyzing targets identified to be discarded and recommending analysis of those above a pre-determined decibel level. For the 2020 dataset, this filtering process was 100% effective at presenting verified targets to the SDW for classification and it was incorporated in the 2021 Season. Future work will identify another validation dataset, re-quantify accuracy, and further tune the filtering process.

IIP analyzed an additional 143 satellite frames (from all sensors) between August 13 and September 2 in support of the International Cooperative Engagement Program for Polar Research (ICE-PPR) Iceberg Tagging Experiment (ITEx21) in Disko Bay. This work will be used to improve IIP's processes and a small example of the benefit can be seen in **Appendix E** where the results were used as an accuracy assessment for the Sentinel-2 iceberg detection script. While no RADARSAT-2 frames were collected and analyzed in the 2021 Ice Season, 12 were obtained for analysis as part of this campaign through IIP's NAIS partnership with the USNIC under the Northern View arrangement between NGA and Canada's Department of National Defense. Having a dedicated person at USNIC to manage RADARSAT-2 ordering requests continued to prove invaluable toward the smooth collection of data.

Reaching outside of the typical area of interest, IIP also analyzed 28 satellite frames between 22 May and 03 June in the vicinity of Iceland and the east coast of Greenland to support USCG Barque EAGLE's visit to Iceland and Arctic Circle crossing. The reconnaissance utilized Sentinel-1 imagery and detected hundreds of icebergs along Greenland's east coast, assisting this historic, non-ice strengthened tall ship operating near ice-infested waters.

Other Reconnaissance Activities:

NAIS Collaboration

In order to maximize aerial iceberg reconnaissance in the North Atlantic, IIP continued to leverage its NAIS partnership with CIS. IIP coordinated flight plans with CIS during periods when IRDs were not deployed to St. John's, NL during the season. **Figure 4-7** depicts the NAIS flight hours for 2021. Data provided includes hours flown by each service. CIS contracted PAL Aerospace for 40.5 patrol hours resulting in a combined total of 227.9 patrol hours in support of NAIS reconnaissance.

Ship Interactions

IRD on-scene patrol time in the HC-130J aircraft is mainly focused on locating and classifying icebergs using

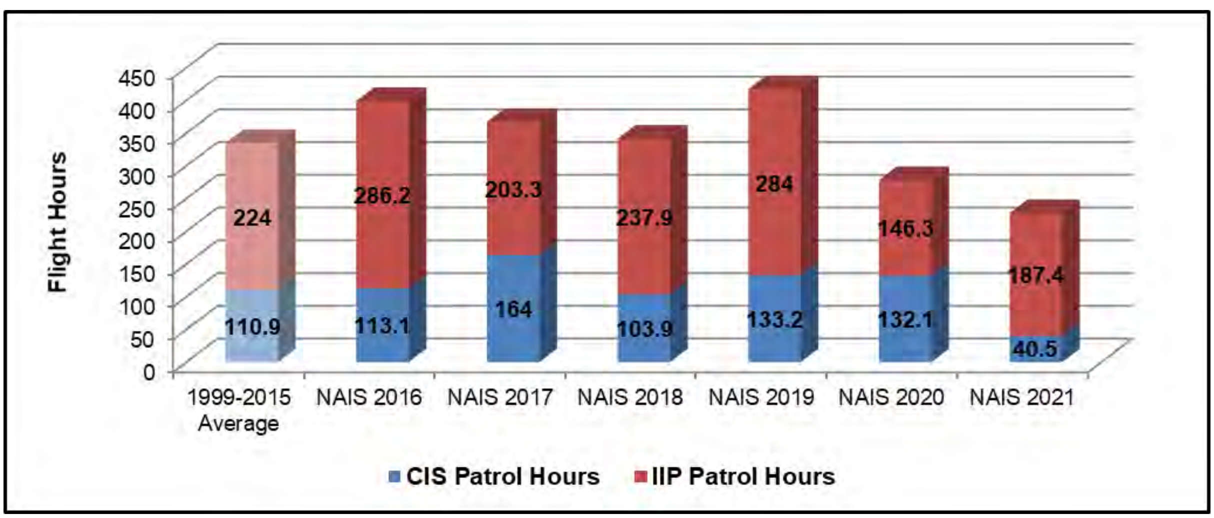

Figure 4-7. NAIS flight hours, a combination of IIP patrol hours and CIS funded PAL Aerospace patrol hours compared to the previous 6-year average.

visual and radar reconnaissance methods. However, during patrols, the IRD will also communicate directly with the maritime community to request recent iceberg sighting information. This communication takes two forms: a sécurité broadcast to all vessels in the vicinity of the aircraft, and direct calls to vessels identified by AIS. The information from the individual vessels is especially useful during periods of reduced visibility, or when numerous small vessels not equipped with AIS are present in the reconnaissance area. Vessel observations are valuable for confirmation of data provided by the aircraft's radar. During the 2021 season, IRDs made 40 general sécurité broadcasts and 25 direct vessel callouts, a decrease of 22% and 65% respectively when compared to the 2020 season. Out of all vessels contacted directly, 50% responded to callouts.

5. Abbreviations and Acronyms

ABF	Active iceBerg File, the iceberg database used for model input
AIS	Automatic Identification System
APN-241	HC-130J Tactical Transport Weather Radar
ASEC	U. S. Coast Guard Air Station Elizabeth City
ASCC	U.S. Coast Guard Air Station Cape Cod
BAPS	iceBerg Analysis and Prediction System
C	Celsius
C-CORE	A not-for-profit research and engineering organization in St. John’s, Newfoundland
CG-5PW	U. S. Coast Guard Director of Marine Transportation Systems
CCG	Canadian Coast Guard
CIIP	Commander, International Ice Patrol
CIS	Canadian Ice Service, an operational unit of the Meteorological Service of Canada
CT	Connecticut
CYYT	St. John’s International Airport
DMI	Danish Meteorological Institute
DWS	Duty Watchstander
ELTA	ELTA Systems Ltd., a group and a wholly-owned subsidiary of Israel Aerospace Industries specifically referring to the ELM-2022A Airborne Maritime Surveillance Radar aboard the HC-130J
EOIR	Electro-Optical Infra-Red
ERMA	Environmental Response Management Application, NOAA
ESA	European Space Agency, owner of the Sentinel-1a satellite
ESRL PSD	Earth Systems Research Laboratory Physical Science Division
FBO	Fixed Base of Operations
GHRSST	Group for High Resolution Sea Surface Temperature
HC-130J	U. S. Coast Guard Long Range Surveillance Maritime Patrol Aircraft
ICE-PPR	International Cooperative Engagement Program for Polar Research
IDS	Iceberg Detection Software
IIP	U. S. Coast Guard International Ice Patrol

IRD	Ice Reconnaissance Detachment
ITEx21	Iceberg Tagging Experiment 2021
ISAR	Inverse Synthetic Aperture Radar
KECG	Air Station Elizabeth City Airport Code
KFMH	Joint Base Cape Cod Airport
KGON	Groton-New London Airport
KML	Keyhole Markup Language
kts	knots
m	meter
mb	millibar
MA	Massachusetts
MCTS	Marine Communications and Traffic Service, Canadian Coast Guard
MD	Maryland
MMS	Minotaur Mission System
M/V	Motor Vessel
N	North (Latitude)
NAIS	North American Ice Service
NAOI	North Atlantic Oscillation Index
NAVAREA	Navigational Area
NAVTEX	Navigational Telex
NAVWARN	Navigational Warning
NC	North Carolina
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NGA	U. S. National Geospatial-Intelligence Agency
NL	Newfoundland and Labrador, Canada
NM	Nautical Mile
NOAA	National Oceanic and Atmospheric Administration
NSIDC	National Snow and Ice Data Center
NSOF	NOAA Satellite Operations Facility
NWS	National Weather Service
OPAREA	Operational Area
OPC	Ocean Prediction Center

OPCEN	Operations Center
PAL Aerospace	Commercial aerial reconnaissance provider based in St. John's, Newfoundland.
POD	Probability of Detection
RADARSAT-2	Canadian C-Band SAR satellite system, owned and operated by MacDonald, Dettwiler, and Associates.
RCM	Radarsat Constellation Mission, Canadian Government C-Band SAR satellite system
Radiofax	Radio Facsimile
RMS	Royal Mail Steamer
SafetyNET	Inmarsat-C Safety Net, automated satellite system for promulgating marine navigational warnings, weather, and other safety information.
SAR	Synthetic Aperture Radar
SDW	Satellite Dayworker
shp	Shape File
SIM	Standard Iceberg Message
SITOR	Simplex Teletype Over Radio
SOLAS	Safety of Life at Sea
SLP	Sea Level Pressure
SRB	Satellite Reconnaissance Branch
SST	Sea Surface Temperature
SVP	Surface Velocity Program
TAC	Total Accumulated Ice Coverage
UKMO	United Kingdom Meteorological Office
U.S.	United States
USCG	U. S. Coast Guard
USCGC	U. S. Coast Guard Cutter
USNIC	U. S. National Ice Center
W	West (Longitude)
WWNWS	World Wide Navigation Warning System
Z	Zulu – Coordinated Universal Time

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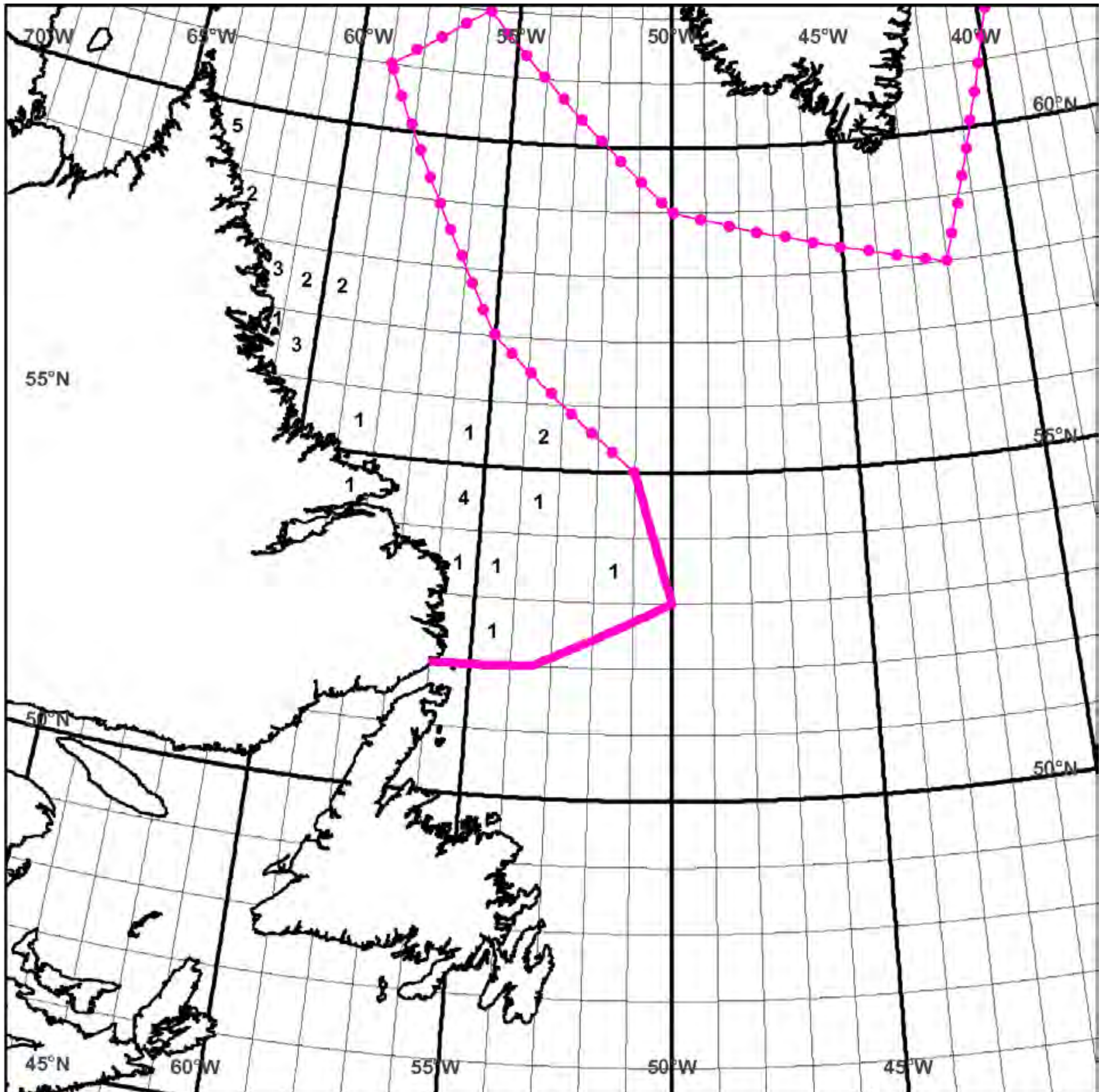
7. Semi-Monthly Iceberg Charts



NORTH AMERICAN ICE SERVICE (NAIS)

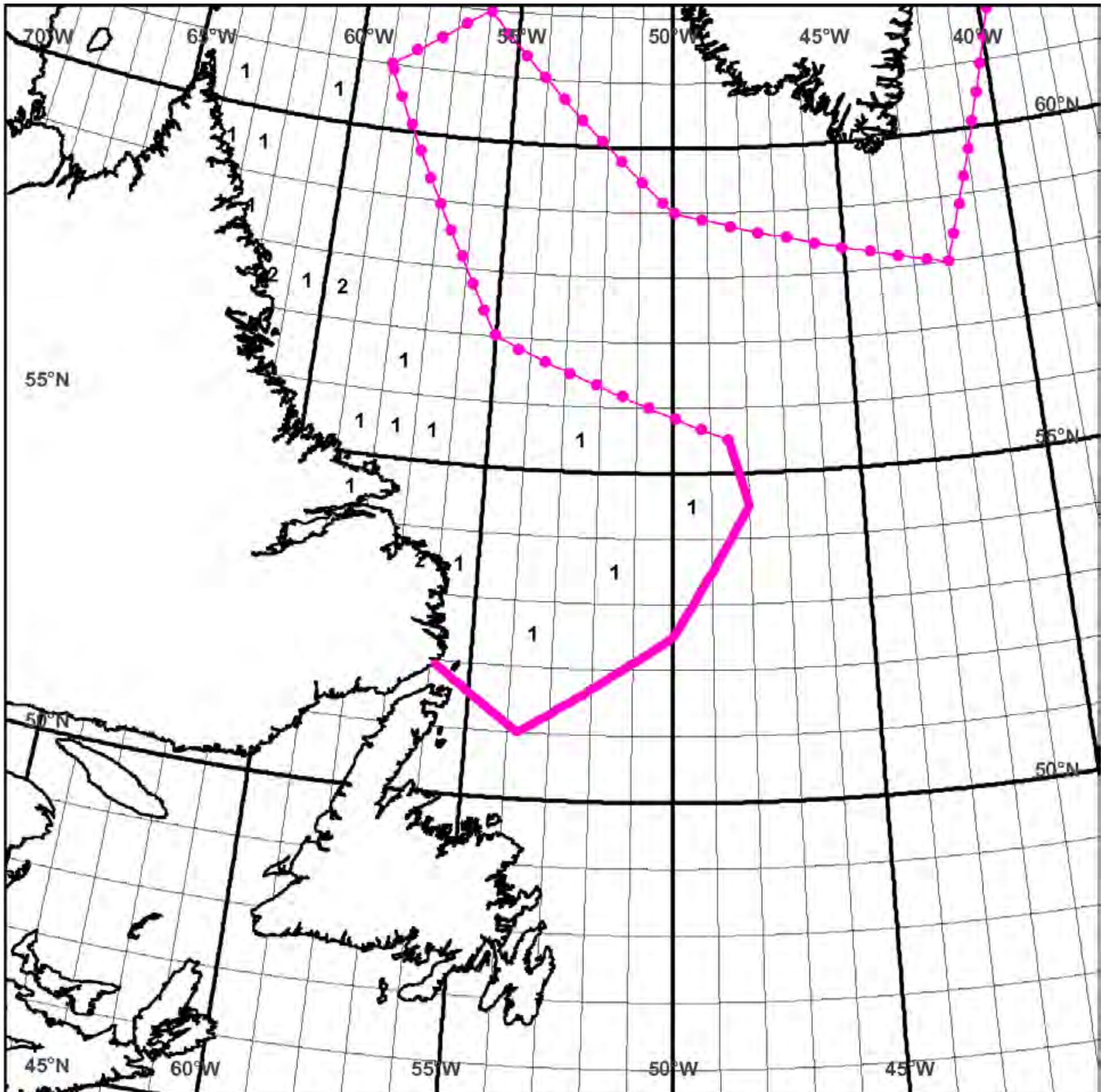
ICEBERG ANALYSIS FOR 0000 UTC

01 OCT 2020

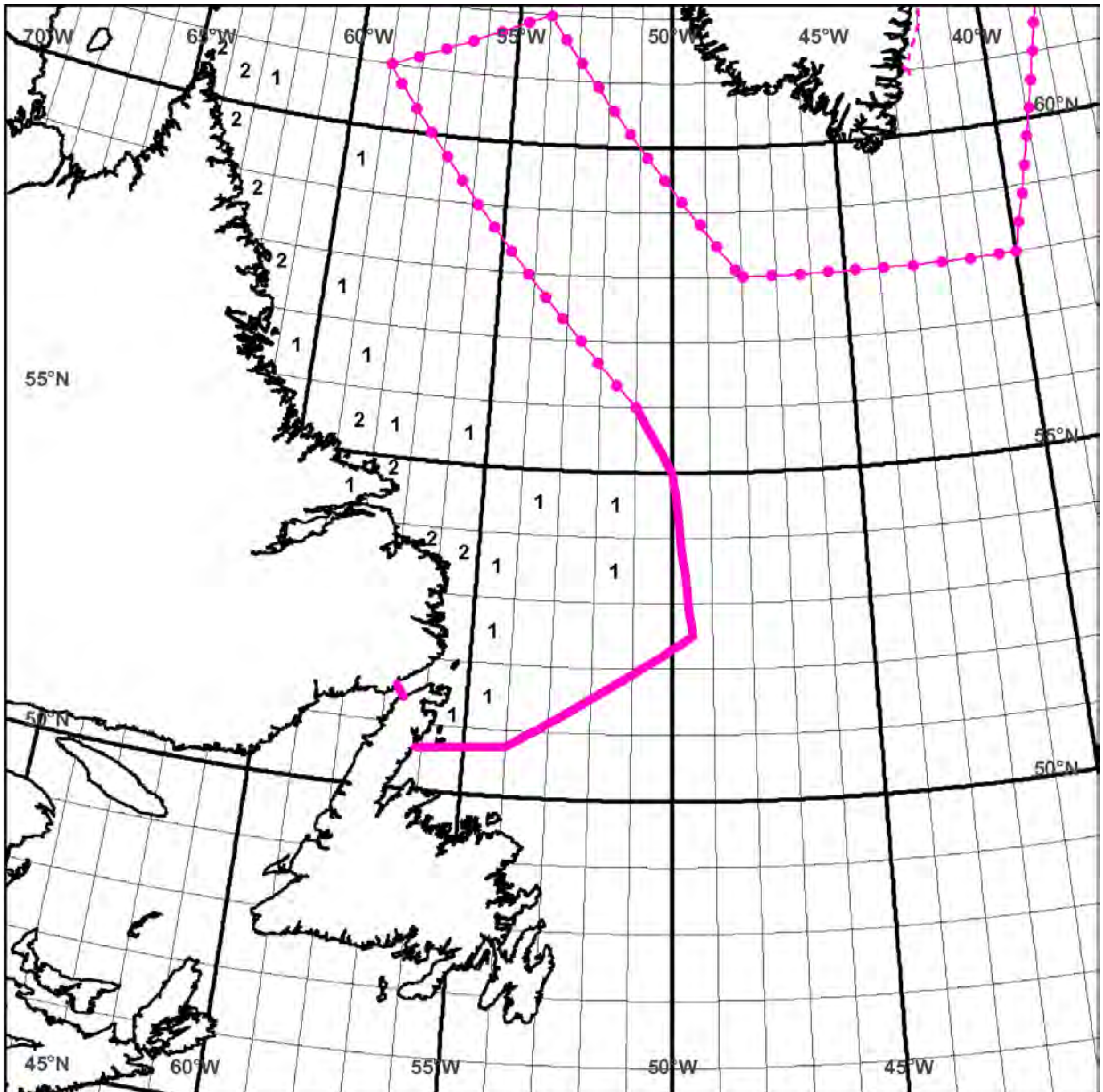
- ESTIMATED ICEBERG LIMIT
- ICEBERG LIMIT
- SEA ICE LIMIT
- # ICEBERGS PER DEGREE SQUARE
- ⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Interior General Flight 27SEP20.



NORTH AMERICAN ICE SERVICE (NAIS)	ICEBERG ANALYSIS FOR 0000 UTC **15 OCT 2020**
ESTIMATED ICEBERG LIMIT ICEBERG LIMIT SEA ICE LIMIT # ICEBERGS PER DEGREE SQUARE ⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT	**NOTE:** **For more information:** **www.navcen.uscg.gov/iip** **www.ice-glaces.ec.gc.ca** **Most Recent Reconnaissance:** **Eastern Limit Iceberg Flight 05OCT20.**



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

01 NOV 2020

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

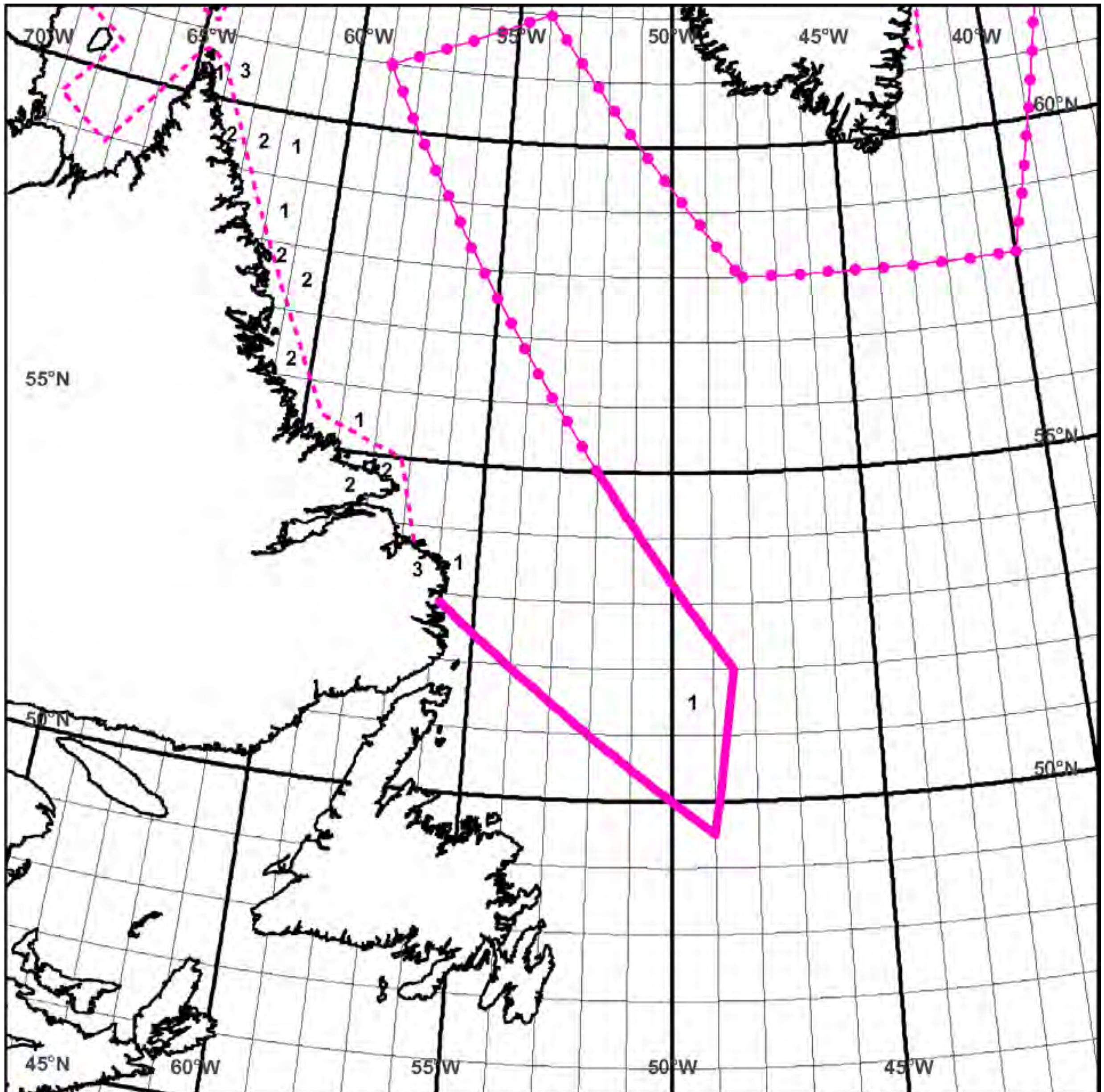
SEA ICE LIMIT

ICEBERGS PER DEGREE SQUARE

RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Southern Limit Iceberg Flight 22OCT20.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

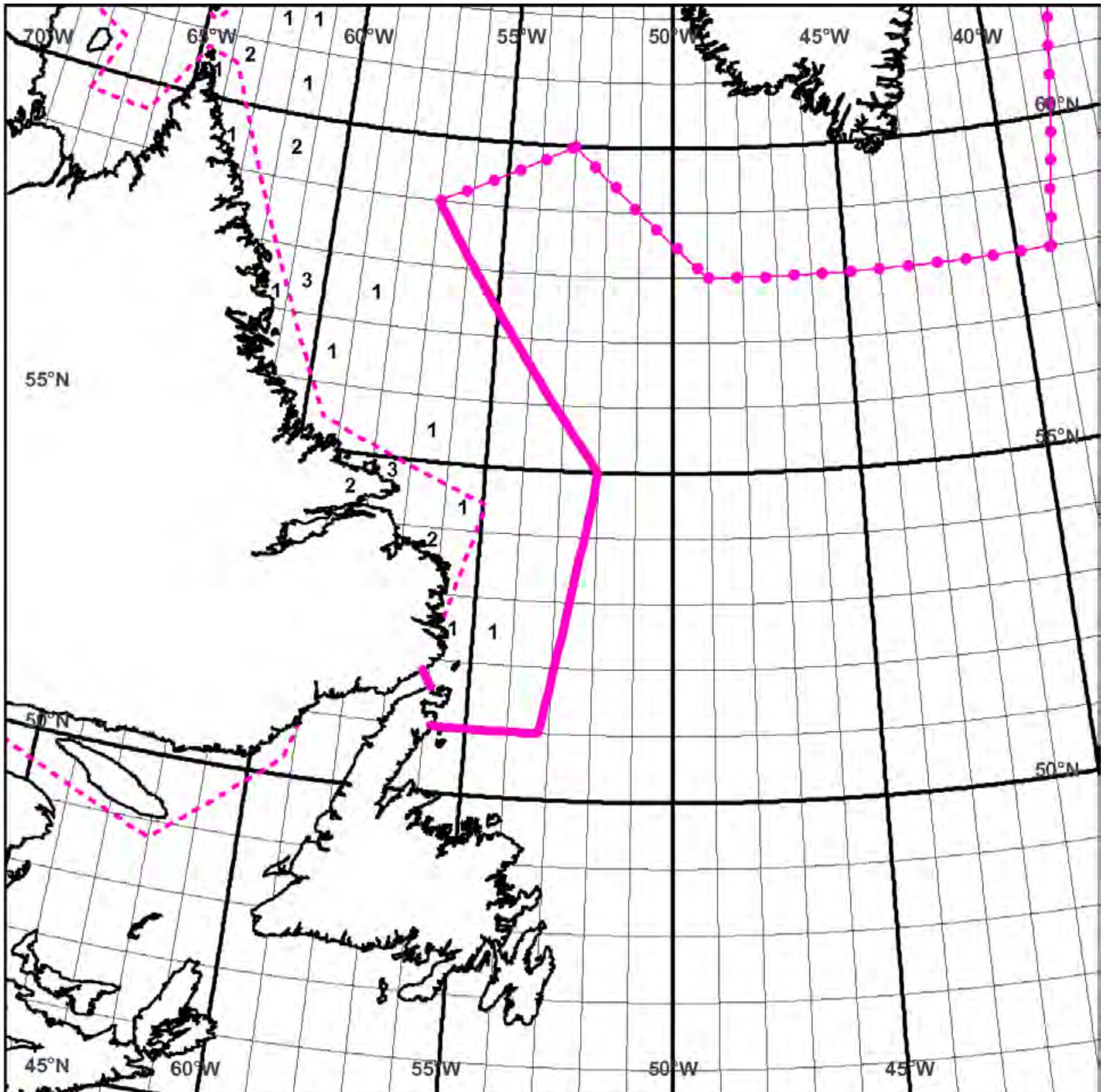
15 NOV 2020

- ESTIMATED ICEBERG LIMIT
- ICEBERG LIMIT
- SEA ICE LIMIT
- # ICEBERGS PER DEGREE SQUARE
- ⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

Significant reduction of iceberg limit due to recent reconnaissance.

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Southern Limit Iceberg Flight 13NOV20.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

01 DEC 2020

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

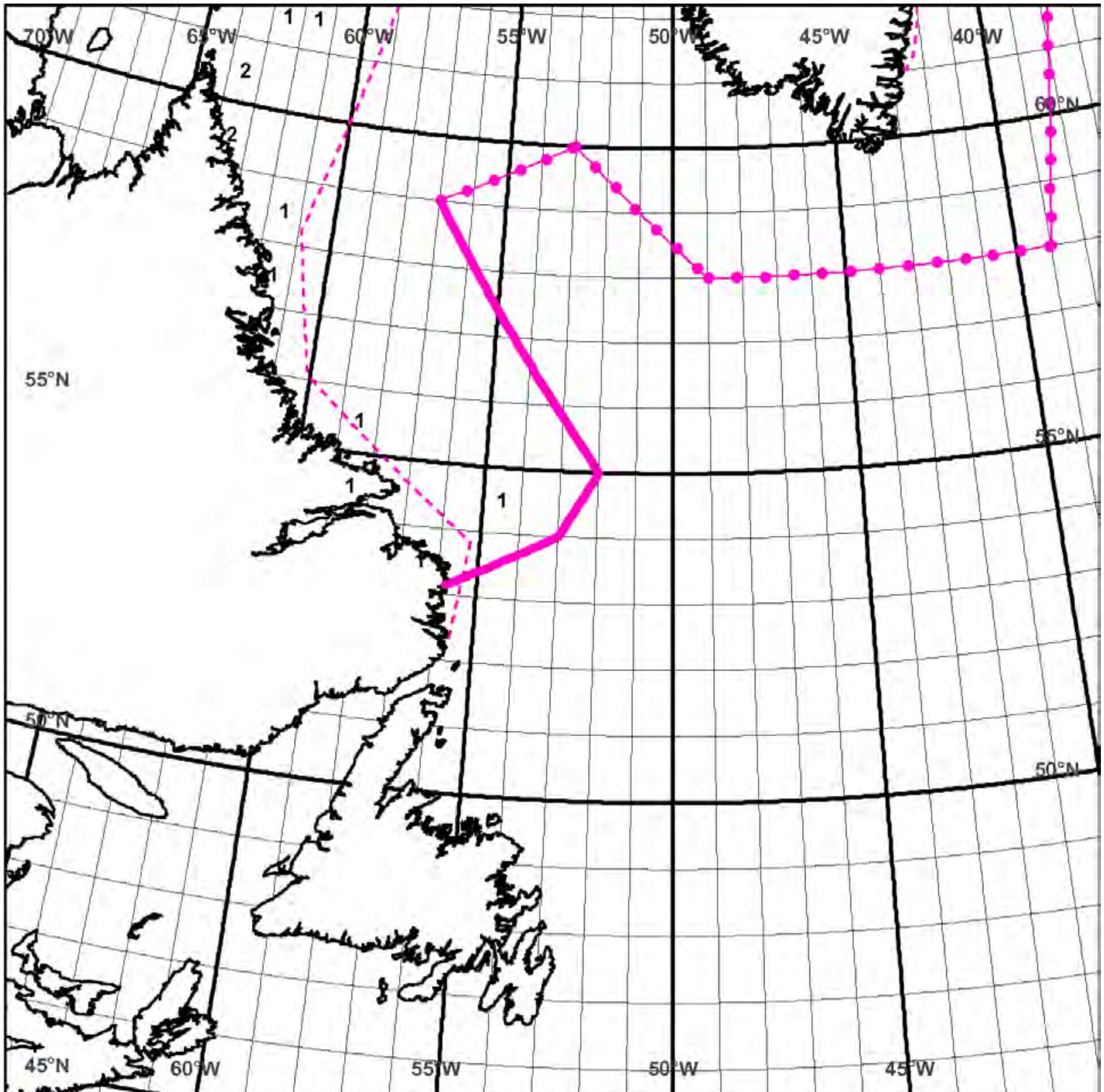
SEA ICE LIMIT

ICEBERGS PER DEGREE SQUARE

⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Southern Limit Iceberg Flight 13NOV20.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

15 DEC 2020

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

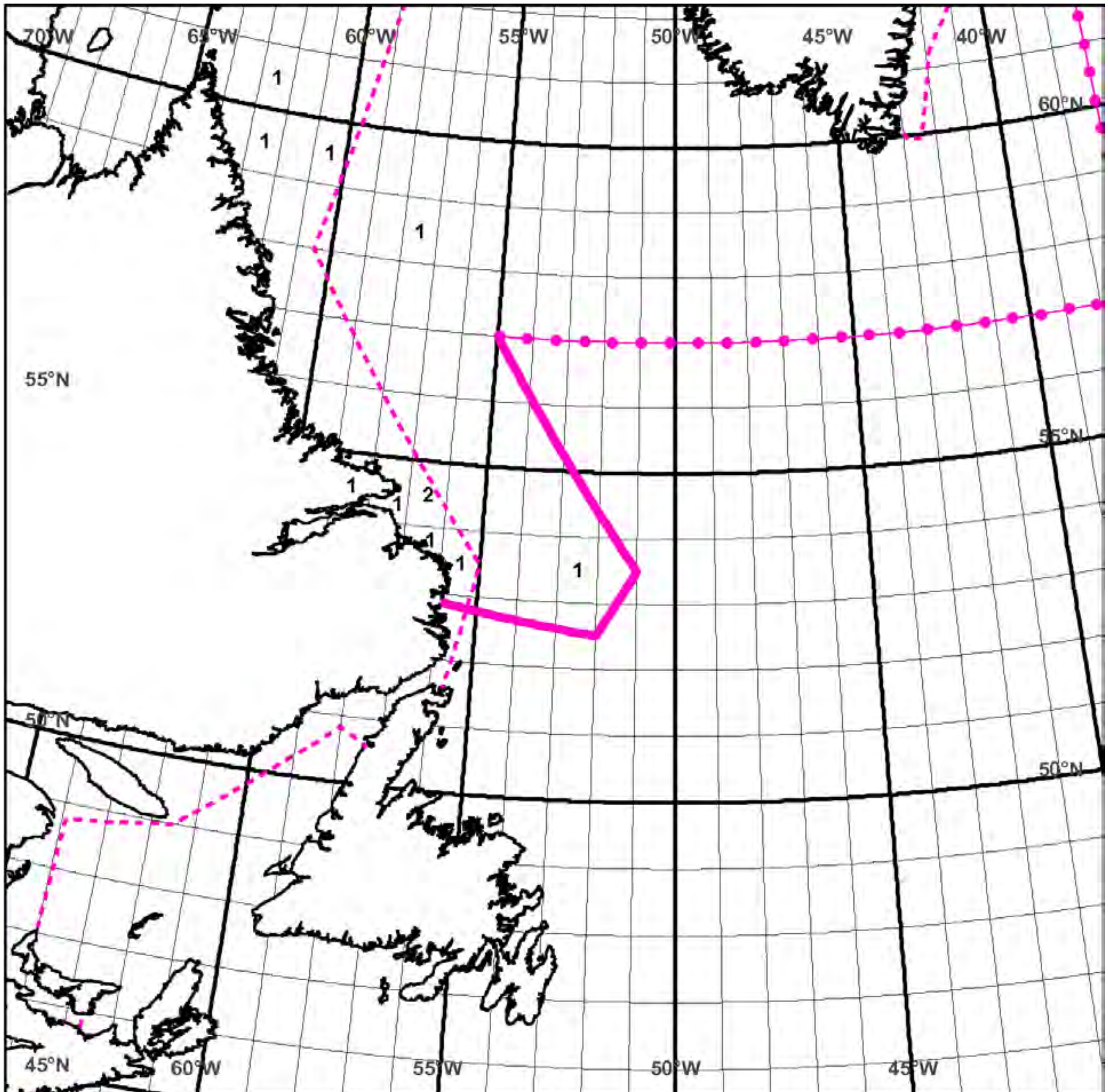
SEA ICE LIMIT

\# ICEBERGS PER DEGREE SQUARE

⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Northern Survey Iceberg Flight 12DEC20.



NORTH AMERICAN ICE SERVICE (NAIS)

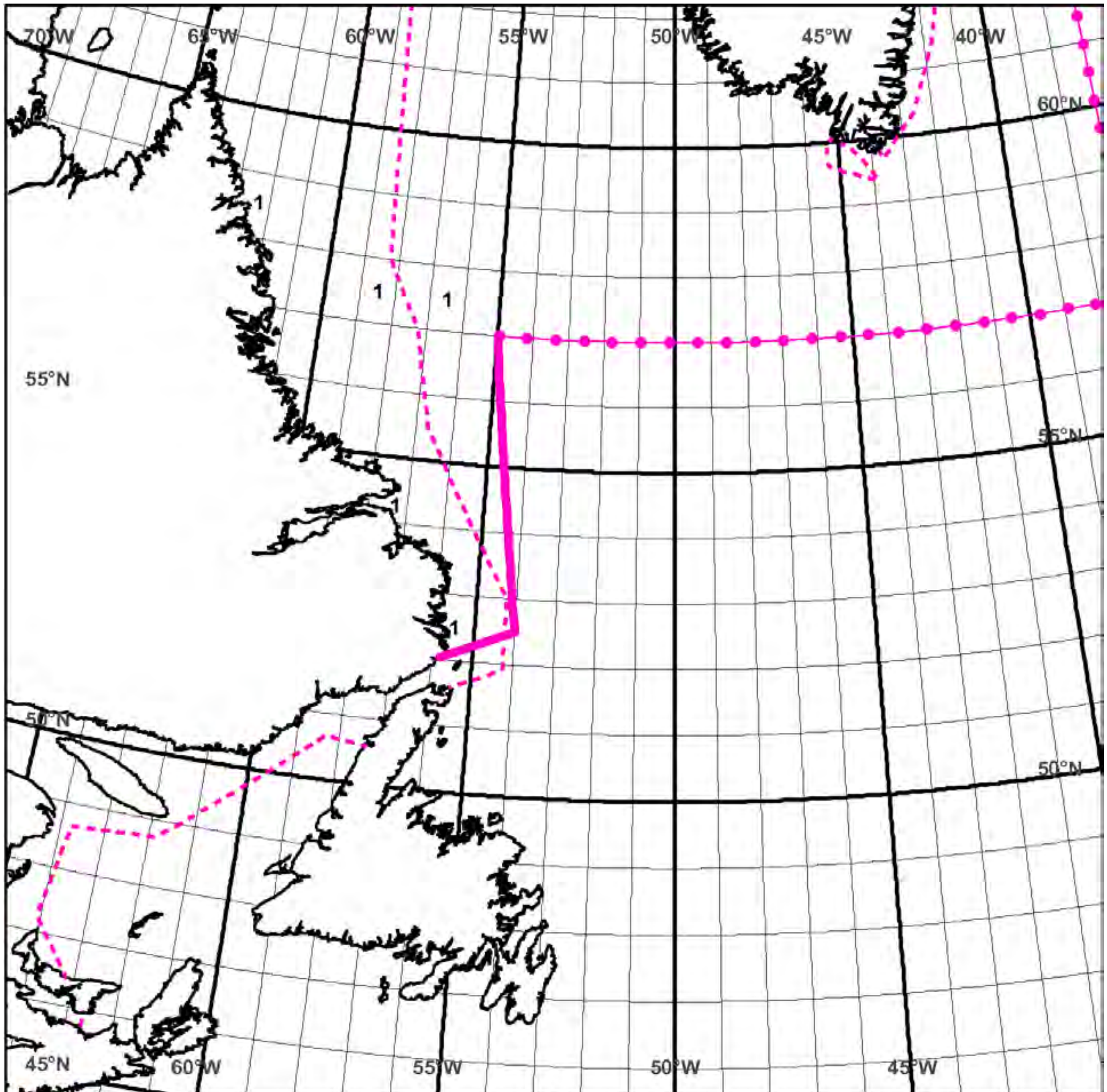
ICEBERG ANALYSIS FOR 0000 UTC

01 JAN 2021

- ESTIMATED ICEBERG LIMIT
- ICEBERG LIMIT
- SEA ICE LIMIT
- # ICEBERGS PER DEGREE SQUARE
- ⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Northern Survey Iceberg Flight 12DEC20.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

15 JAN 2021

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

SEA ICE LIMIT

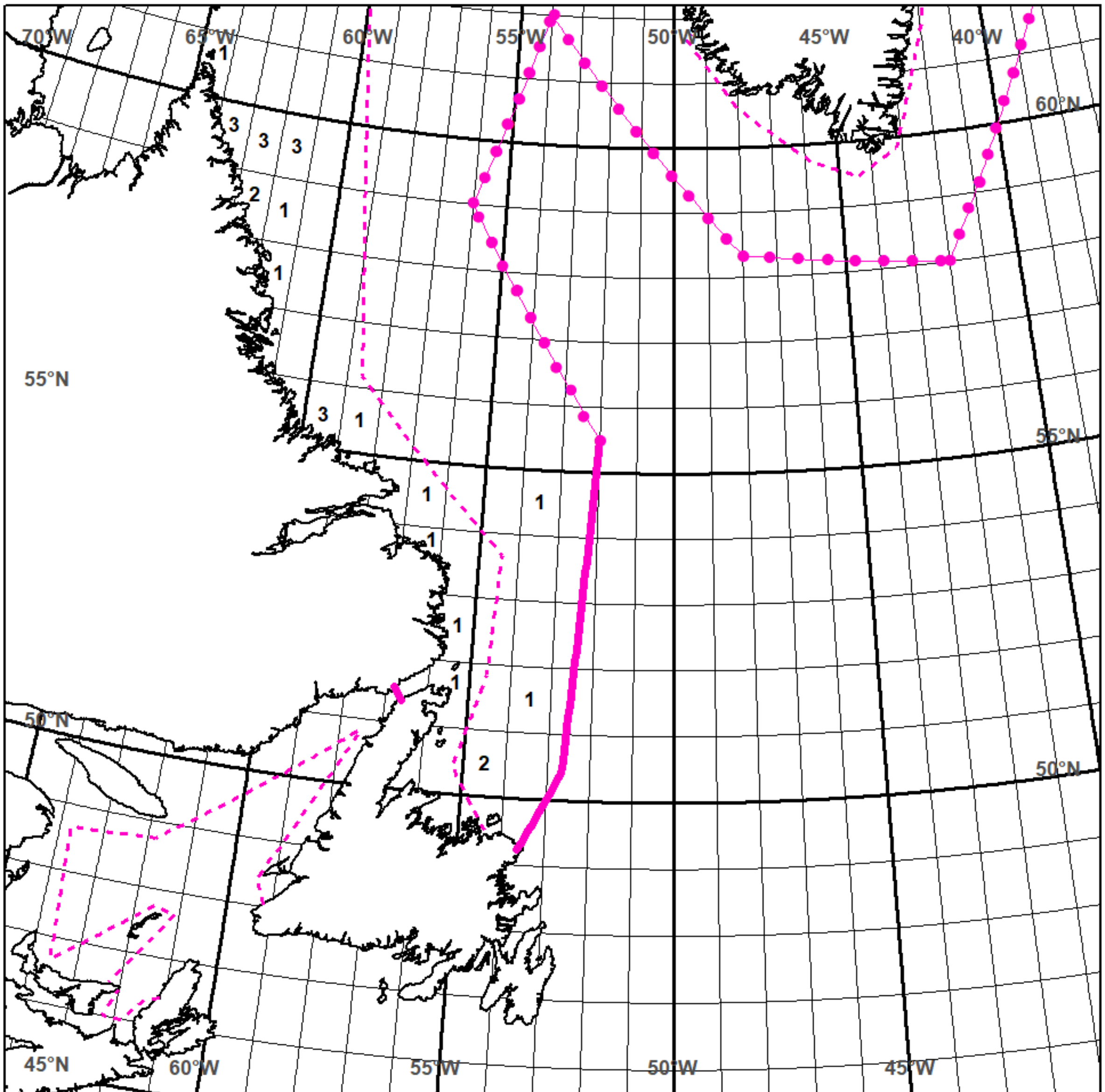
\# ICEBERGS PER DEGREE SQUARE

⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

Significant reduction of iceberg limit due to recent reconnaissance.

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Southern Limit Iceberg Flight 13JAN21.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

01 FEB 2021

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

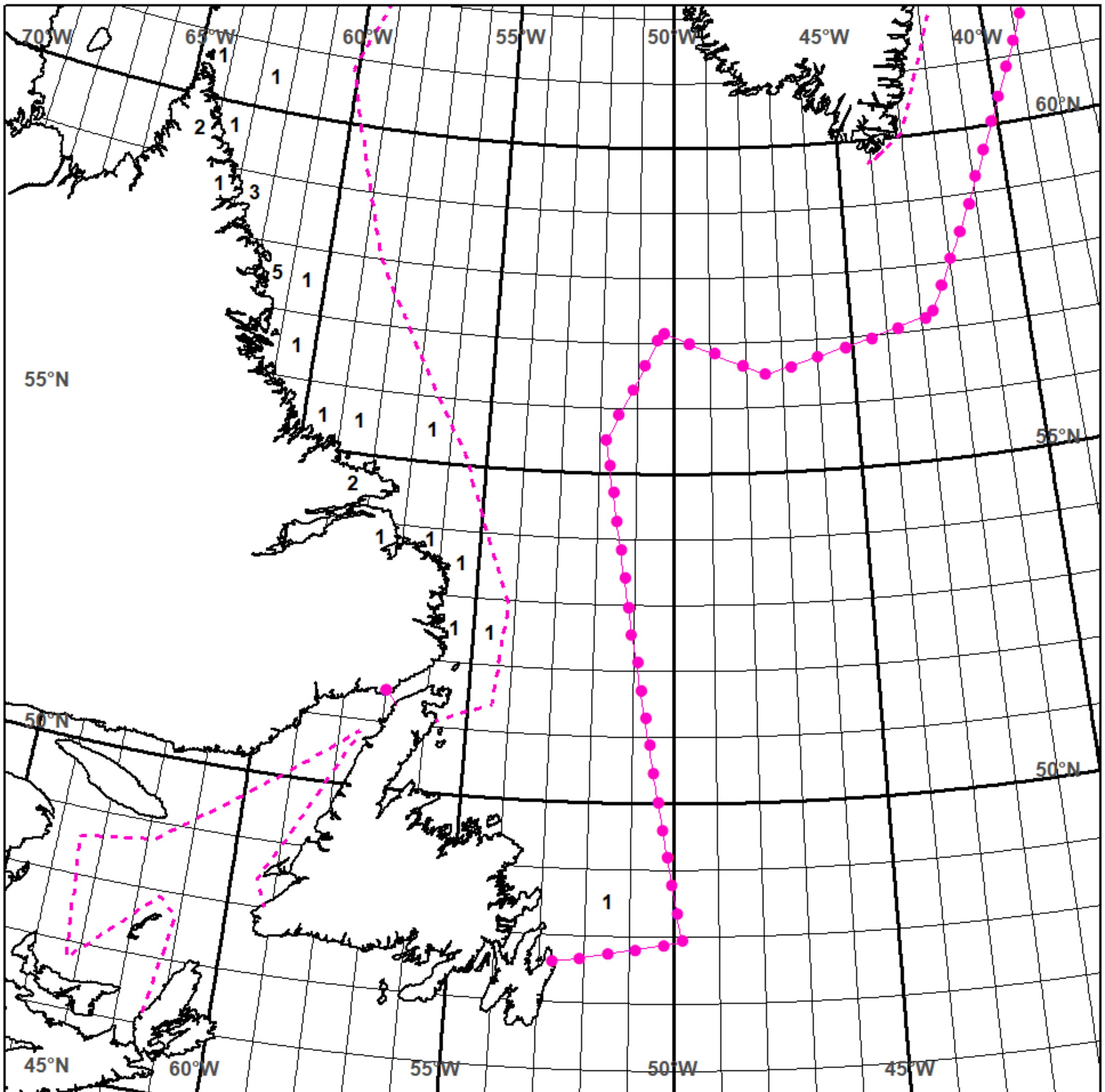
SEA ICE LIMIT

\# ICEBERGS PER DEGREE SQUARE

⨂ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Southern Limit General Flight 29JAN21.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

15 FEB 2021

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

SEA ICE LIMIT

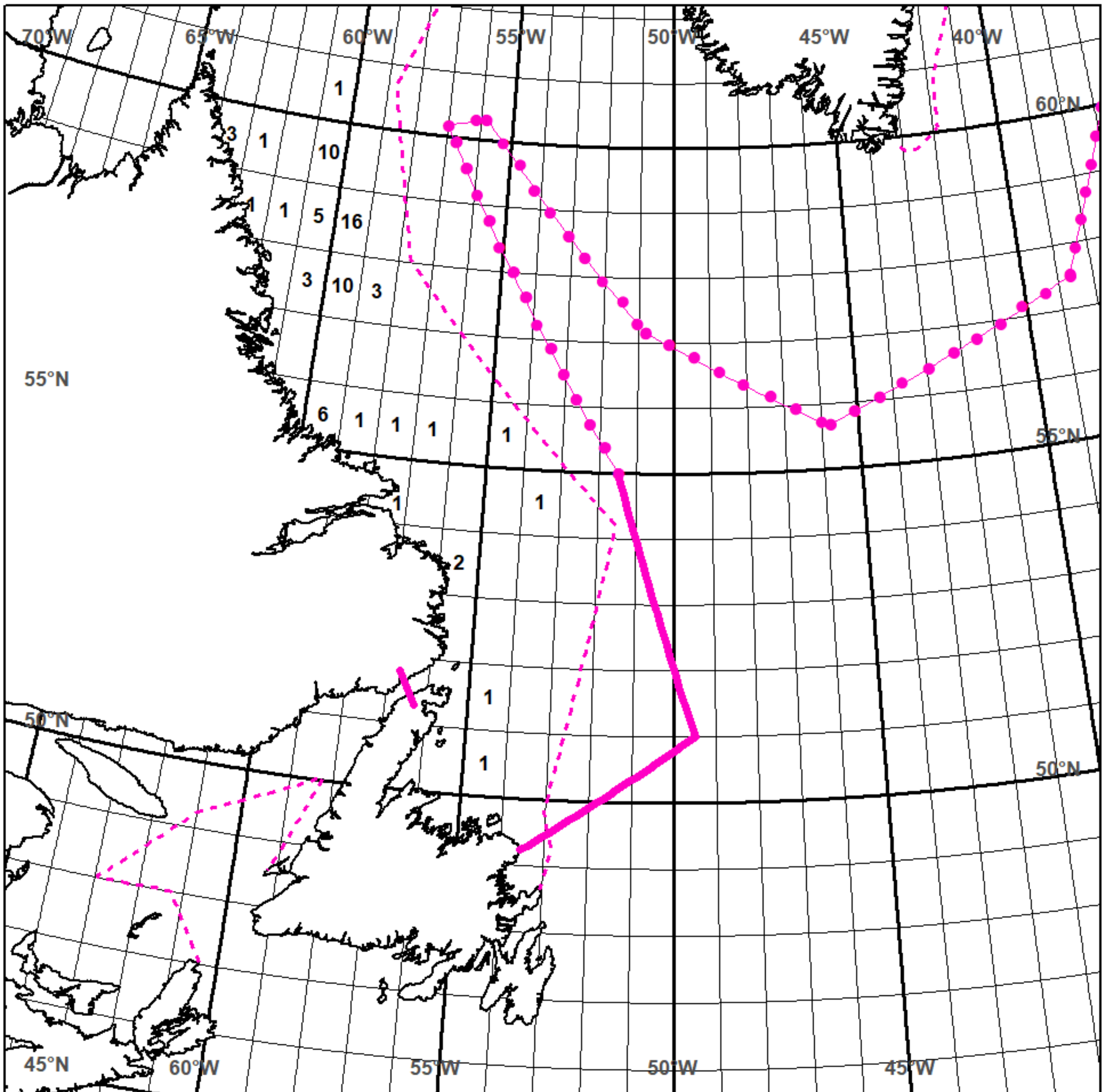
\# ICEBERGS PER DEGREE SQUARE

⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

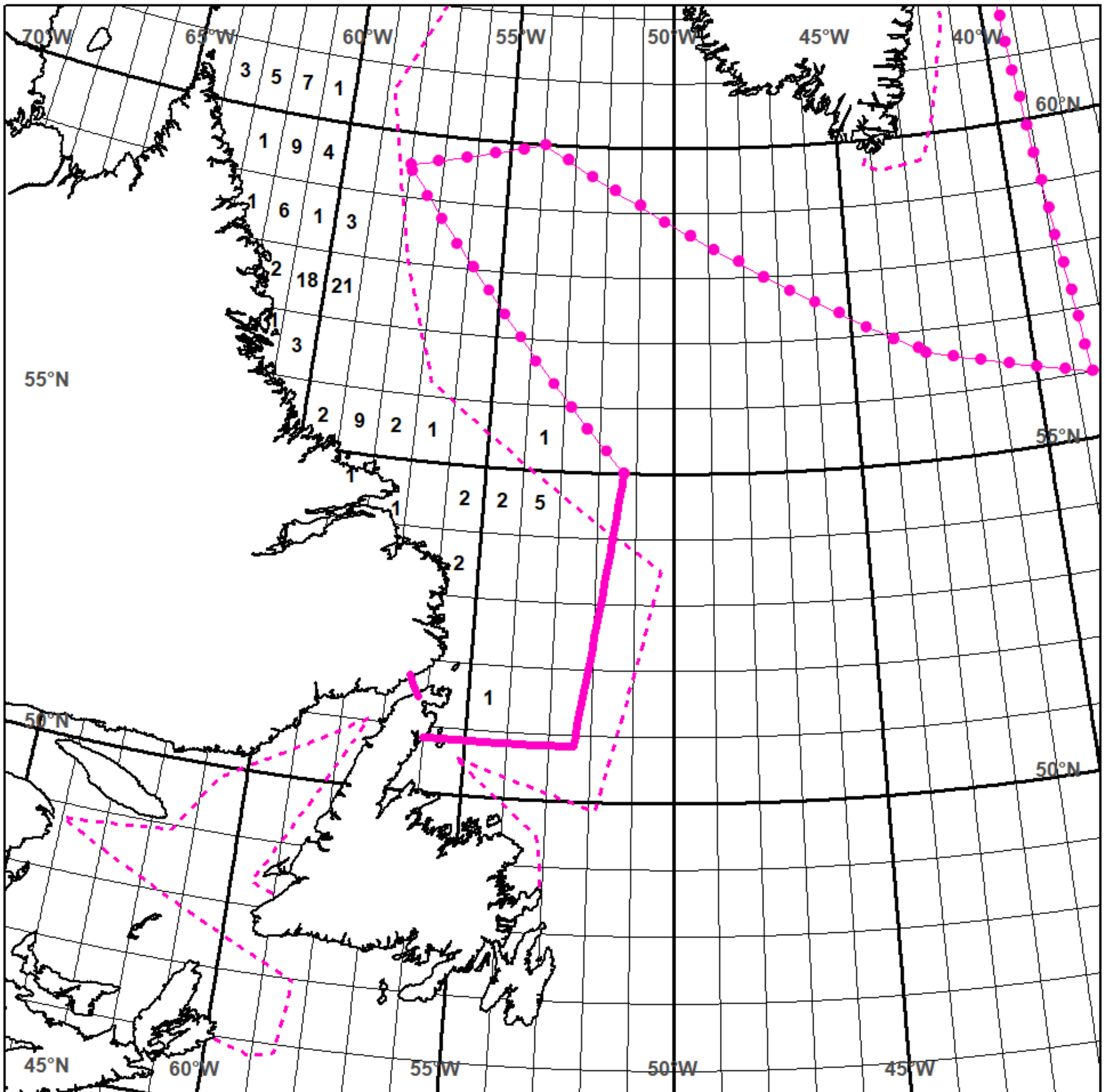
NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Southern Limit Iceberg Flight 14FEB21.

WARNING! The International Ice Patrol is experiencing reduced iceberg reconnaissance. Please navigate with caution.



NORTH AMERICAN ICE SERVICE (NAIS)	ICEBERG ANALYSIS FOR 0000 UTC **01 MAR 2021**
ESTIMATED ICEBERG LIMIT ICEBERG LIMIT SEA ICE LIMIT # ICEBERGS PER DEGREE SQUARE ⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT	**NOTE:** **For more information:** **www.navcen.uscg.gov/iip** **www.ice-glaces.ec.gc.ca** **Most Recent Reconnaissance:** **Southern Limit Iceberg Flight 27FEB21.**



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

15 MAR 2021

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

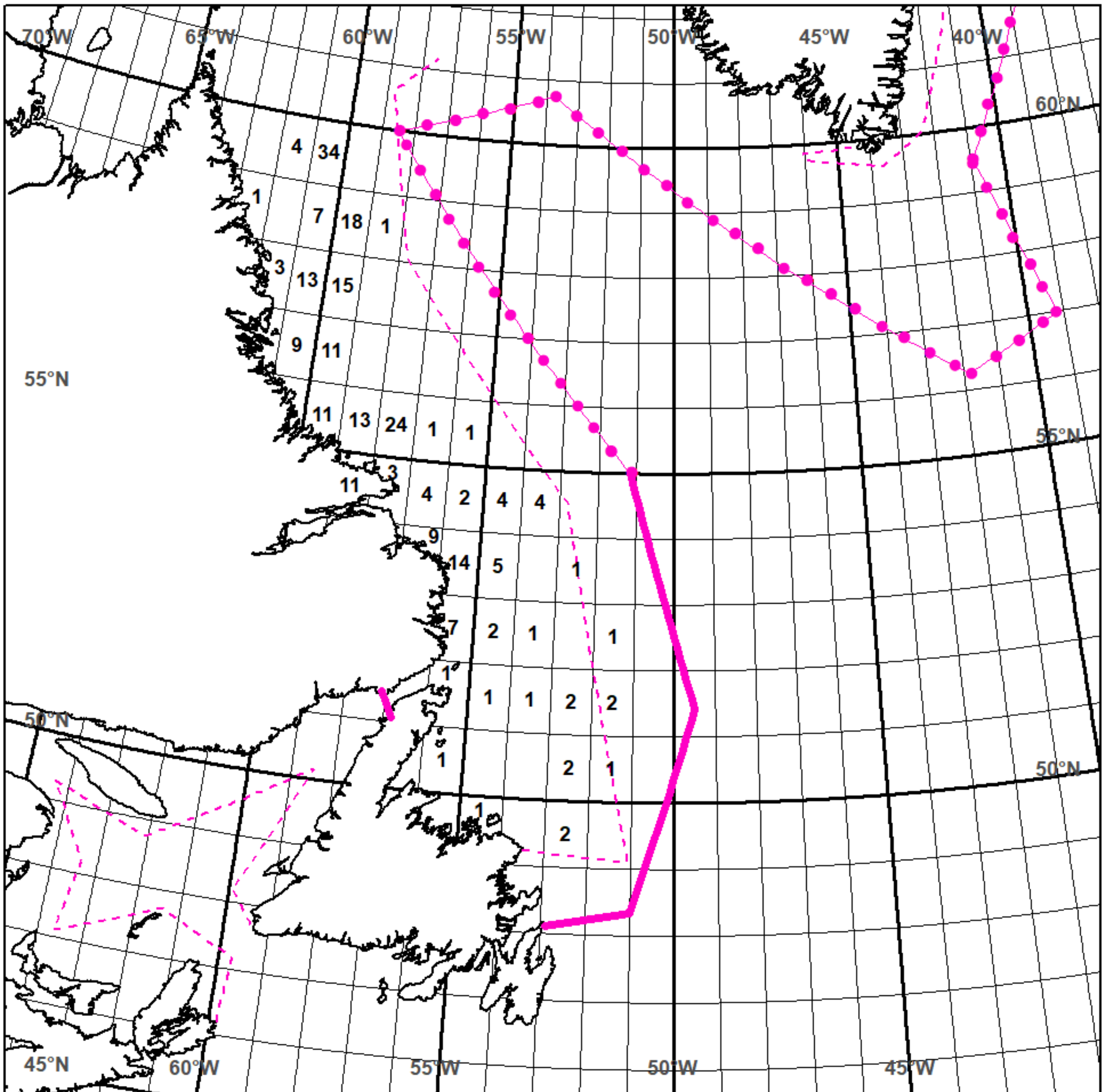
SEA ICE LIMIT

ICEBERGS PER DEGREE SQUARE

RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Southern Limit Iceberg Flight 08MAR21.



NORTH AMERICAN ICE SERVICE (NAIS)

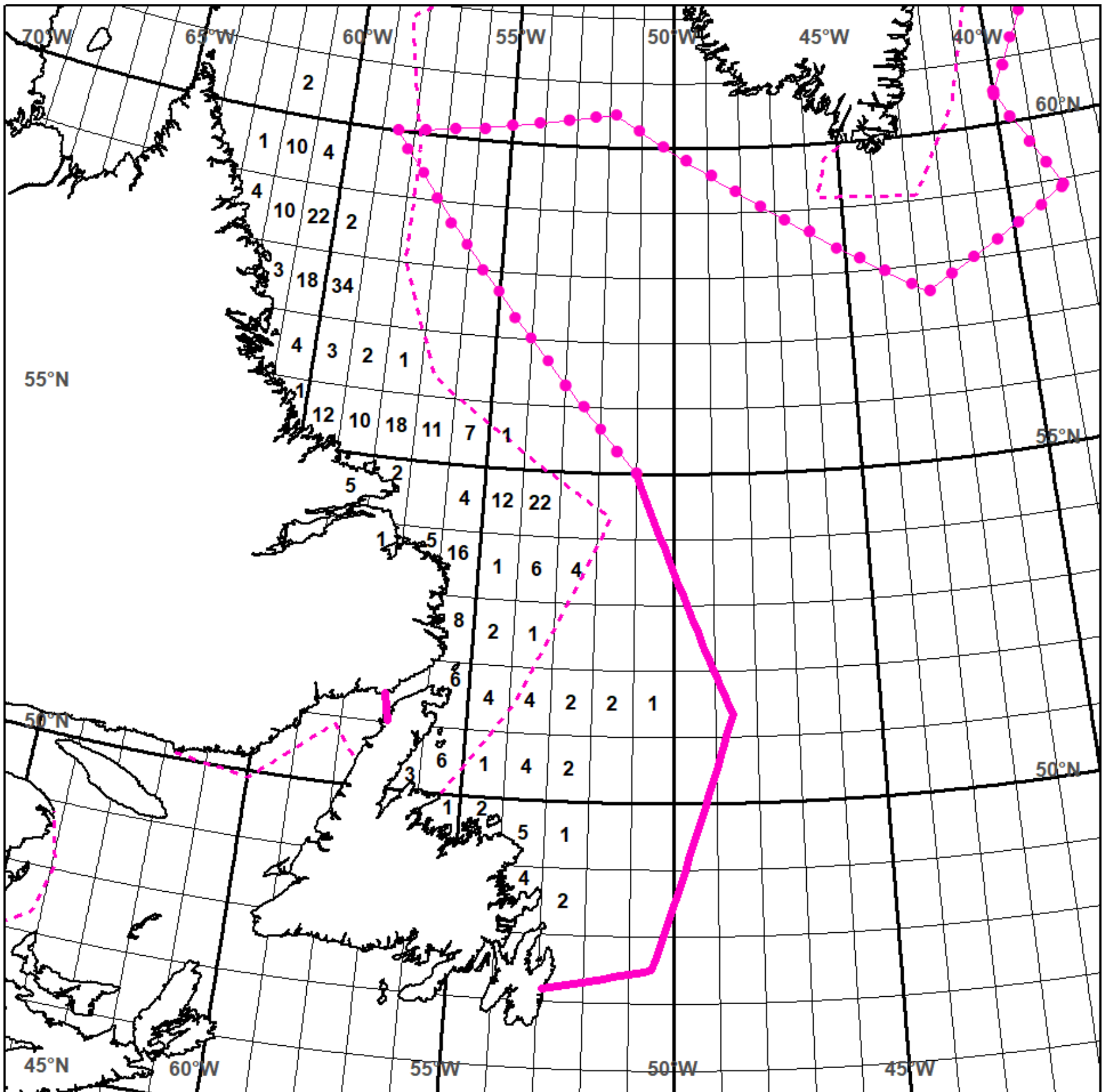
ICEBERG ANALYSIS FOR 0000 UTC

01 APR 2021

- ESTIMATED ICEBERG LIMIT
- ICEBERG LIMIT
- SEA ICE LIMIT
- # ICEBERGS PER DEGREE SQUARE
- ⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Interior General Flight 31MAR21.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

15 APR 2021

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

SEA ICE LIMIT

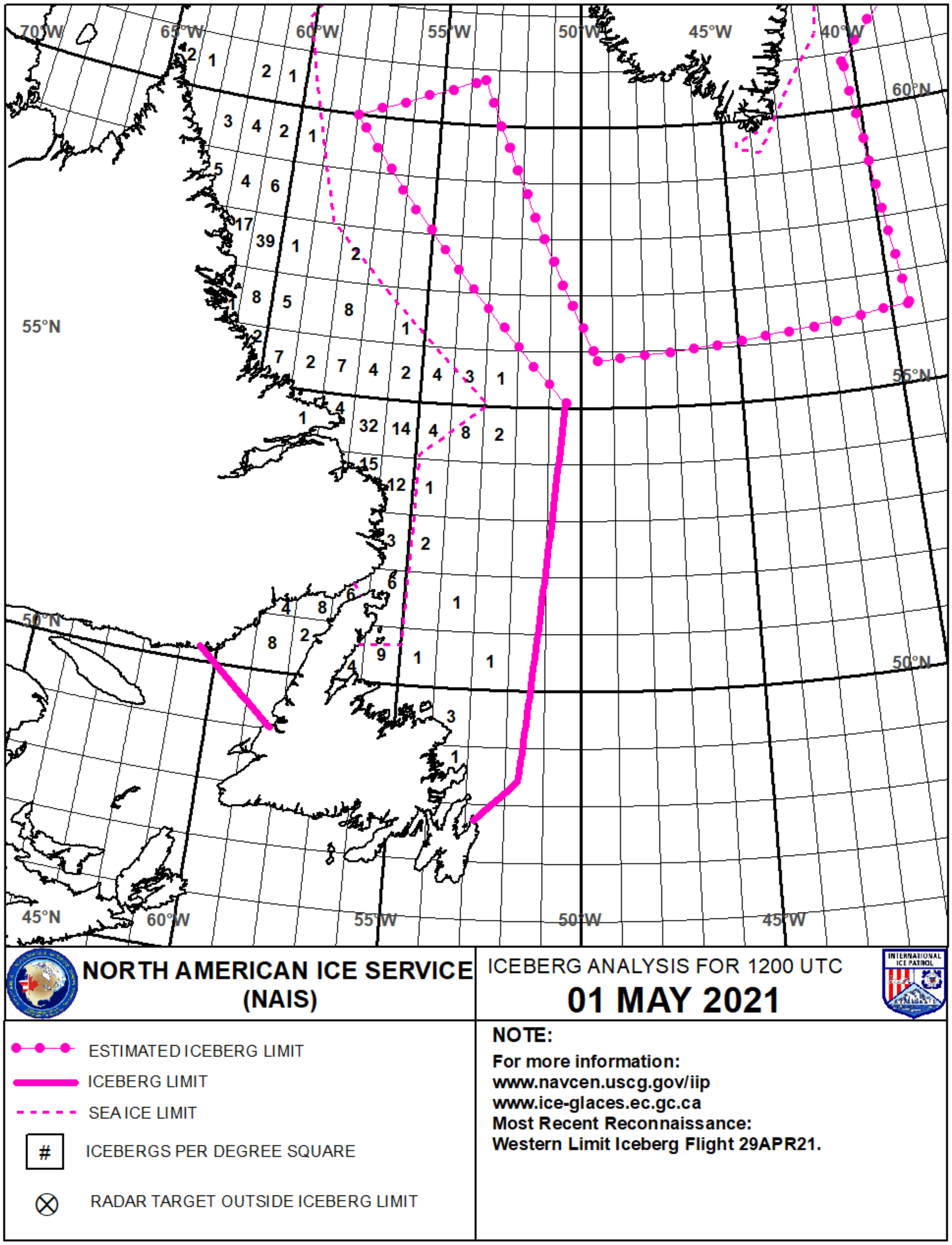
ICEBERGS PER DEGREE SQUARE

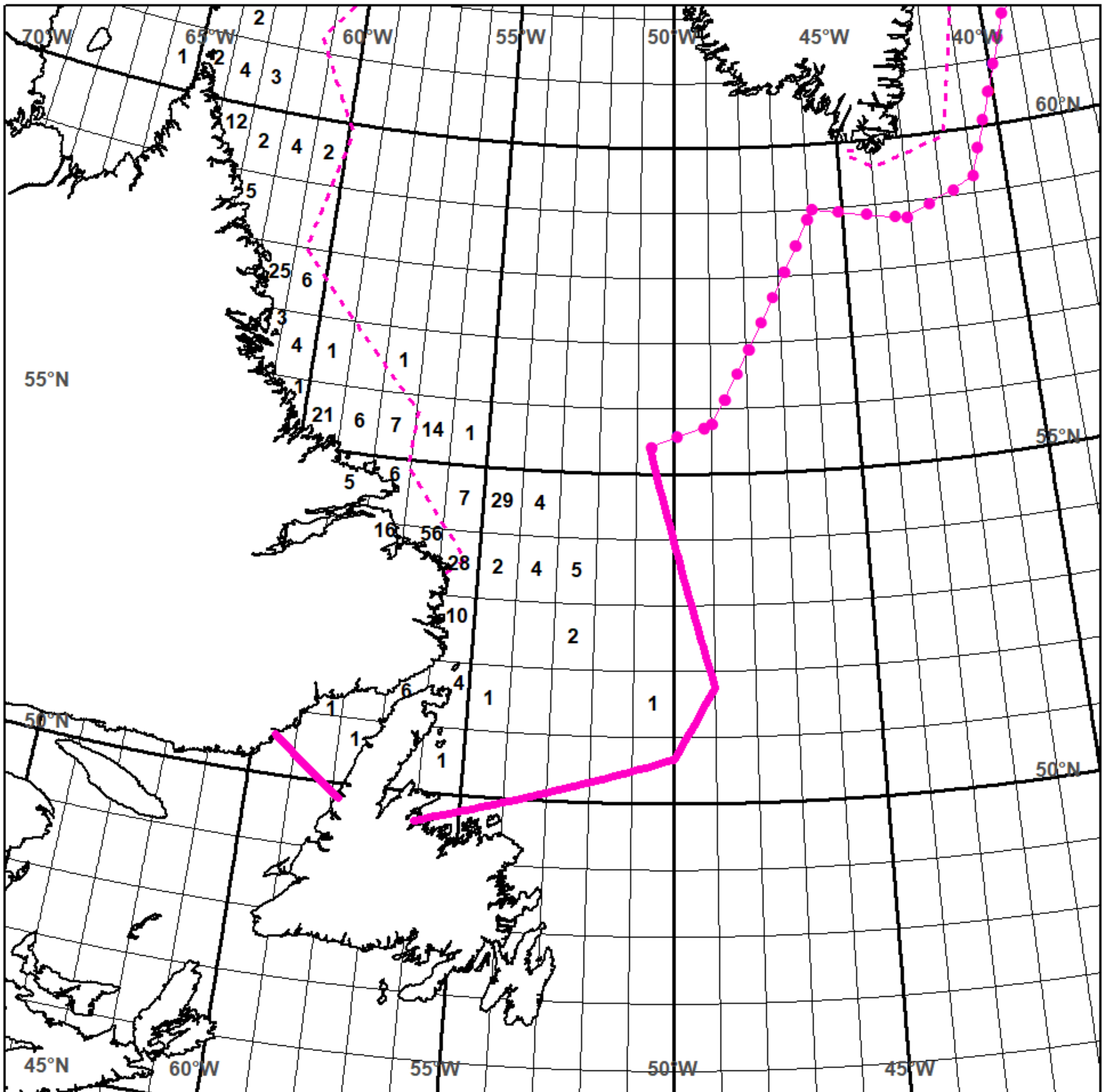
RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

Today we commemorate the 109th anniversary of the sinking of the RMS Titanic.

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Southern Limit General Flight 14APR21.


70°W
65°W
60°W
55°W
50°W
45°W
40°W
60°N
55°N
50°N
45°N
NORTH AMERICAN ICE SERVICE
(NAIS)
ICEBERG ANALYSIS FOR 1200 UTC
01 MAY 2021
ESTIMATED ICEBERG LIMIT
ICEBERG LIMIT
SEA ICE LIMIT
ICEBERGS PER DEGREE SQUARE
RADAR TARGET OUTSIDE ICEBERG LIMIT
NOTE:
For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Western Limit Iceberg Flight 29APR21.



NORTH AMERICAN ICE SERVICE (NAIS)

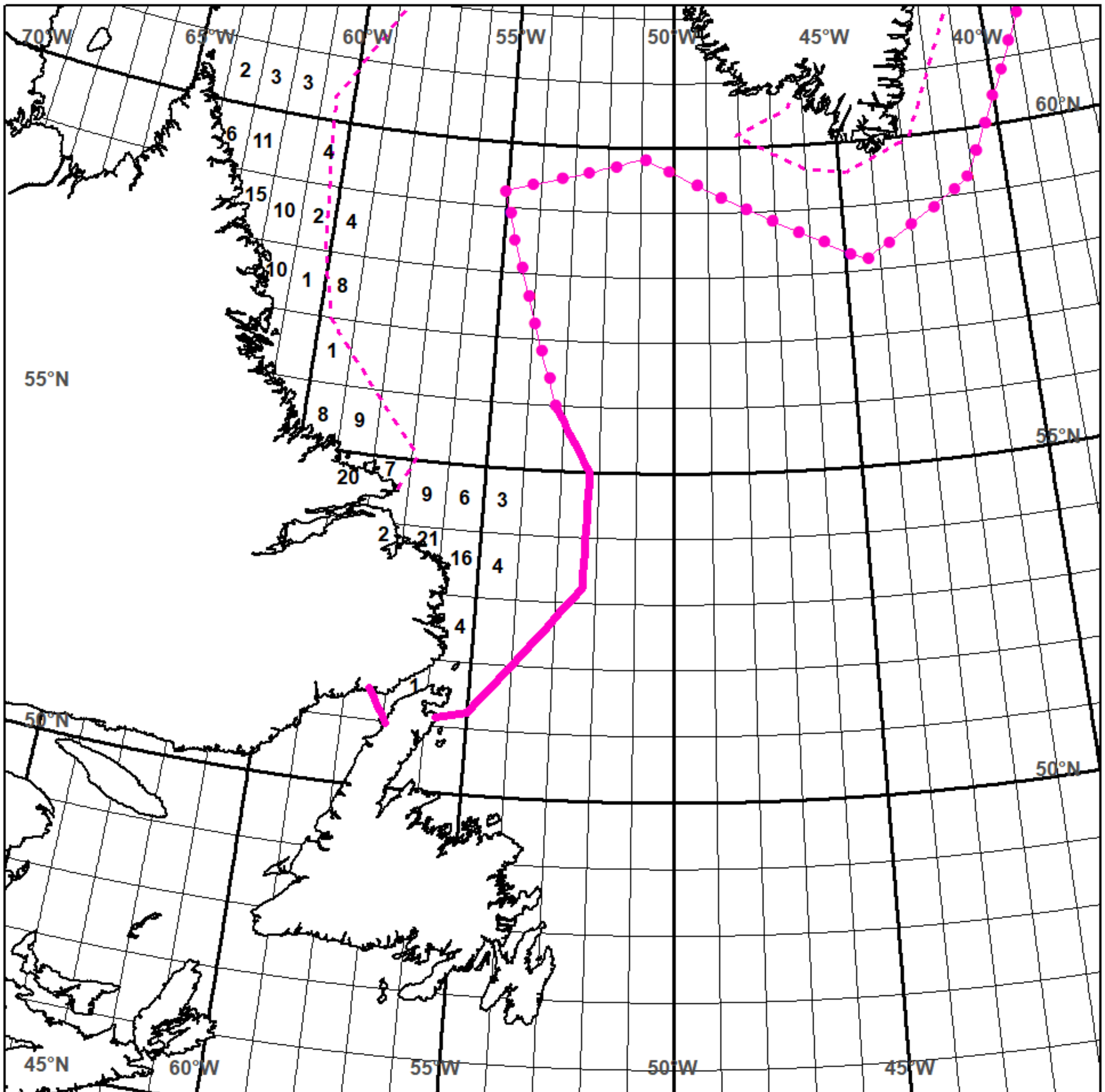
ICEBERG ANALYSIS FOR 0000 UTC

15 MAY 2021

- ESTIMATED ICEBERG LIMIT
- ICEBERG LIMIT
- SEA ICE LIMIT
- # ICEBERGS PER DEGREE SQUARE
- ⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Northern Survey Iceberg Flight 13MAY21.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

01 JUN 2021

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

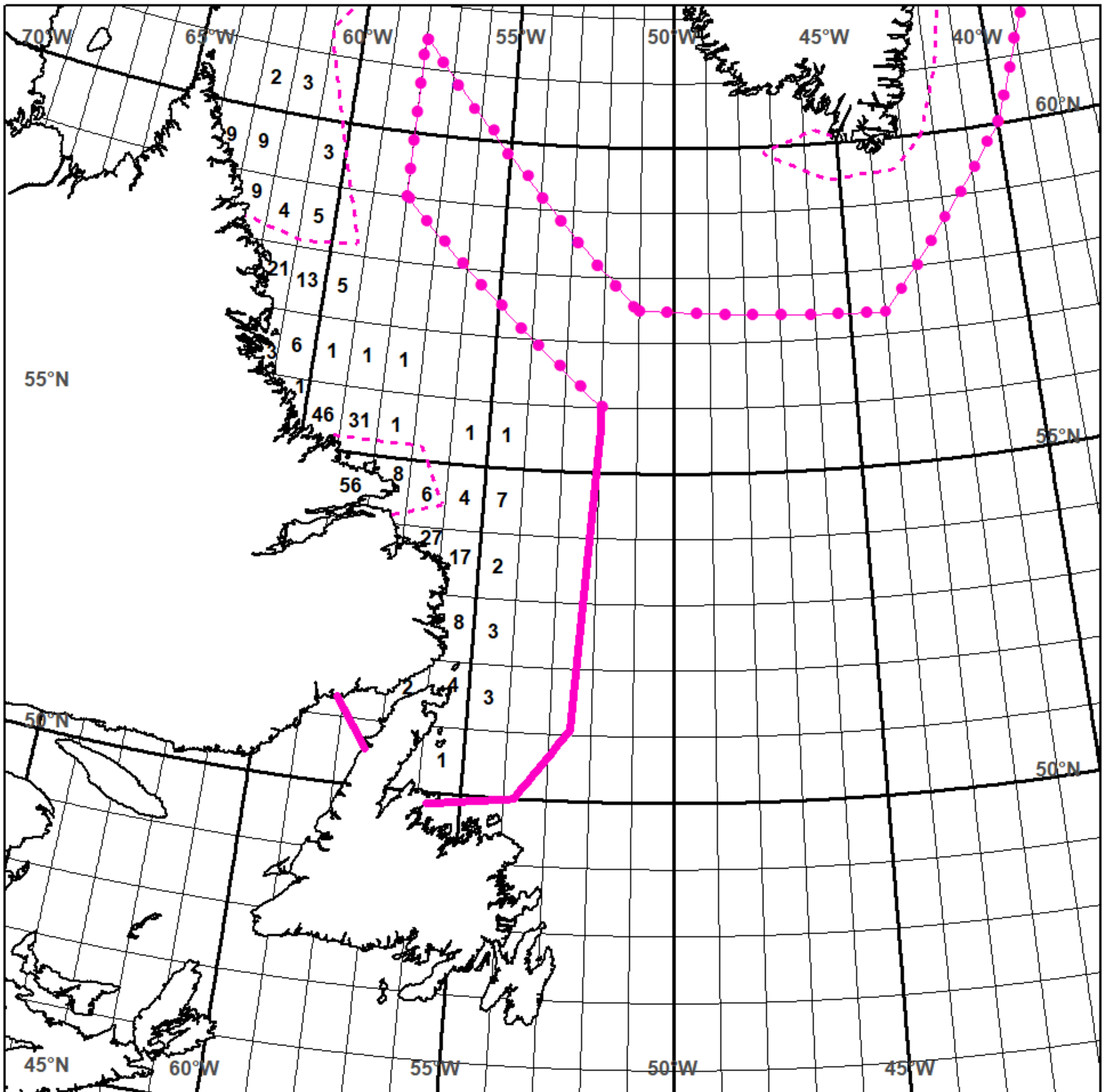
SEA ICE LIMIT

\# ICEBERGS PER DEGREE SQUARE

RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Western Limit Iceberg Flight 28MAY21.

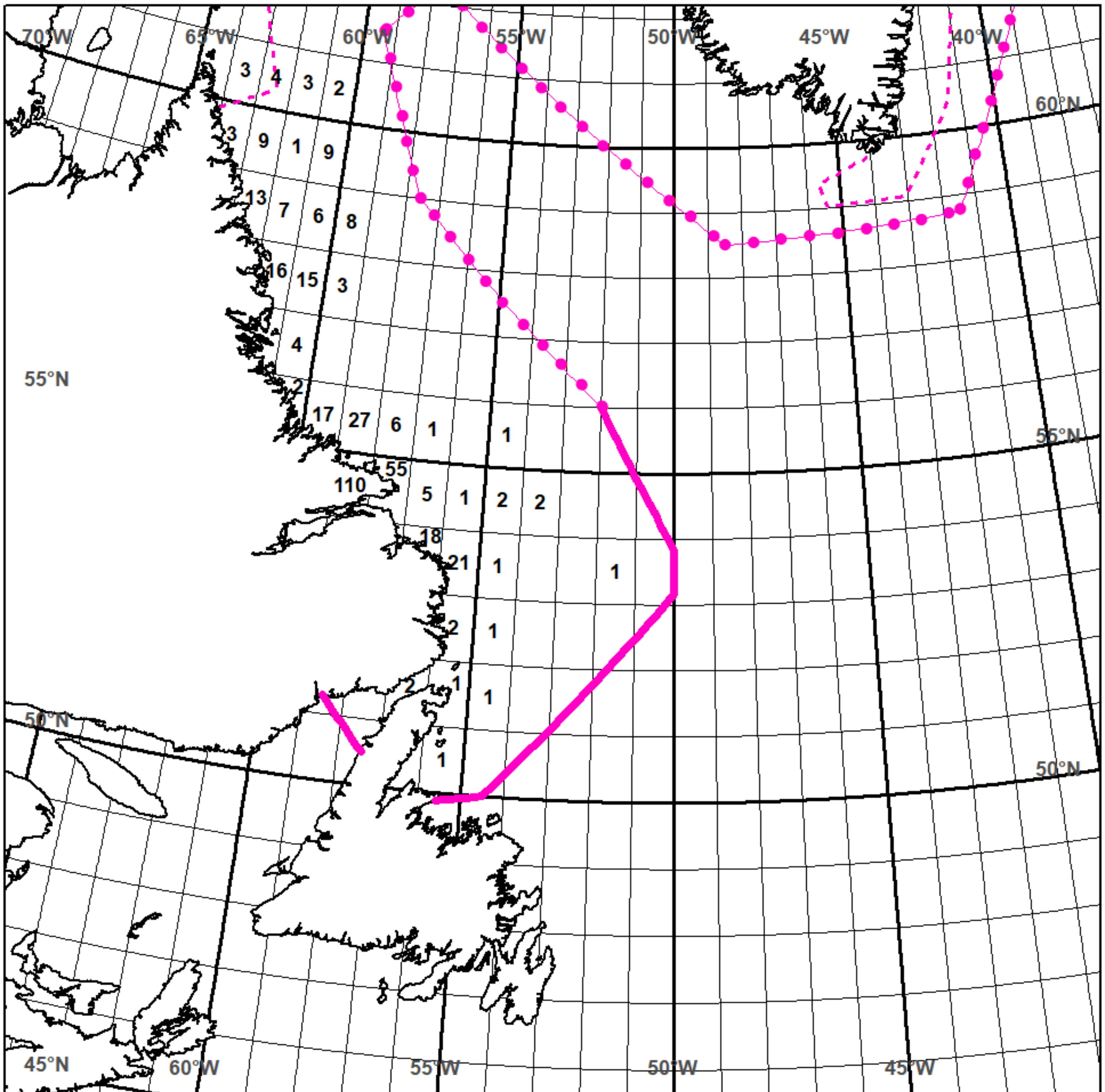


NORTH AMERICAN ICE SERVICE
(NAIS)

ICEBERG ANALYSIS FOR 0000 UTC
15 JUN 2021

ESTIMATED ICEBERG LIMIT
ICEBERG LIMIT
SEA ICE LIMIT
ICEBERGS PER DEGREE SQUARE
⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:
For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Interior General Flight 12JUN21.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

01 JUL 2021

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

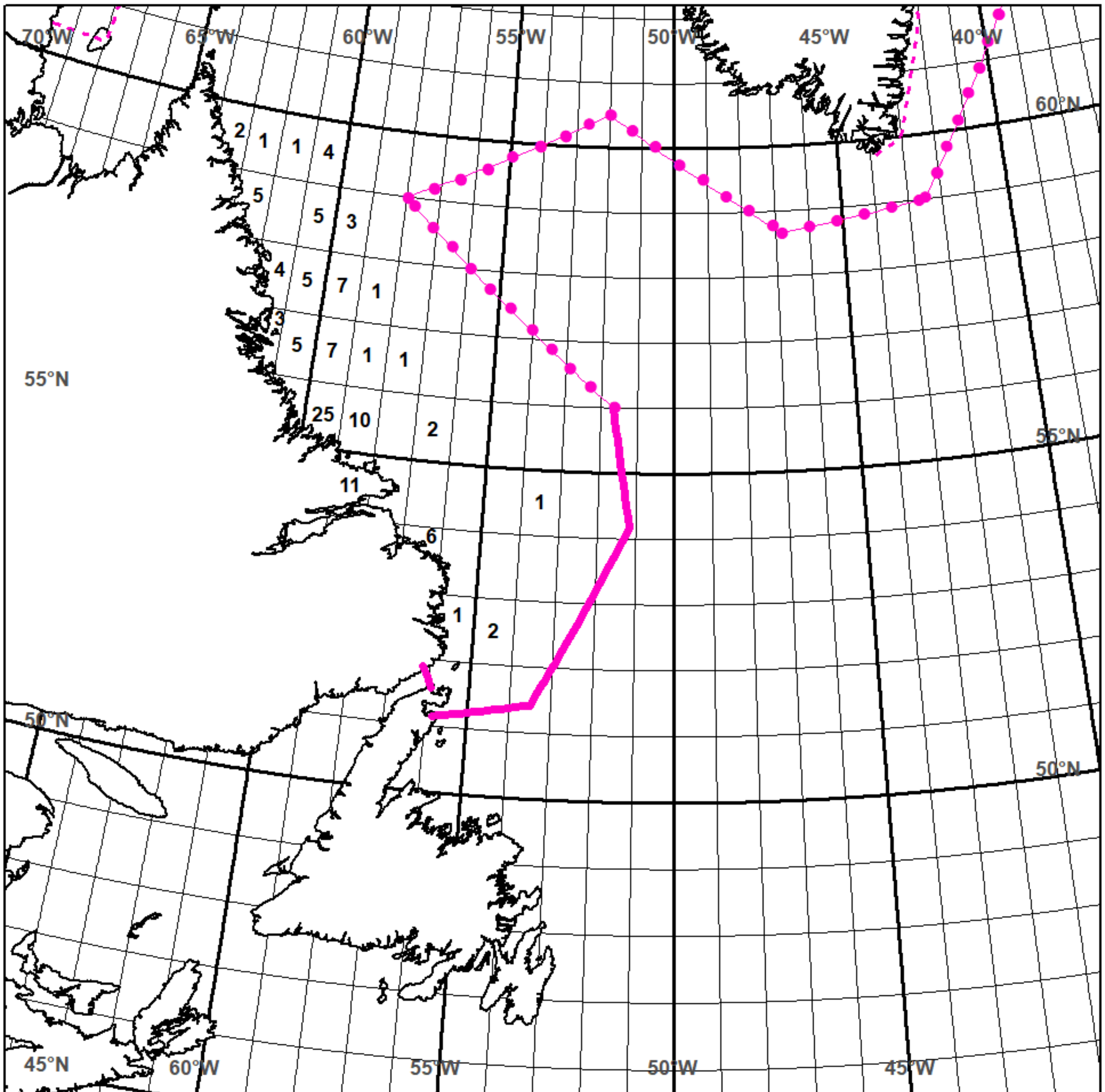
SEA ICE LIMIT

ICEBERGS PER DEGREE SQUARE

RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Interior Satellite Pass 28JUN21.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

15 JUL 2021

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

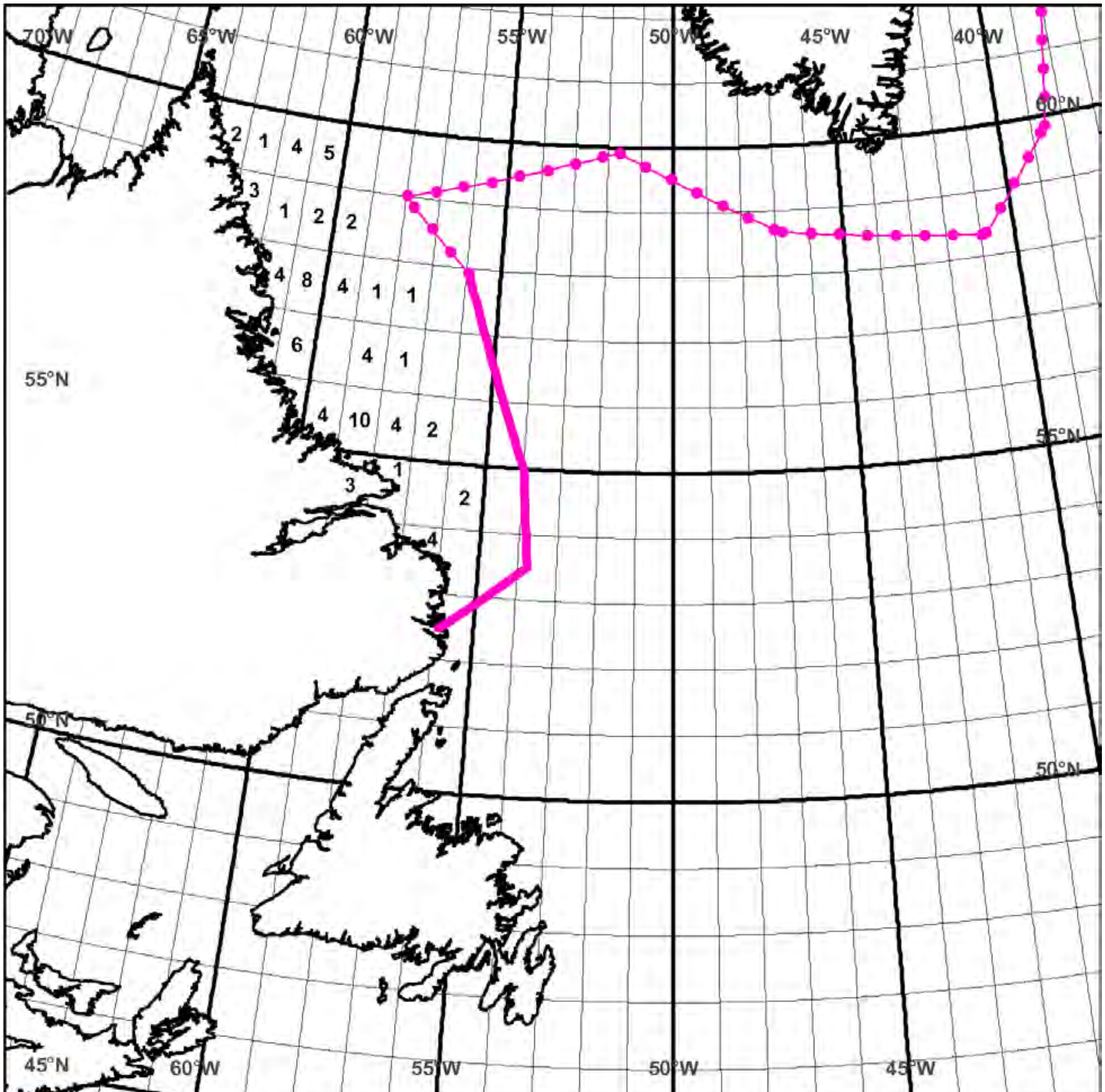
SEA ICE LIMIT

ICEBERGS PER DEGREE SQUARE

⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Northern Survey Satellite Pass 13JUL21.



NORTH AMERICAN ICE SERVICE (NAIS)

ICEBERG ANALYSIS FOR 0000 UTC

01 AUG 2021

ESTIMATED ICEBERG LIMIT

ICEBERG LIMIT

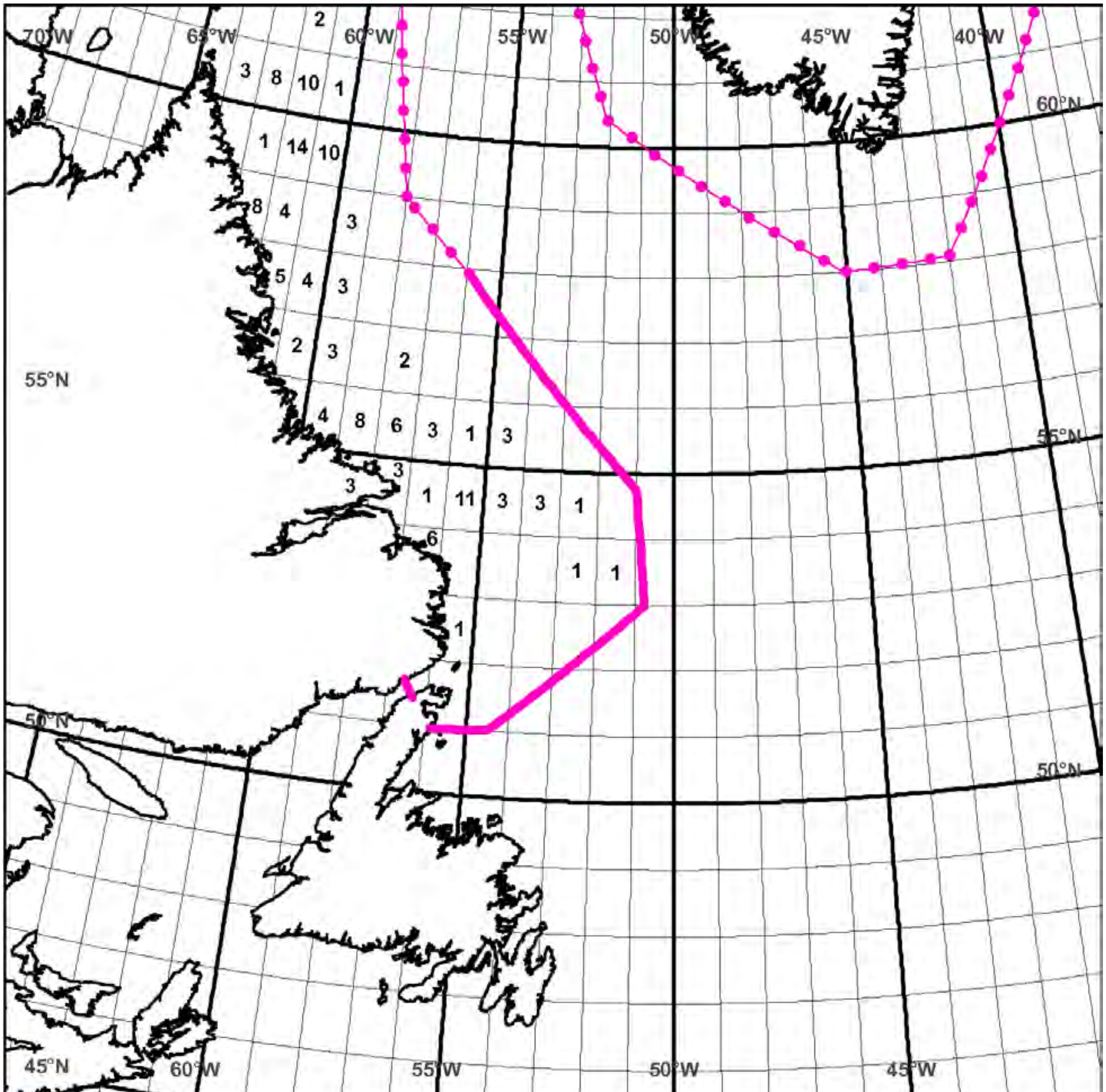
SEA ICE LIMIT

\# ICEBERGS PER DEGREE SQUARE

⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Interior General Flight 28JUL21.



NORTH AMERICAN ICE SERVICE (NAIS)

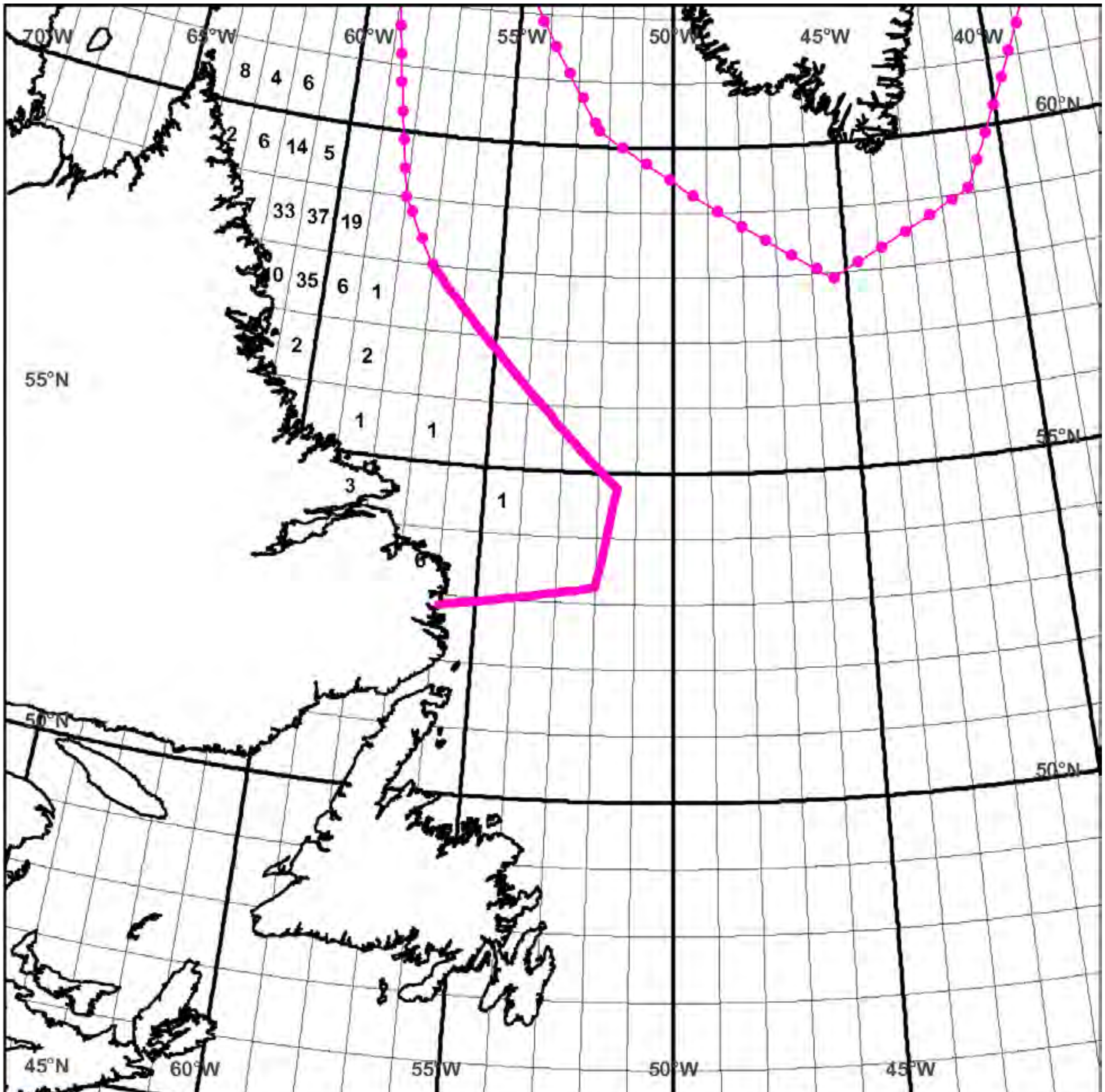
ICEBERG ANALYSIS FOR 0000 UTC

15 AUG 2021

- ESTIMATED ICEBERG LIMIT
- ICEBERG LIMIT
- SEA ICE LIMIT
- # ICEBERGS PER DEGREE SQUARE
- ⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Eastern Limit Iceberg Flight 05AUG21.



NORTH AMERICAN ICE SERVICE (NAIS)

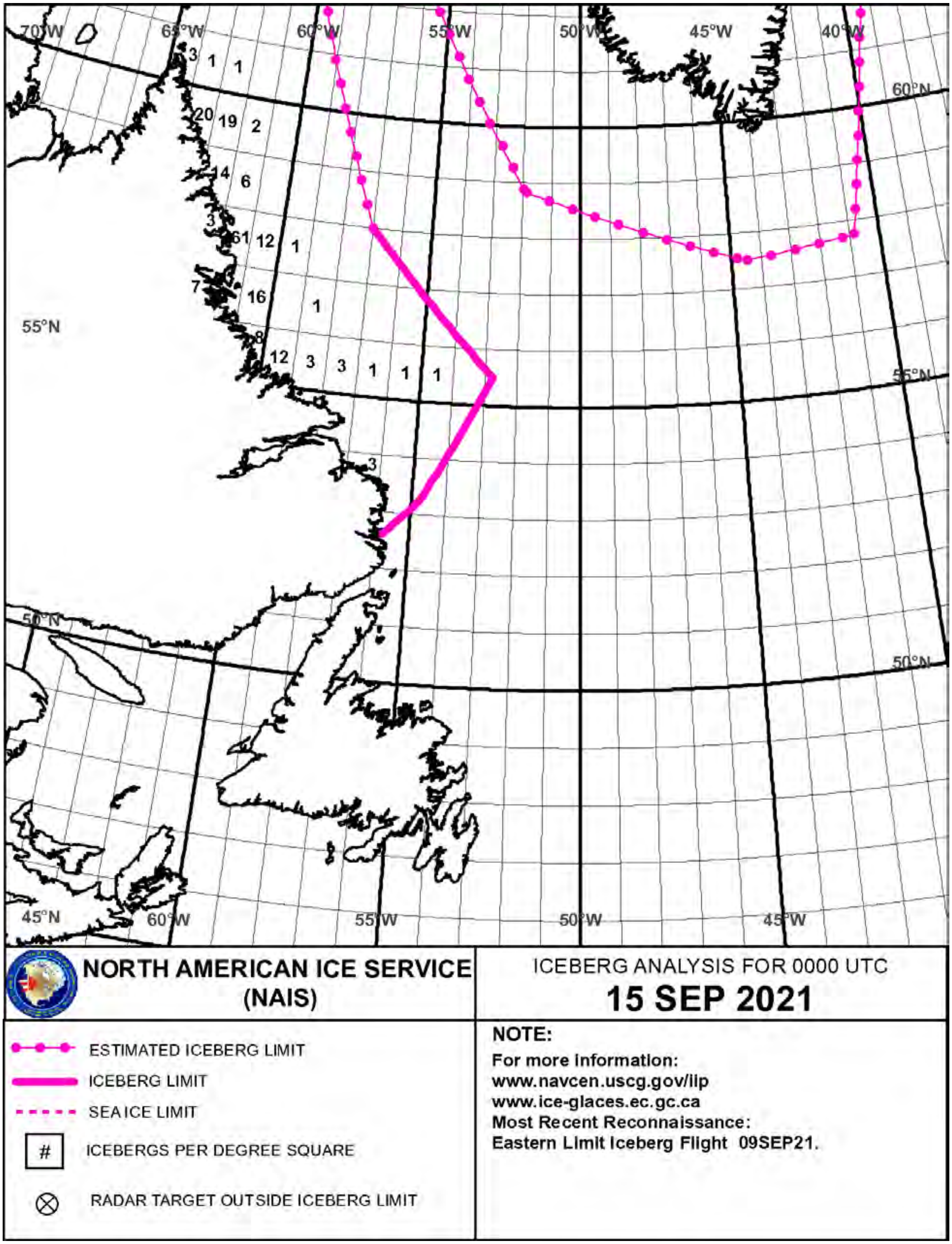
ICEBERG ANALYSIS FOR 0000 UTC

01 SEP 2021

- ESTIMATED ICEBERG LIMIT
- ICEBERG LIMIT
- SEA ICE LIMIT
- # ICEBERGS PER DEGREE SQUARE
- ⊗ RADAR TARGET OUTSIDE ICEBERG LIMIT

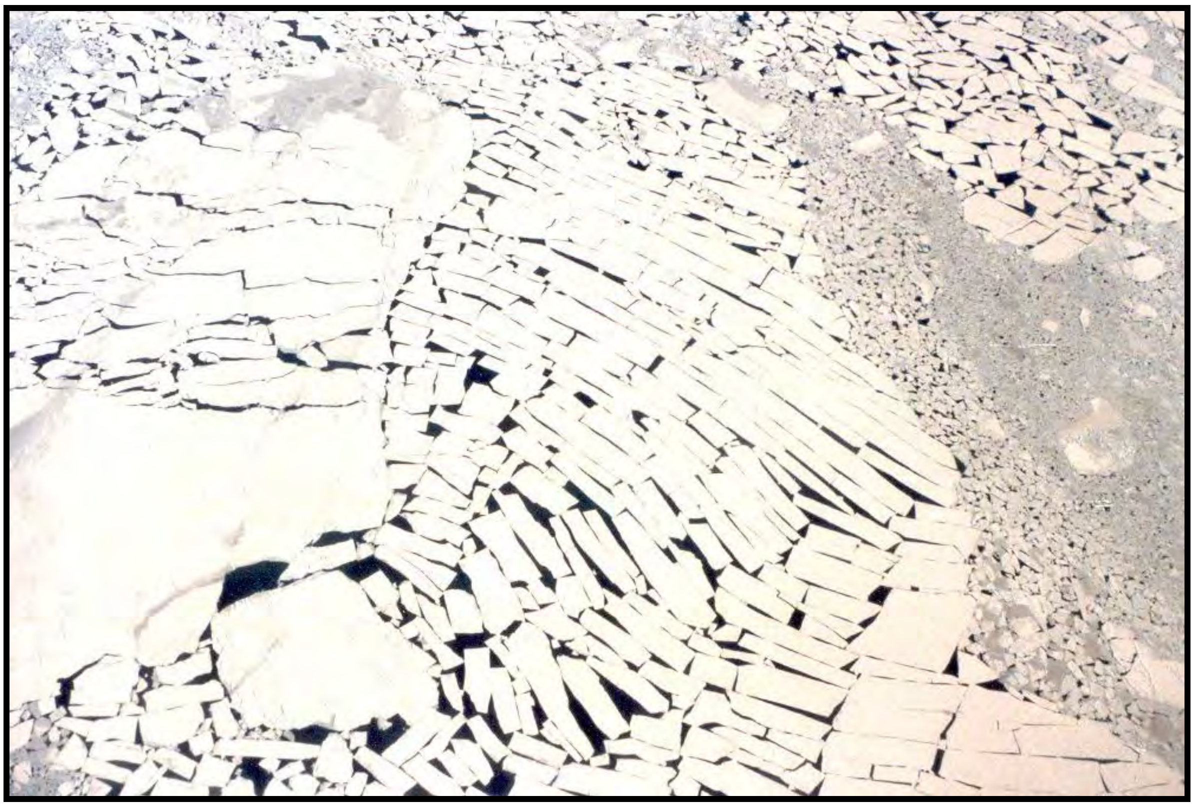
NOTE:

For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Eastern Limit Iceberg Flight 21AUG21.

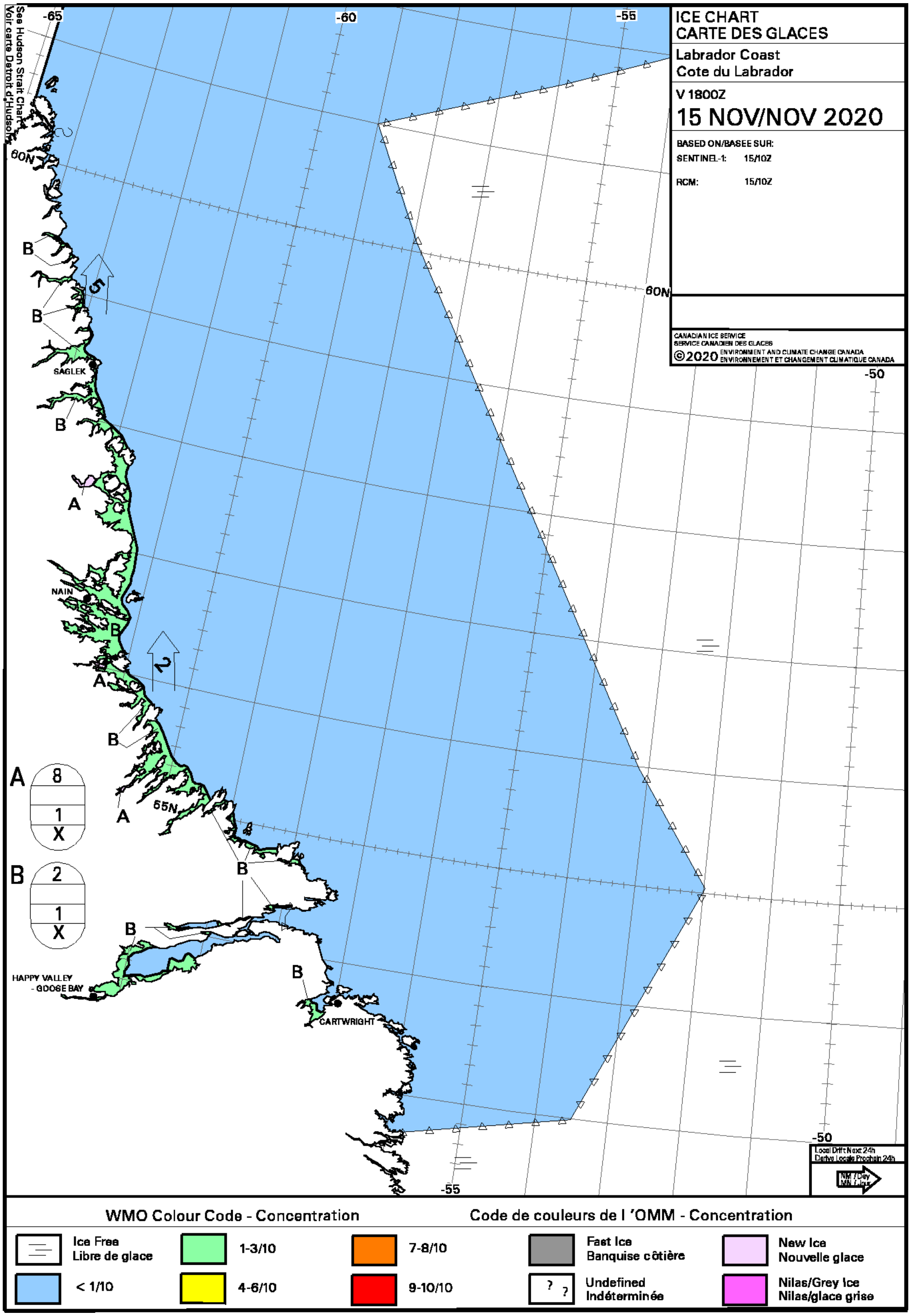


70°W
65°W
60°W
55°W
50°W
45°W
40°W
60°N
55°N
50°N
45°N
3 1 1
20 19 2
14 6
3
61 12 1
7 16 1
8
12 3 3 1 1 1
3
NORTH AMERICAN ICE SERVICE
(NAIS)
ICEBERG ANALYSIS FOR 0000 UTC
15 SEP 2021
ESTIMATED ICEBERG LIMIT
ICEBERG LIMIT
SEA ICE LIMIT
ICEBERGS PER DEGREE SQUARE
RADAR TARGET OUTSIDE ICEBERG LIMIT
NOTE:
For more information:
www.navcen.uscg.gov/iip
www.ice-glaces.ec.gc.ca
Most Recent Reconnaissance:
Eastern Limit Iceberg Flight 09SEP21.

8. Monthly Sea-Ice Charts



The following sea-ice charts for Northeast Newfoundland Waters are produced by the Canadian Ice Service. Months without measureable sea ice concentration on the charts were omitted.



ICE CHART
CARTE DES GLACES
Labrador Coast
Cote du Labrador
V 1800Z
15 NOV/NOV 2020
BASED ON/BASEE SUR:
SENTINEL-1: 15/10Z
RCM: 15/10Z
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
©2020 ENVIRONMENT AND CLIMATE CHANGE CANADA
ENVIRONNEMENT ET CHANGEMENT CLIMATIQUE CANADA
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Libre de glace
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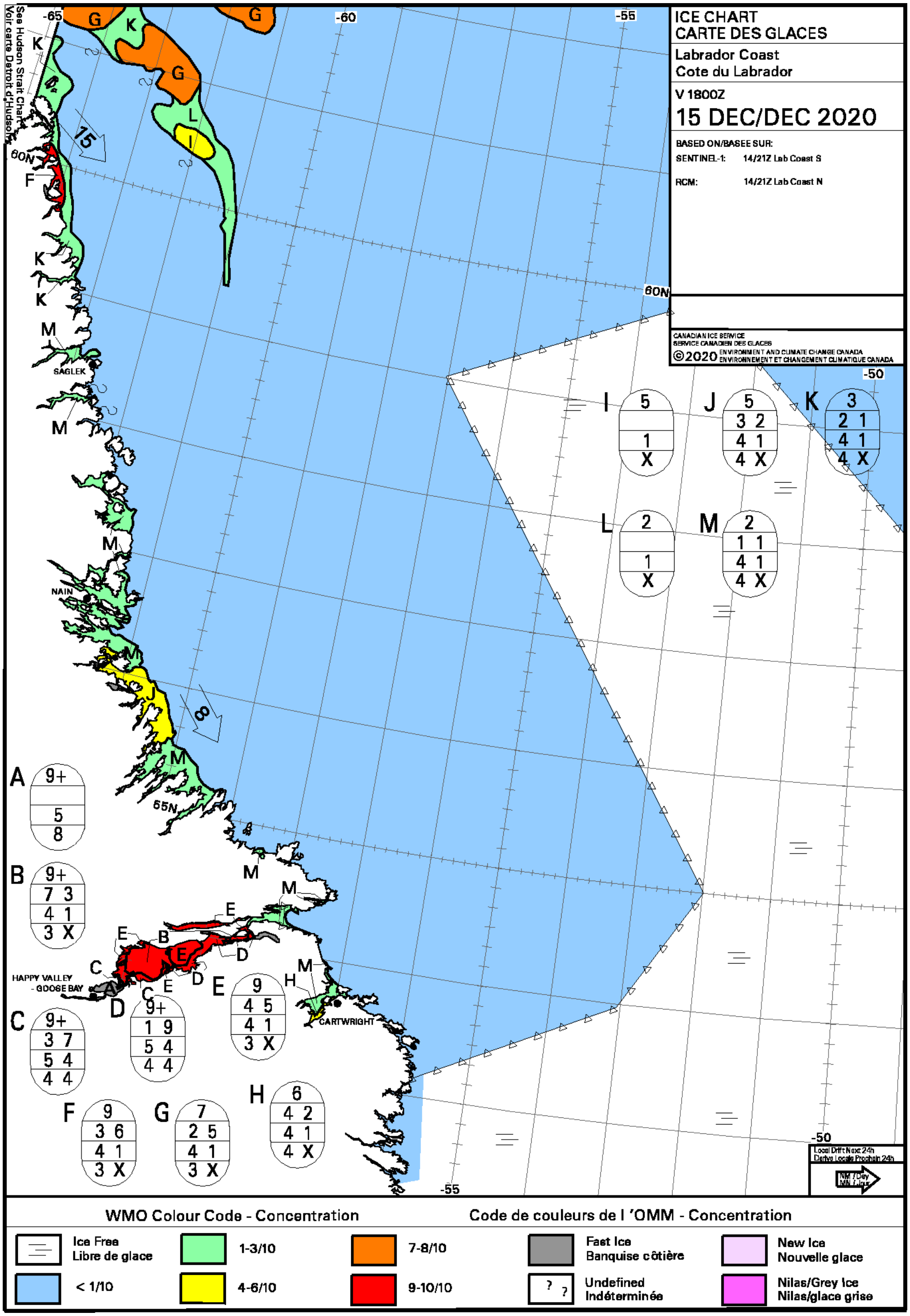
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HAPPY VALLEY - GOOSE BAY
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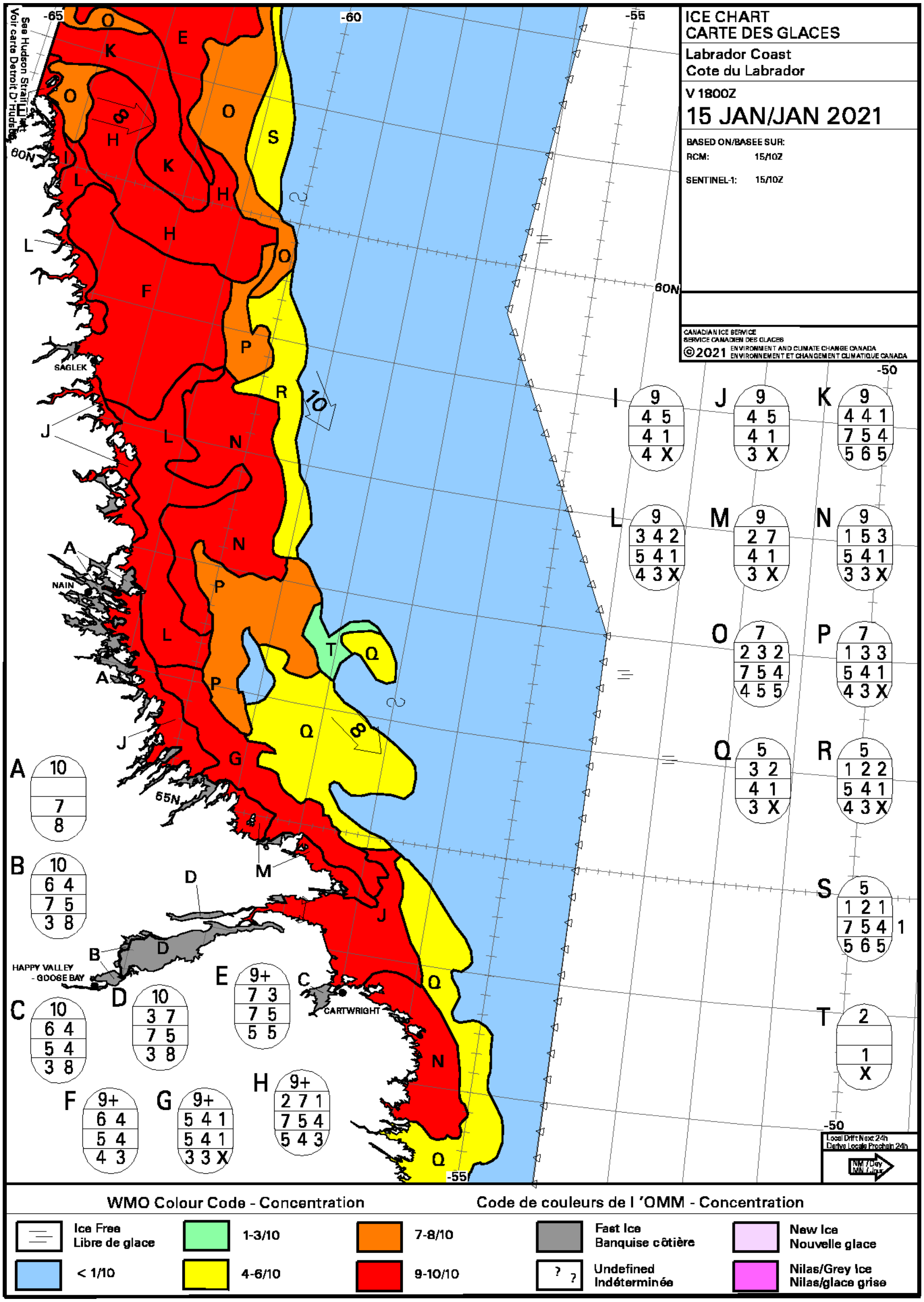

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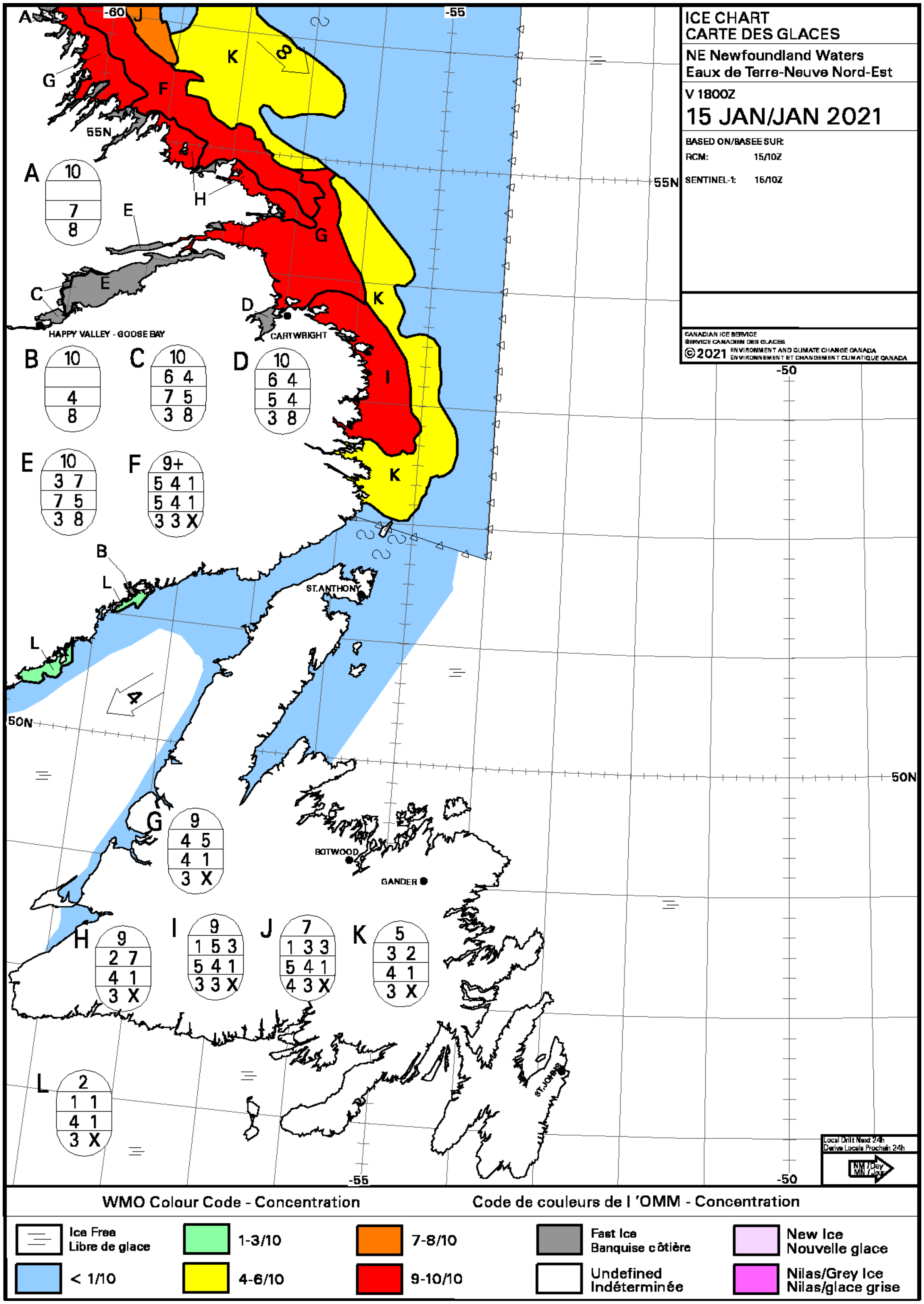
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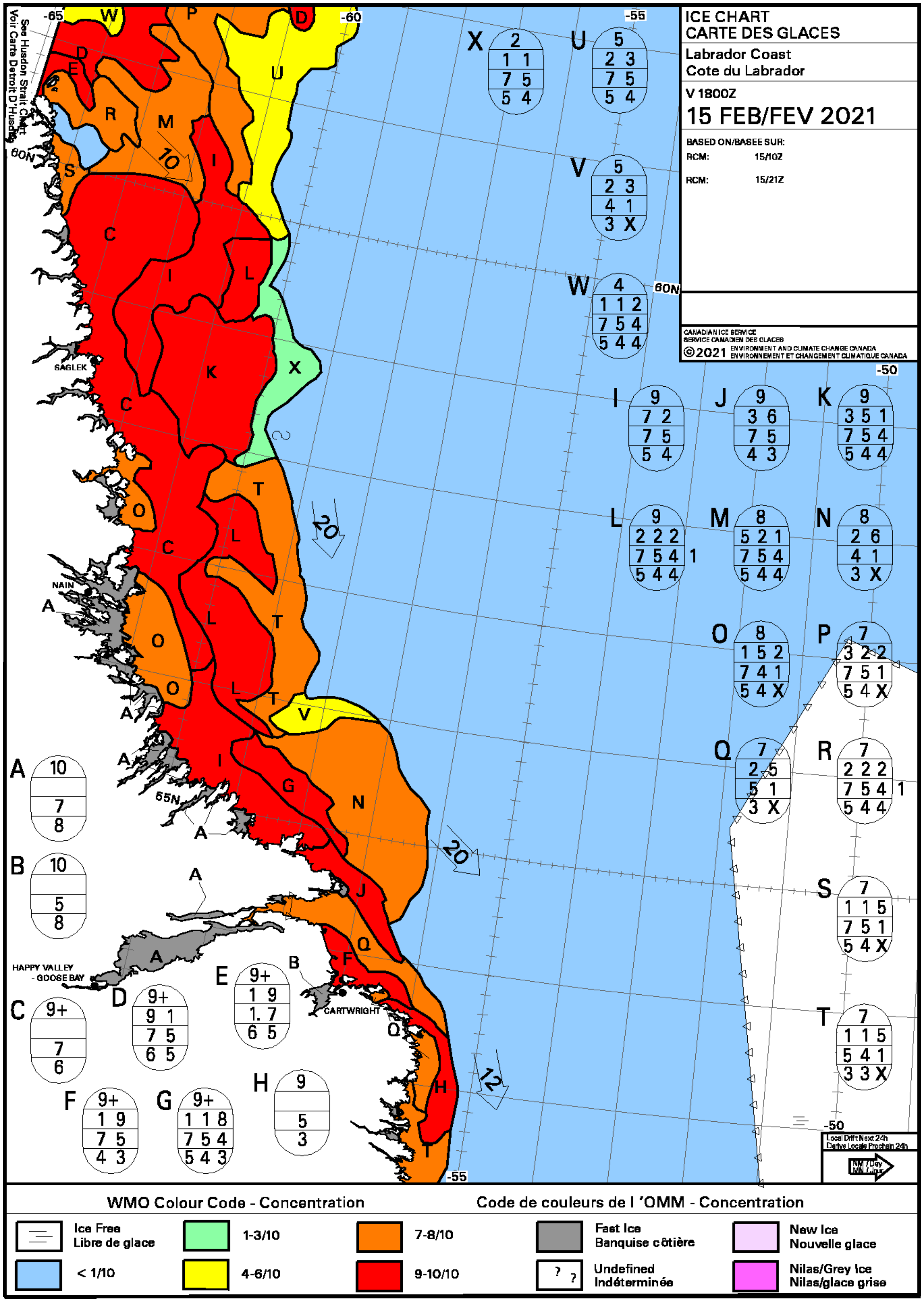
Nilas/glace grise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Cote du Labrador
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CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
©2021 ENVIRONMENT AND CLIMATE CHANGE CANADA
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See Hudson Strait Chart
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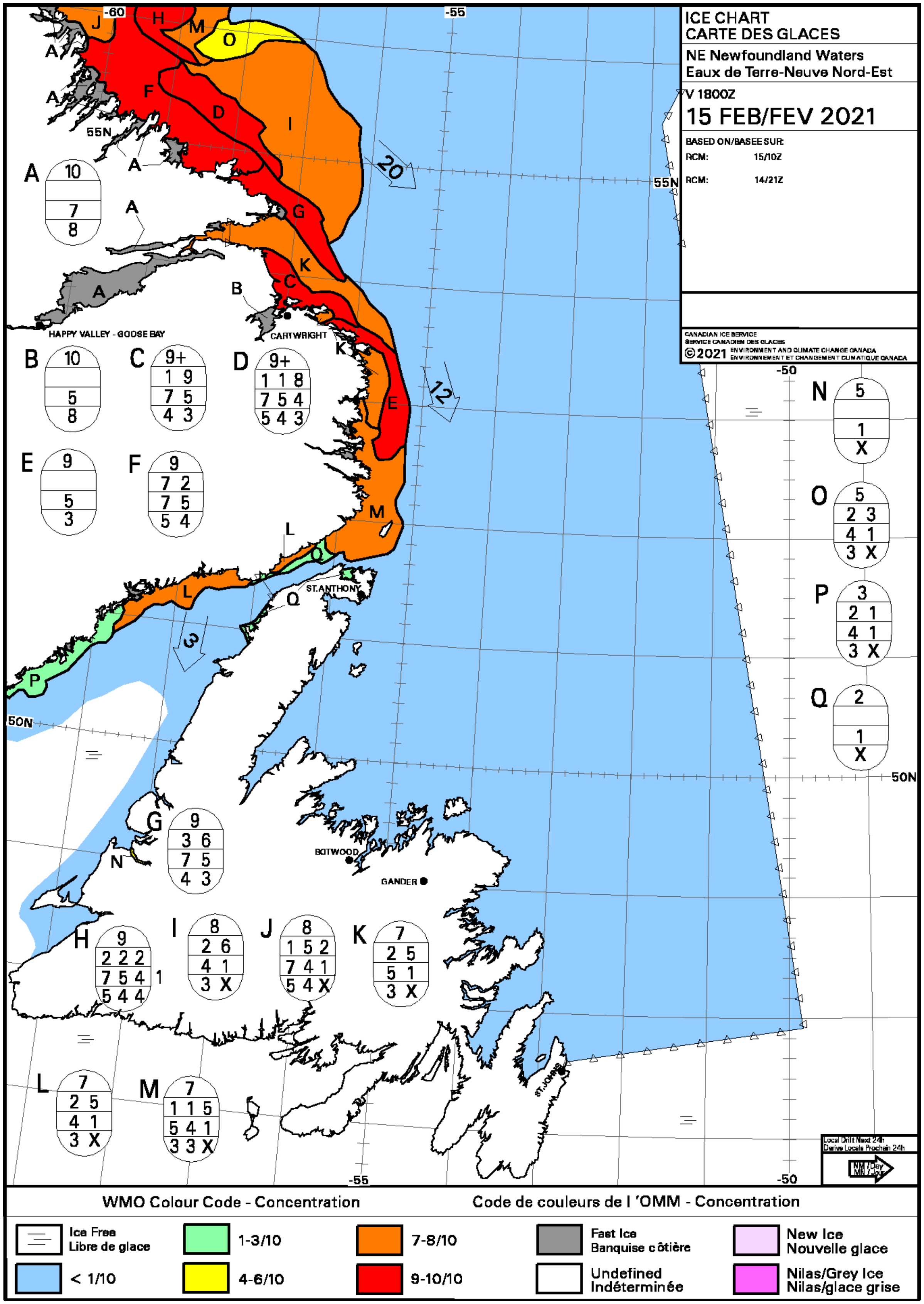
Nouvelle glace
Nilas/Grey Ice
Nilas/glace grise



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V 1800Z
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CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
©2021 ENVIRONMENT AND CLIMATE CHANGE CANADA
ENVIRONNEMENT ET CHANGEMENT CLIMATIQUE CANADA
HAPPY VALLEY - GOOSE BAY
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BOTWOOD
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L 7 / 2 5 / 4 1 / 3 X
M 7 / 1 1 5 / 5 4 1 / 3 3 X
N 5 / 1 / X
O 5 / 2 3 / 4 1 / 3 X
P 3 / 2 1 / 4 1 / 3 X
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MN/Jour
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Code de couleurs de l 'OMM - Concentration
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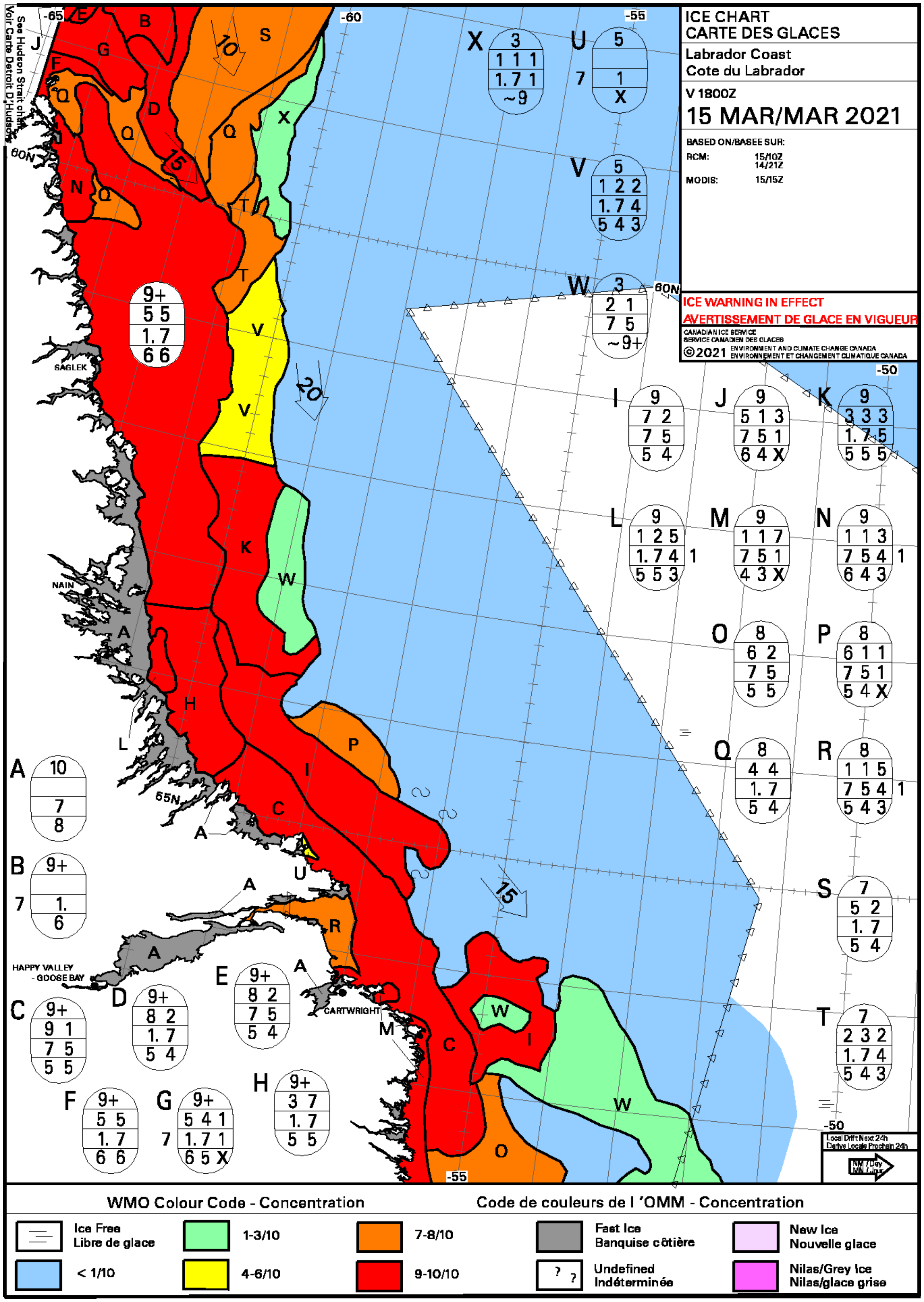
Nouvelle glace
Nilas/Grey Ice
Nilas/glace grise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Labrador Coast
Cote du Labrador
V 1800Z
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BASED ON/BASEE SUR:
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MODIS: 15/15Z
ICE WARNING IN EFFECT
AVERTISSEMENT DE GLACE EN VIGUEUR
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
©2021 ENVIRONMENT AND CLIMATE CHANGE CANADA
ENVIRONNEMENT ET CHANGEMENT CLIMATIQUE CANADA
See Hudson Strait chart
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New Ice
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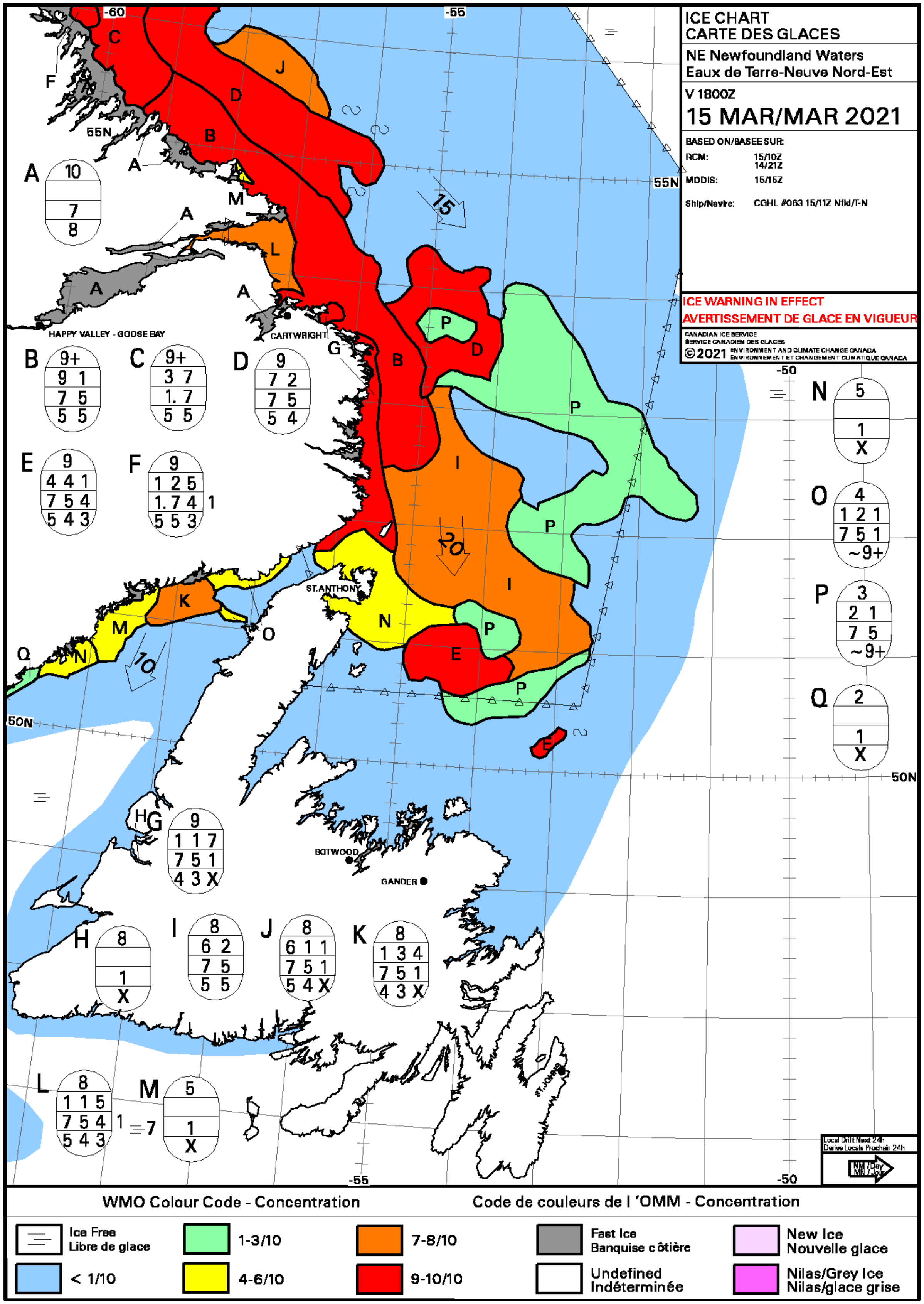
Nilas/Grey Ice
Nilas/glace grise


ICE CHART
CARTE DES GLACES
NE Newfoundland Waters
Eaux de Terre-Neuve Nord-Est
V 1800Z
15 MAR/MAR 2021
BASED ON/BASEE SUR:
RCM: 15/10Z 14/21Z
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Ship/Navire: CGHL #063 15/11Z Nfld/T-N
ICE WARNING IN EFFECT
AVERTISSEMENT DE GLACE EN VIGUEUR
CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
©2021 ENVIRONMENT AND CLIMATE CHANGE CANADA
ENVIRONNEMENT ET CHANGEMENT CLIMATIQUE CANADA
HAPPY VALLEY - GOOSE BAY
CARTWRIGHT
ST.ANTHONY
BOTWOOD
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Local Drift Next 24h
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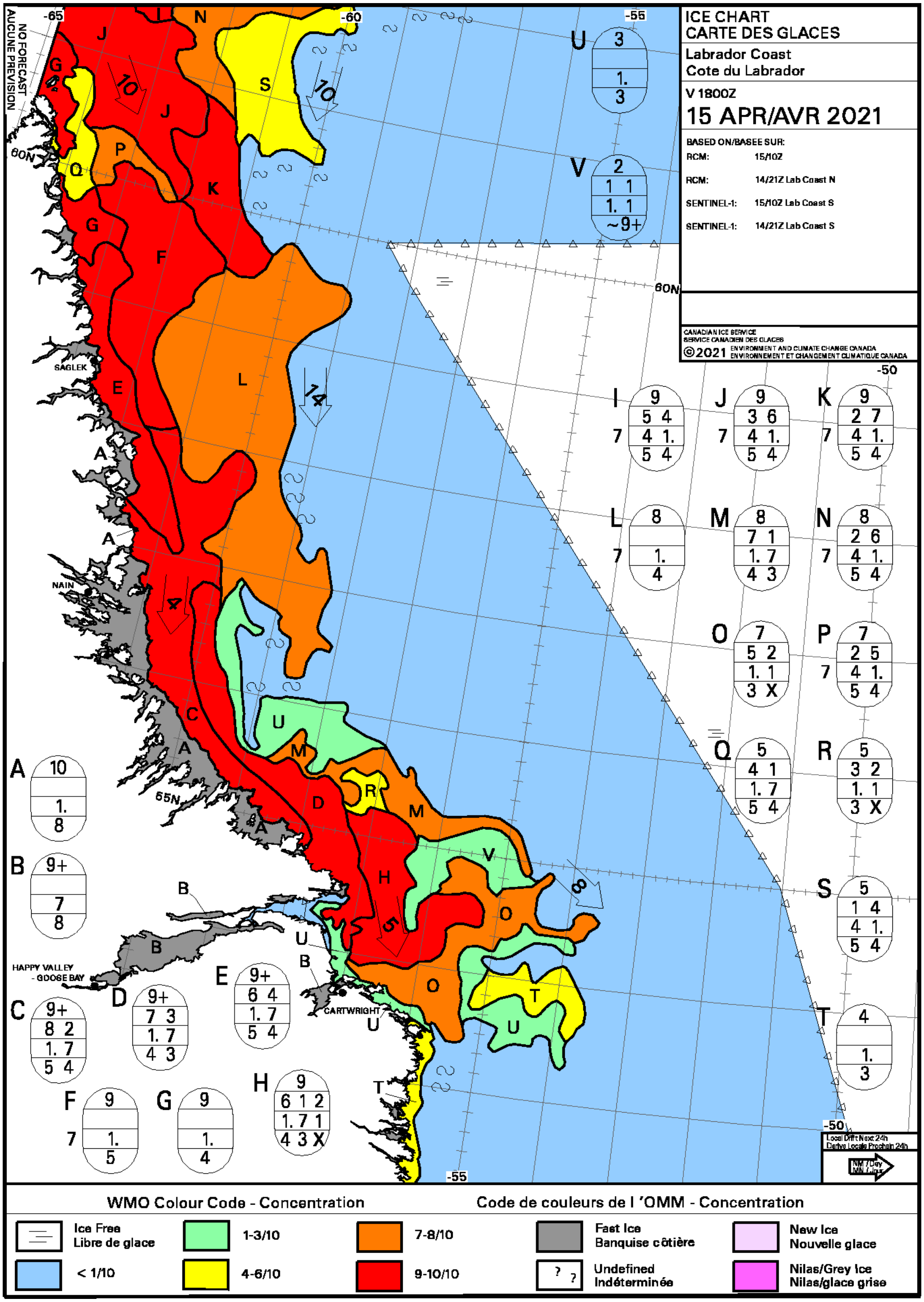
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Labrador Coast
Cote du Labrador
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15 APR/AVR 2021
BASED ON/BASEE SUR:
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CANADIAN ICE SERVICE
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HAPPY VALLEY - GOOSE BAY
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Dérive Locale Prochain 24h
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WMO Colour Code - Concentration
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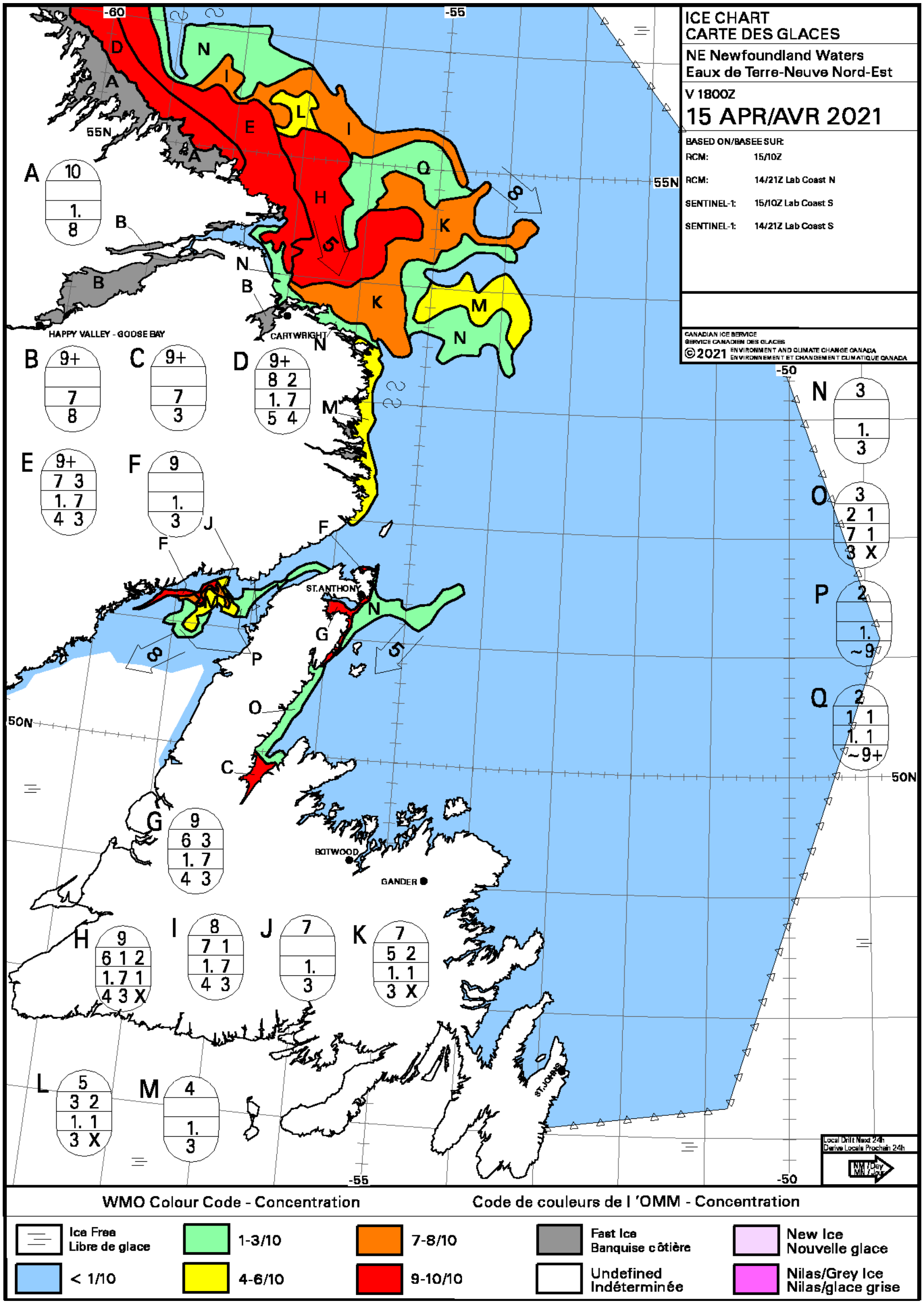
ICE CHART
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NE Newfoundland Waters
Eaux de Terre-Neuve Nord-Est
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CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
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HAPPY VALLEY - GOOSE BAY
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GANDER
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E 9+ / 7 3 / 1. 7 / 4 3
F 9 / 1. / 3
G 9 / 6 3 / 1. 7 / 4 3
H 9 / 6 1 2 / 1. 7 1 / 4 3 X
I 8 / 7 1 / 1. 7 / 4 3
J 7 / 1. / 3
K 7 / 5 2 / 1. 1 / 3 X
L 5 / 3 2 / 1. 1 / 3 X
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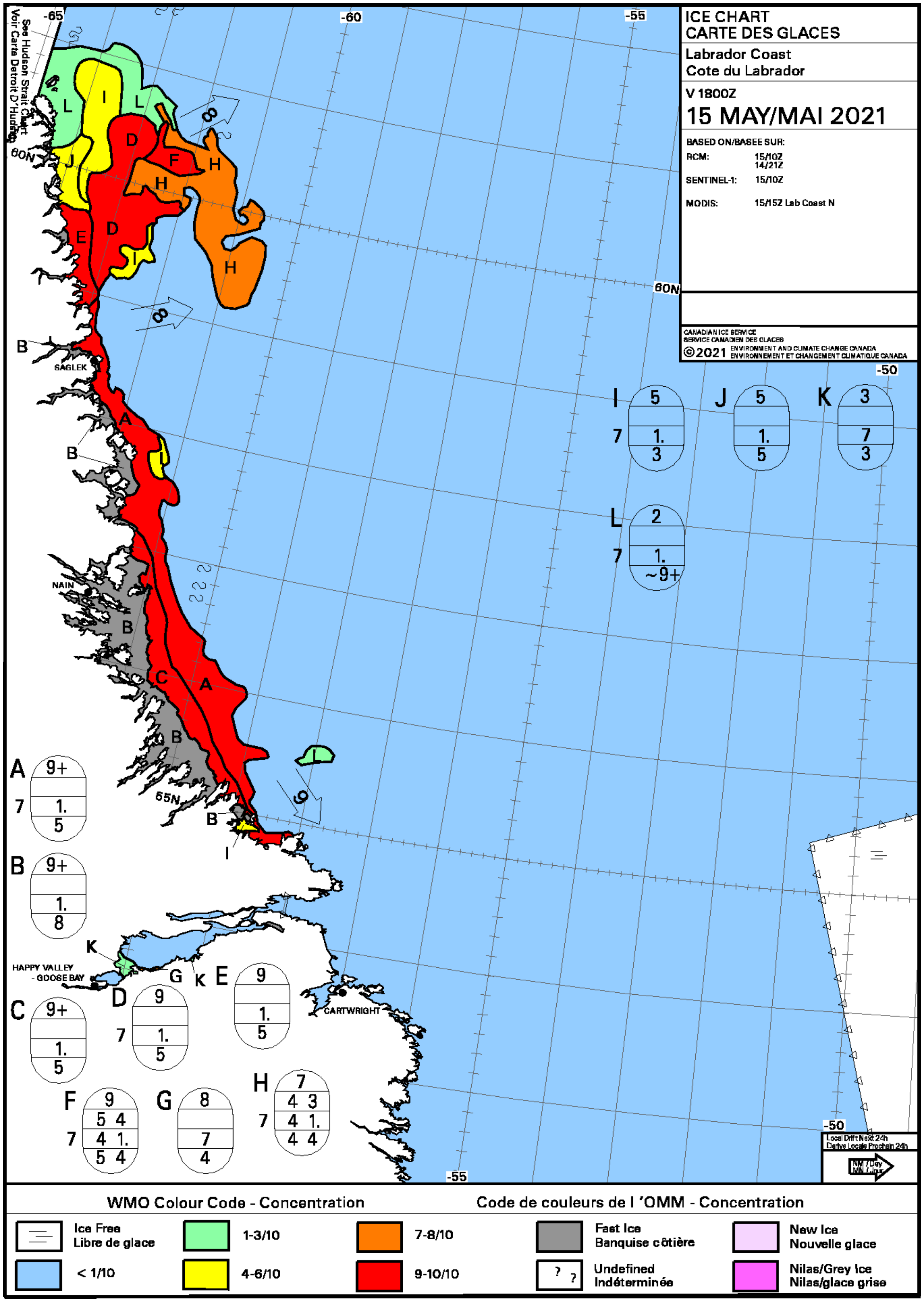
ICE CHART
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Labrador Coast
Cote du Labrador
V 1800Z
15 MAY/MAI 2021
BASED ON/BASEE SUR:
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CANADIAN ICE SERVICE
SERVICE CANADIEN DES GLACES
©2021 ENVIRONMENT AND CLIMATE CHANGE CANADA
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See Hudson Strait Chart
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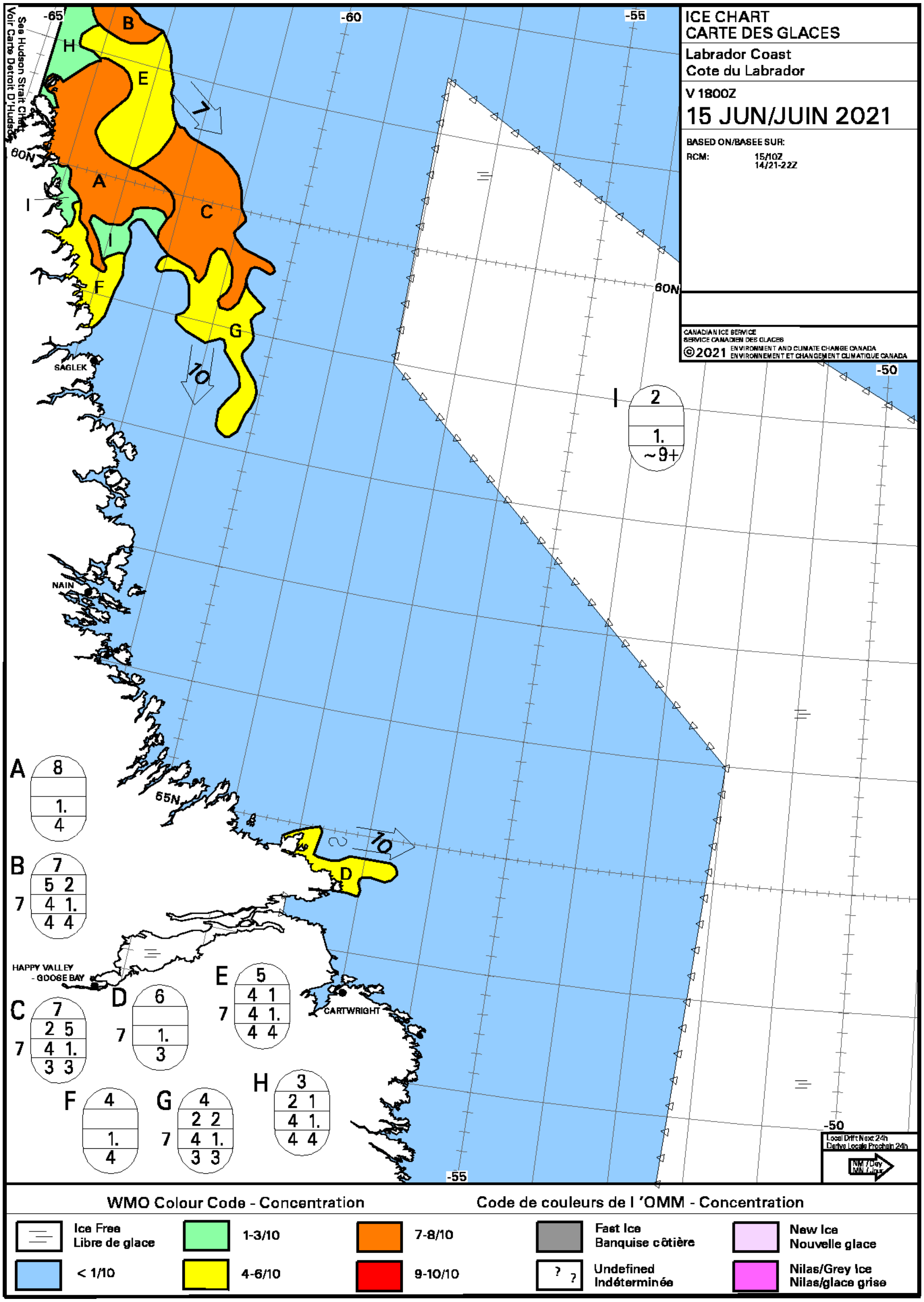

ICE CHART
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Nilas/glace grise

9. Acknowledgements

Commander, International Ice Patrol acknowledges the following organizations for providing information and assistance:

Aerospace Corporation

Canadian Coast Guard

Canadian Forces

Canadian Ice Service

Canadian Maritime Atlantic Command Meteorological and Oceanographic Centre

Canadian Meteorological Centre

Cold Regions Research Engineering Laboratory

C-CORE

Department of Fisheries and Oceans Canada

Danish Meteorological Institute

European Space Agency

German Federal Maritime and Hydrographic Agency

International Cooperative Engagement Program for Polar Research (ICE-PPR)

Joint Arctic Command

MacDonald, Dettwiler and Associates

National Geospatial-Intelligence Agency

National Research Council Canada

National Oceanic and Atmospheric Administration

NOAA Office of Satellite Products and Operations

National Weather Service

Nav Canada Flight Information Center

PAL Aerospace

PAL Aviation Services

Titanic Society of Atlantic Canada

Transport Canada

USCG Air Station Elizabeth City

USCG Air Station Cape Cod

USCG Assistant Commandant for Intelligence

USCG Atlantic Area

USCG Aviation Training Center Mobile

USCG Academy

USCG Cutter ESCANABA (WMEC-907)

USCG Barque EAGLE (WIX-327)

USCGC HEALY (WAGB-20)

USCG Cutter MAPLE (WLB-207)

USCG Cutter RICHARD SNYDER (WPC-1127)

USCG Director of Marine Transportation Systems

USCG First District

USCG Maritime Fusion Intelligence Center Atlantic

USCG Navigation Center

USCG Research and Development Center

U.S. Department of Homeland Security Science & Technology Directorate

U.S. National Ice Center

U.S. National Reconnaissance Office

U.S. Naval Fleet Numerical Meteorology and Oceanography Center

U.S. Naval Information Warfare Center Pacific

U.S. Naval Research Laboratory

It is important to recognize the outstanding efforts of the personnel assigned to the International Ice Patrol during the 2021 Ice Year:

CDR M. T. Hirschberg

LCDR C. B. Bell

LCDR D. W. Rudnickas

Mr. M. R. Hicks

Mrs. B. J. Lis

Ms. J. L. Sabal

LT A. R. Hamel

LT S. K. Griswold

MSTC N. D. Brophy

MST1 S. A. Baumgartner

MST1 M. A. Berlin

YN1 W. R. Lawrence

IS1 M. A. Patti

IS1 V. A. Pacheco

IS2 P. D. Miller

MST2 J. Ambro

MST2 M. J. Brown

MST2 R. M. Hogan

MST2 J. P Leser

MST2 M. Loughlin

MST3 B. V. Dames

IS3 J. H. Dominguez

Appendix A

Ship Reports for Ice Year 2021

Ships Reporting by Flag	Reports
CANADA	
CCGS DES GROSEILLIERS	2
EBROBORG	1
CCGS HENRY LARSEN	5
CCGS JEAN GOODWILL	1
* CCGS TERRY FOX	9
UMIAK 1	6
MARSHALL ISLANDS	
FEDERAL CARIBOU	1
FEDERAL RUHR	1
FEDERAL SABLE	1
FEDERAL WESER	1
NETHERLANDS	
FIVELBORG	3

* Denotes the CARPATHIA award winner.

IIP awards the vessel that submits the most iceberg reports each year. The award is named after the CARPATHIA, the vessel credited with rescuing 705 survivors from the TITANIC disaster.

Appendix B. Tailored Iceberg Products in Support of U.S. Coast Guard Cutters

LT Alex Hamel

B-1. Introduction

Following the first successful iteration of providing custom, risk-based iceberg products to a Coast Guard vessel in 2017, the International Ice Patrol (IIP) significantly expanded its tailored iceberg support and aided with the safe navigation of five different vessels operating around Greenland and the Labrador Sea in 2021. These Coast Guard cutters ranged in icebreaking capability from a polar-capable medium icebreaker to vessels with no ice strengthening at all. Three of the cutters were assigned to participate in the international training exercises NANOOK and ARGUS, one was responsible for completing science operations throughout the Arctic and Baffin Bay, and the fifth cutter was conducting a training cruise to include a visit to Reykjavik, Iceland. This endeavor marked IIP's continued efforts to support a different type of customer: one that typically does not receive iceberg warning products, is transiting well north of the Iceberg Limit, and expects to encounter significant iceberg populations. IIP's longstanding statutory mission to monitor the iceberg danger in the North Atlantic Ocean and provide relevant iceberg warning products to the maritime community has, until recently, been solely executed with the transatlantic shipping community in mind, a user base that is typically focused on avoiding icebergs at all cost.

This support was an excellent showcase of the inter-agency cooperation that is so essential to IIP's operations. For the majority of the cutter support provided in 2021, iceberg reconnaissance was completed by the Danish Meteorological Institute (DMI) using an automated classification algorithm to detect and classify (small, medium, large, etc.) icebergs using the European Commission's Sentinel-1 Synthetic Aperture Radar (SAR) imagery. This custom support could not have been provided without the contributions from DMI.

This Appendix describes the vessels supported and the routes they took through the IIP Area of Responsibility (AOR), details the types of products produced, introduces a prototype product utilized during the support period, and reviews feedback received from the cutters on the usefulness and accuracy of the products.

B-2. Background

B-2-A History of Tailored Iceberg Products for U.S. Coast Guard Assets

IIP first provided tailored support to a Coast Guard vessel in August of 2017. USCGC MAPLE (WLB 207) completed a transit of the Northwest Passage that brought it from its previous home in Alaska to its new homeport in North Carolina. For four days after the conclusion of the Northwest Passage transit, MAPLE received what would be the first custom iceberg products from IIP to help manage the risk to the ship imposed by icebergs. The standard agreed upon by the International Ice Charting Working Group

(IICWG) for communicating the risk associated with the iceberg populations throughout the area was the “Isolated,” “Few,” and “Many” scale designed to depict the proximity between icebergs (**Figure B-1**). This product has evolved significantly since 2017, and the most contemporary version of it is described in greater detail later in this Appendix.

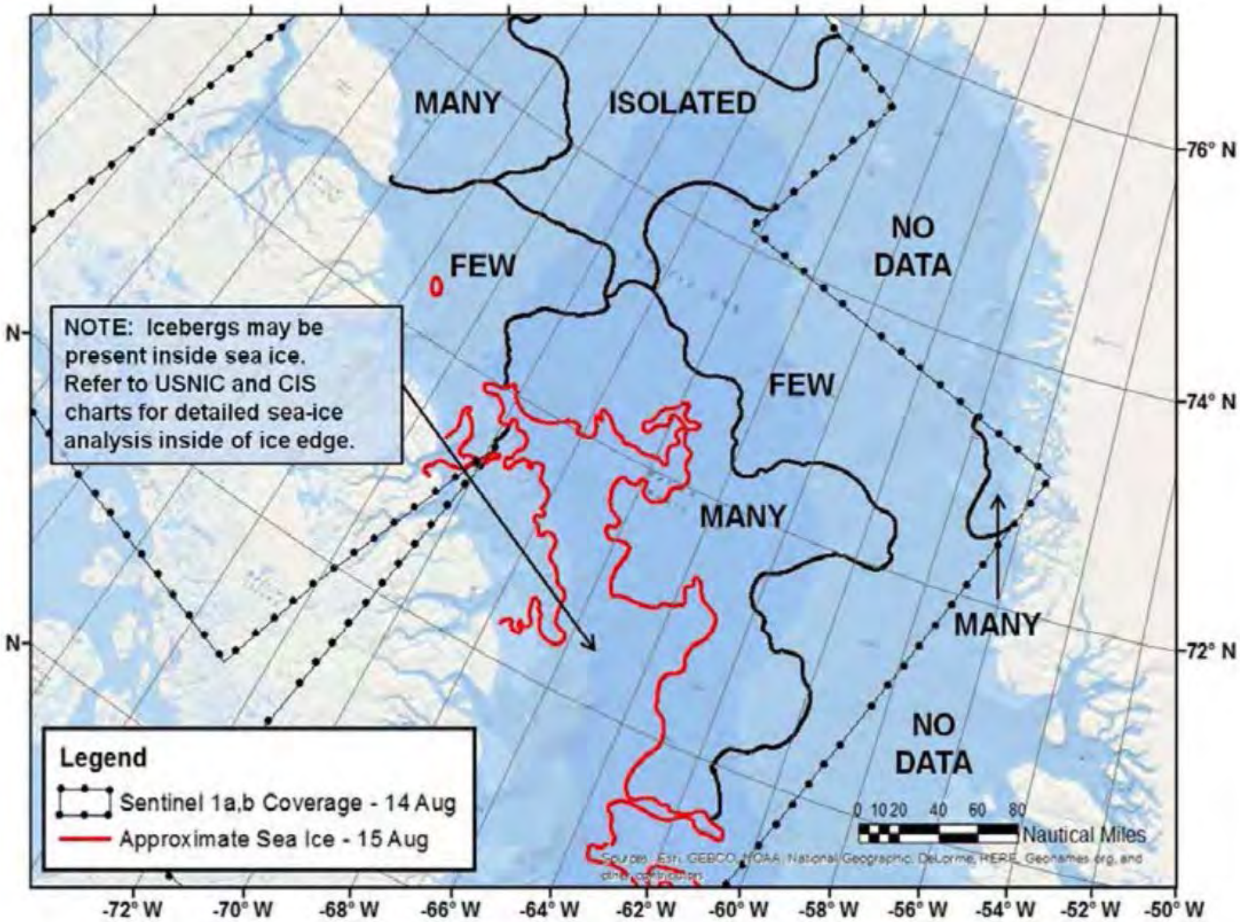

Figure B-1. Example of an Isolated/Few/Many product received by CGC MAPLE in 2017.

From 09 July – 20 September 2020, IIP supported USCGC TAHOMA (WMEC 908) and USCGC CAMPBELL (WMEC 909) during their participation in the international training operations NANOOK and ARGUS off the west coast of Greenland. Neither TAHOMA nor CAMPBELL is an ice-class vessel, and CAMPBELL was the first vessel of its class to cross the Arctic Circle. Appendix C in IIP’s 2020 Annual Report details IIP’s support to CAMPBELL and TAHOMA (IIP, 2020). Unlike MAPLE with its ice-strengthened hull, CAMPBELL was particularly vulnerable to damage from an iceberg collision, and it was their specific need for high frequency support that drove IIP’s deeper dive into tailored risk-based products for mariners operating in iceberg-infested waters.

This mission required significant build-up, product development, and reconnaissance planning. Multiple prototype products were sent to the cutter in the months preceding their departure, and a custom satellite-based reconnaissance plan was enacted to make sure that (a) icebergs were being spotted by satellite at a useful frequency, and (b) an intuitive and useful product was produced and released often enough to minimize the risk to the vessel. It was this mission that truly set the foundation for IIP's 2021 support.

B-2-A Cutter Descriptions and Missions

Following the successful completion of Operations NANOOK and ARGUS in 2020, IIP's capability for tailored support was advertised to other Coast Guard assets operating in Arctic waters in 2021. **Figures B-2** through **B-5** depict each cutter supported by IIP during 2021 and their route through the area of responsibility.

USCGC MAPLE (WLB 207) received iceberg support from 06-30 June 2021 for their participation in the search and rescue Operation ARGUS. MAPLE is a seagoing buoy tender based out of Atlantic Beach, NC capable of light icebreaking. The crew of MAPLE, most notably the Commanding Officer, had a strong background in ice operations and were largely familiar with the risks associated with sea ice and icebergs.

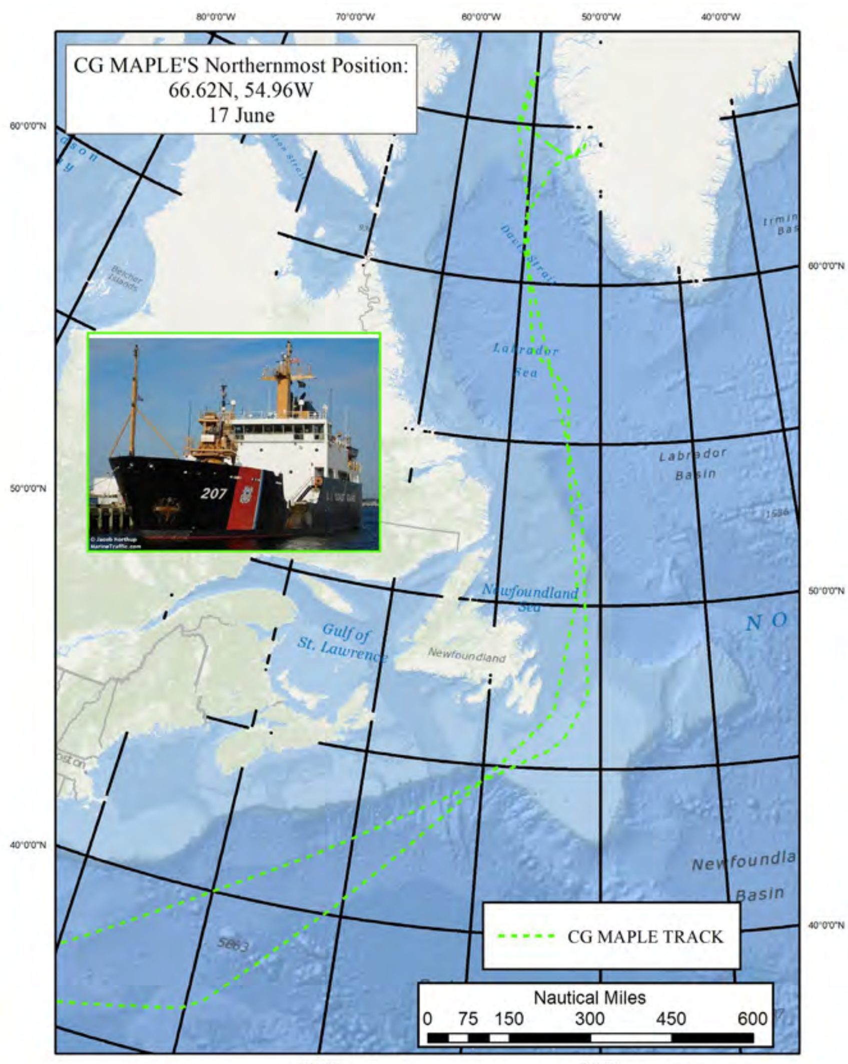

Figure B-2. CGC MAPLE's participation in Operation ARGUS, June 2021.

USCGC ESCANABA (WMEC 907) is a medium endurance cutter in the same class as CAMPBELL. ESCANABA was joined by the Fast Response Cutter USCGC RICHARD SNYDER (WPC 1127) for participation in Operation NANOOK in Baffin Bay from 02-23 August 2021. Neither cutter is equipped with a strengthened hull for ice operations, nor

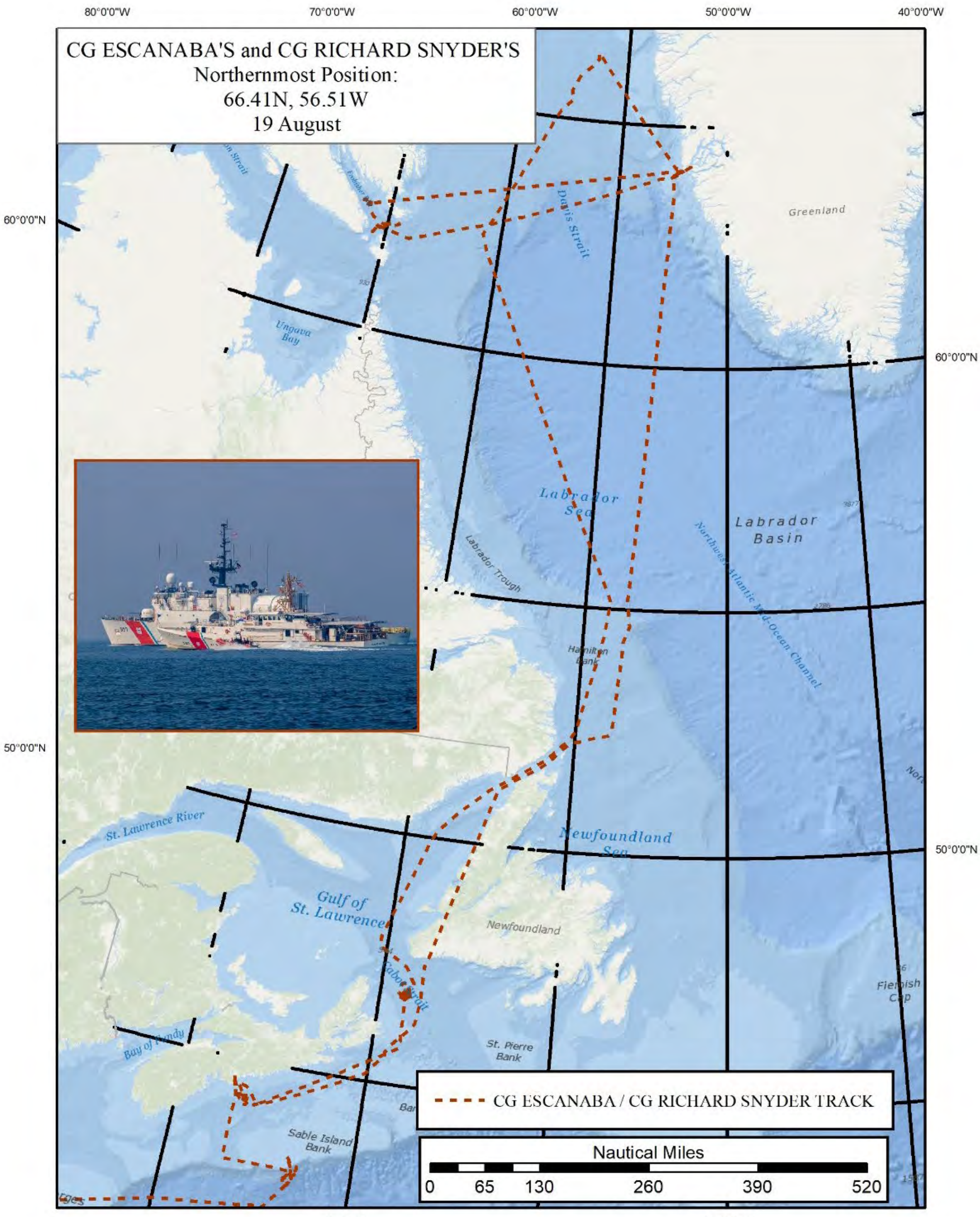

Figure B-3. CGC ESCANABA's and CGC RICHARD SNYDER's participation in Operation NANOOK, August 2021.

was either crew experienced with operating in ice-infested waters. RICHARD SNYDER was the first patrol boat in her class to cross the Arctic Circle.

USCG Barque EAGLE (WIX 327) is the Coast Guard's training vessel for the future officers of the service. EAGLE is a tall ship, a relic of World War II, and received iceberg support for her trip to Reykjavik, Iceland between 22 May and 03 June. EAGLE was

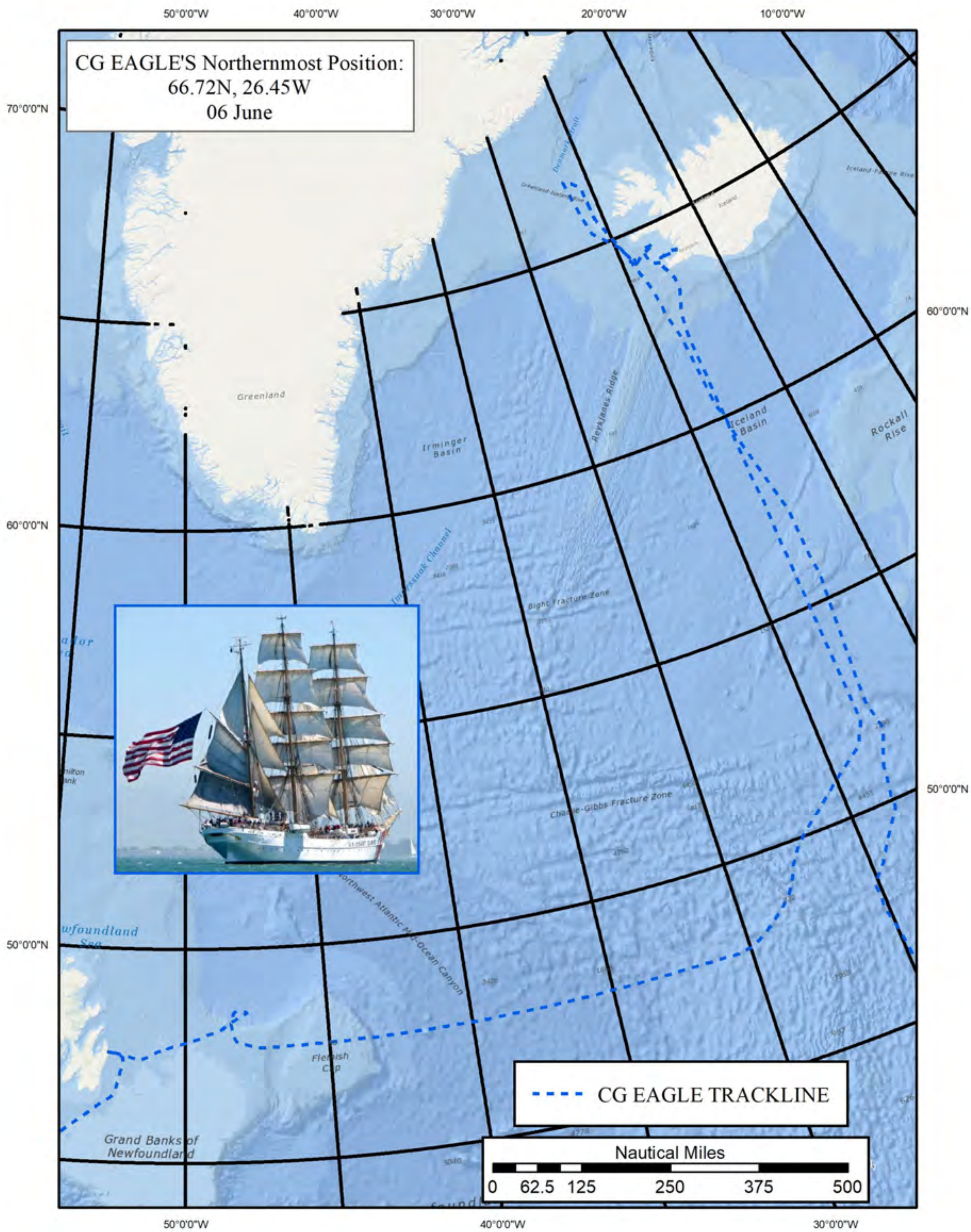

Figure B-4. CG Barque EAGLE's transit to Reykjavik, May/June 2021.

unique amongst the other supported units in that she had no intentions to transit through iceberg-infested waters, but still transited north of the published Iceberg Limit.

USCGC HEALY (WAGB 20) is the Coast Guard's largest vessel and is classified as a medium icebreaker. A vessel designed for continuous icebreaking and polar research,

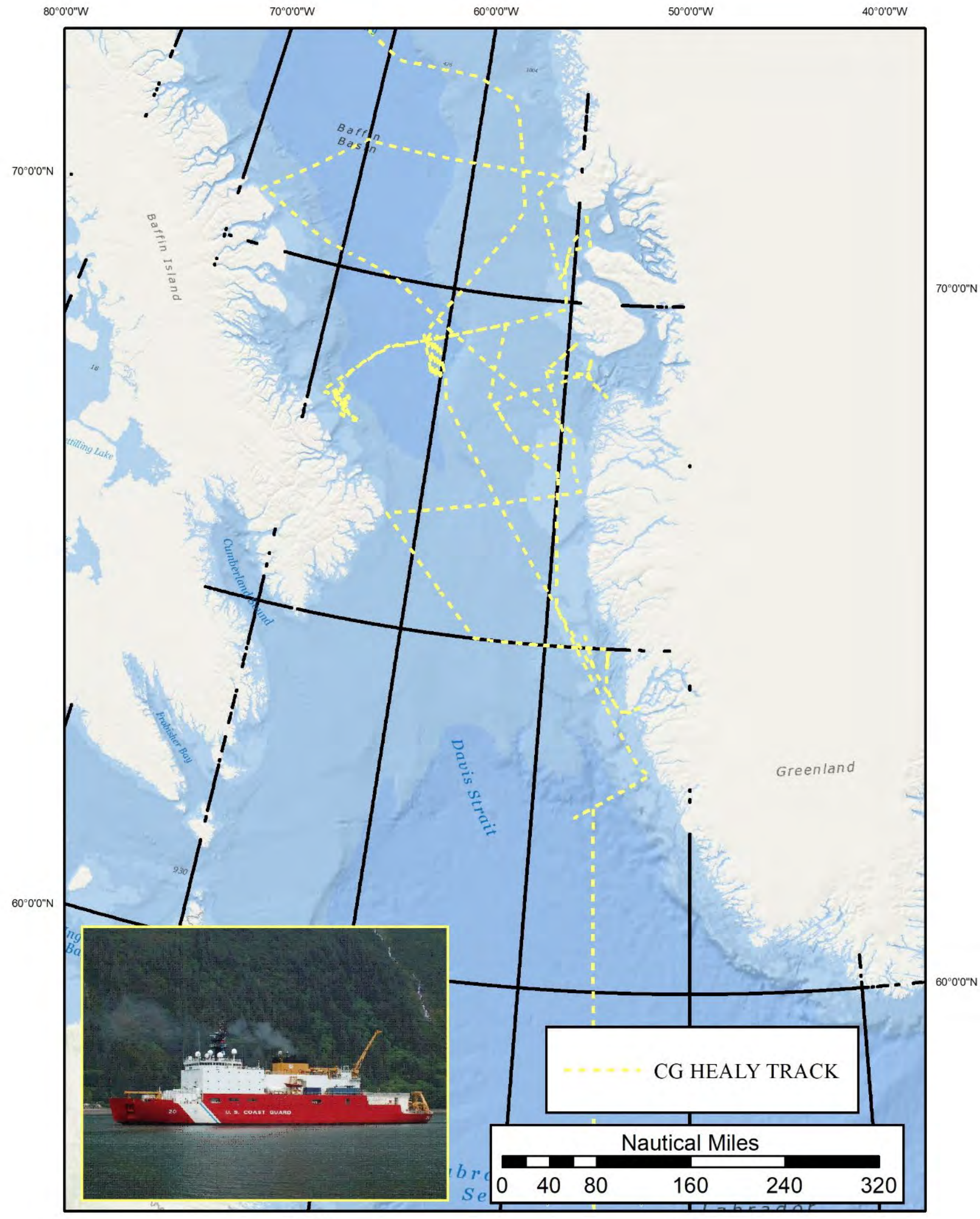

Figure B-5. CGC HEALY science operations in Baffin Bay during September and October 2021.

her crew was comfortable and experienced operating in high-risk ice areas. HEALY received iceberg report for science operations throughout Baffin Bay and the Labrador Sea from 07 September – 05 October 2021.

B-2-B Iceberg Products Provided

The first type of product provided to the supported cutters was the Isolated/Few/Many iceberg proximity chart. This is a risk-based product useful to navigators for identifying areas where icebergs are closer together, and by correlation, typically more densely populated. It evolved significantly between the 2017 support for MAPLE and the 2020 support for CAMPBELL, but 2021's product went largely unchanged from the precedent set in 2020. **Figure B-6** is an example of the Isolated/Few/Many products received

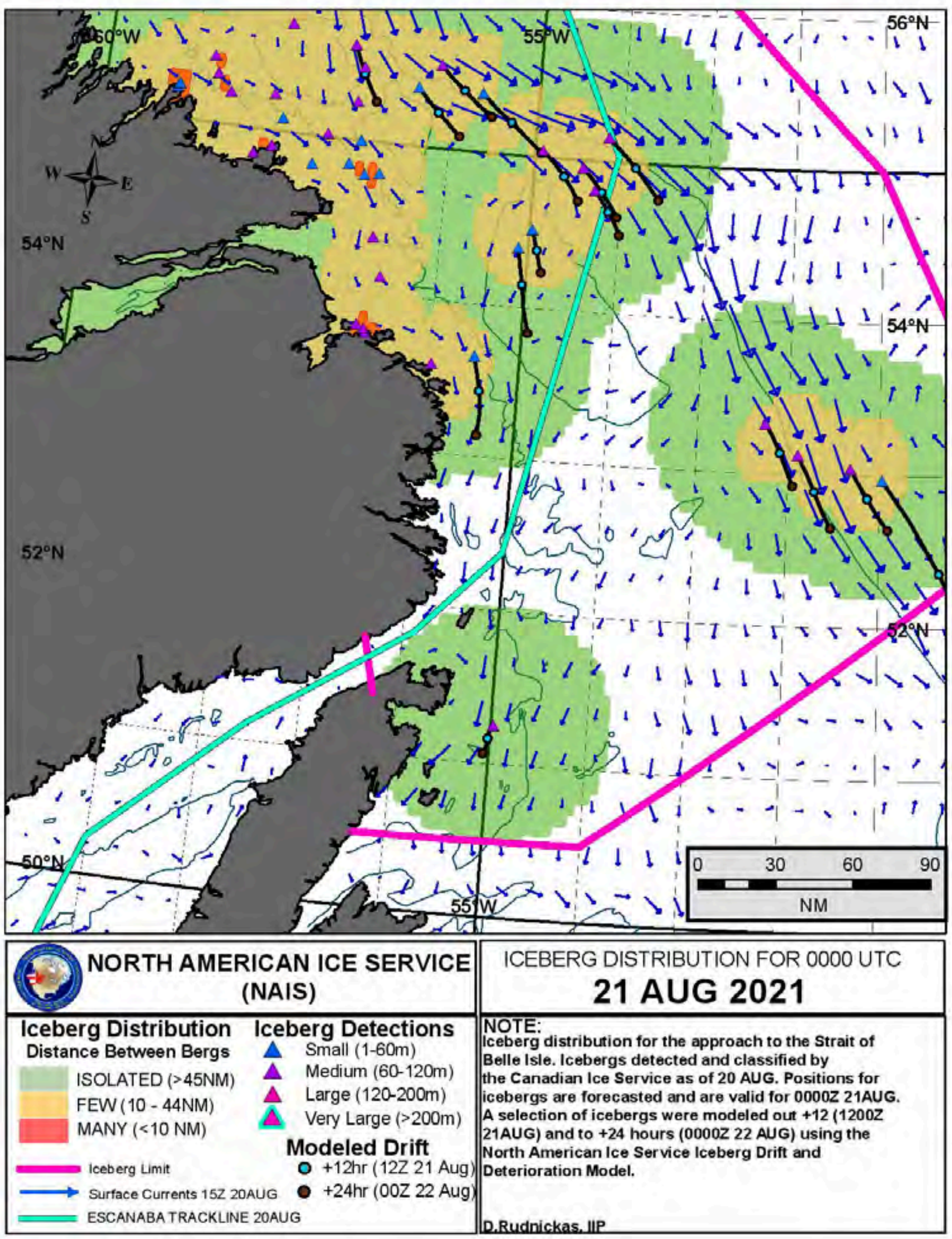

Figure B-6. Example Isolated/Few/Many product received by USCGC ESCANABA from August 21, 2021.

by ESCANABA during Operation NANOOK. The principal features on this product include estimated iceberg positions modeled forward from their original sightings to the valid time of the product using the North American Ice Service (NAIS) Iceberg Drift and Deterioration Model, and green/yellow/red contours drawn around the iceberg population in accordance with the following definitions:

- “Isolated”: Greater than 45 NM between icebergs
- “Few”: 10-44 NM between icebergs
- “Many”: Less than 10 NM between icebergs

These colored regions are designed to correspond with the likelihood of encountering icebergs dangerous to navigation. Also included was the Iceberg Limit (when applicable), surface currents from the Canadian East Coast Ocean Model, the intended movement of the cutter, and forecasted positions for future valid times. The Isolated/Few/Many product was the principal method for communicating iceberg danger to the supported cutters.

The second type of product distributed was a prototype Drift Forecast chart. The purpose of this product was to show finer detail and depict the predicted motion of icebergs on larger scales (zoomed in) when operations or transits were planned through populations of icebergs anticipated to be fairly dense. **Figure B-7** depicts an example of the product, and was sent to the cutter during a period of prolonged operations just outside the port of Nuuk, Greenland where they could expect to encounter a sizeable iceberg population. Similar to the Isolated/Few/Many product, icebergs were modeled forward using the NAIS model, however the endpoint of the model was selected 24 hours beyond the expected valid time of the product. For example, a product designed to be valid at 0000Z on the night of 18 June would be prepared by running an iceberg drift and deterioration model valid at 0000Z 19 June. This allowed the following features to be displayed on the chart:

(1) Original observed iceberg position and size.
(2) Modeled drift track of each iceberg.
(3) Estimated positions and area of uncertainty for valid time of product.
(4) Estimated positions and area of uncertainty for +24 hours.

Showing (1) the original observed position and size along with (2) the drift track was useful to demonstrate the age (and therefore reliability) of the data. While the dates of the sightings were also included in the legend of the product, longer drift tracks can indicate older sightings. Tracks were also useful to show the general direction of flow of the iceberg population, useful for helping navigators chart courses out of the general path of movement. Only icebergs expected to be in the vicinity of the cutter at the valid time of the product were entered into the model to save processing time, but all sightings were still displayed (hence some bergs not having tracks). The display of (3) estimated positions were designed to show the predicted distribution of the iceberg population at the valid time, and also (4) a day into the future to help with voyage planning. Each iceberg in those populations received a circular buffer of uncertainty with its radius sized in accordance

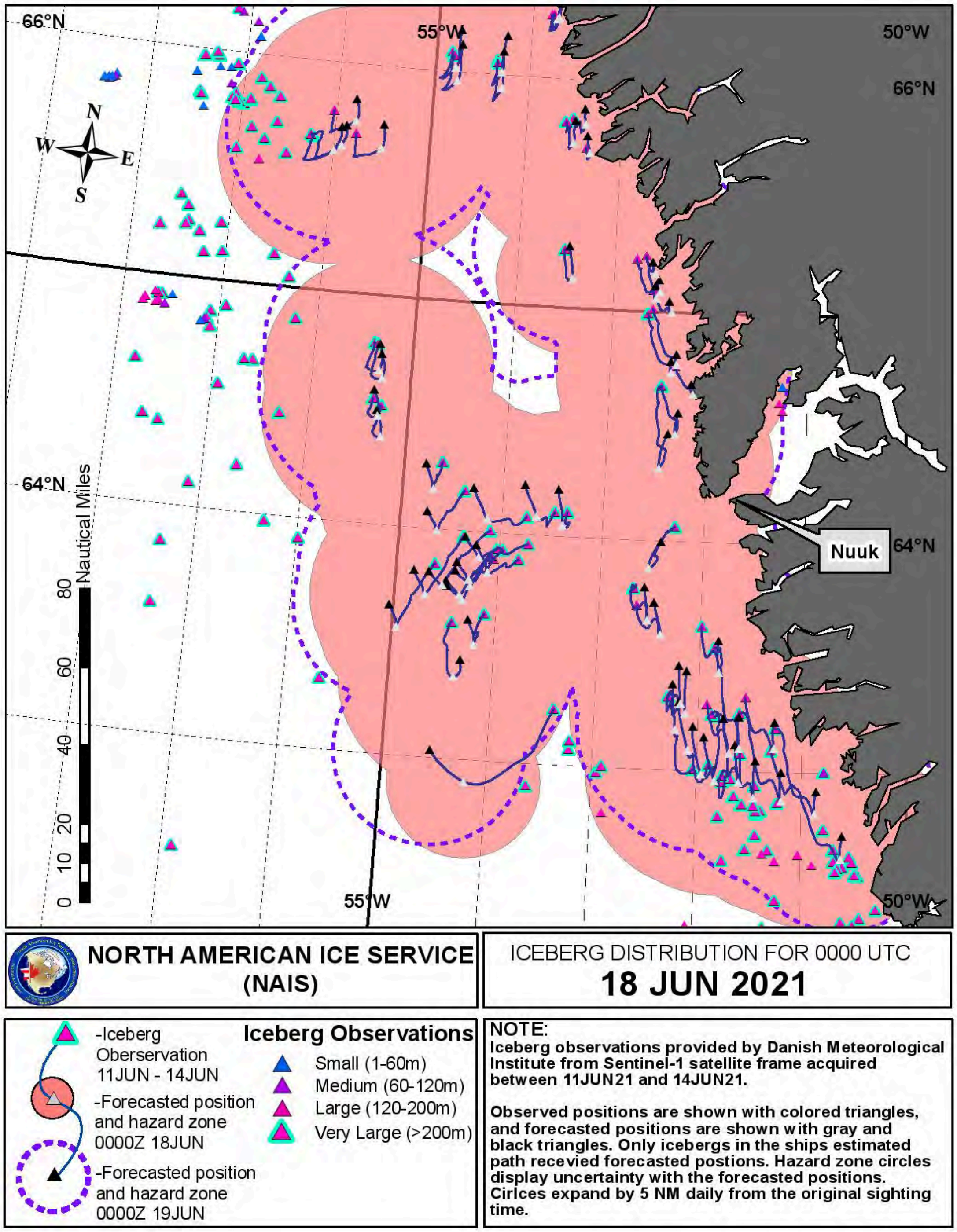

Figure B-7. Drift Forecast product received by USCGC MAPLE.

with IIP standard operation procedures (+5 nautical miles per day on drift). The result was a colored area of uncertainty around the modeled icebergs (shaded pink in **Figure B-7**), and a drifting/expanding area of uncertainty to accompany the +24 hour estimated positions (purple dotted area) for assisting with voyage planning.

The third and final style of product distributed was custom for USCG Barque EAGLE (**Figure B-8**). Due to the unique nature of EAGLE's voyage intentions (cross the

Iceberg Limit but still minimize iceberg interactions) and unlikelihood of the cutter actually encountering icebergs, a simplified product was created that included only recent satellite detections of icebergs in the vicinity of Southeast Greenland. This assisted EAGLE in her Arctic Circle crossing and port visit to Reykjavik. Unlike other products during 2021, IIP conducted all of the satellite reconnaissance for this support effort in-house.

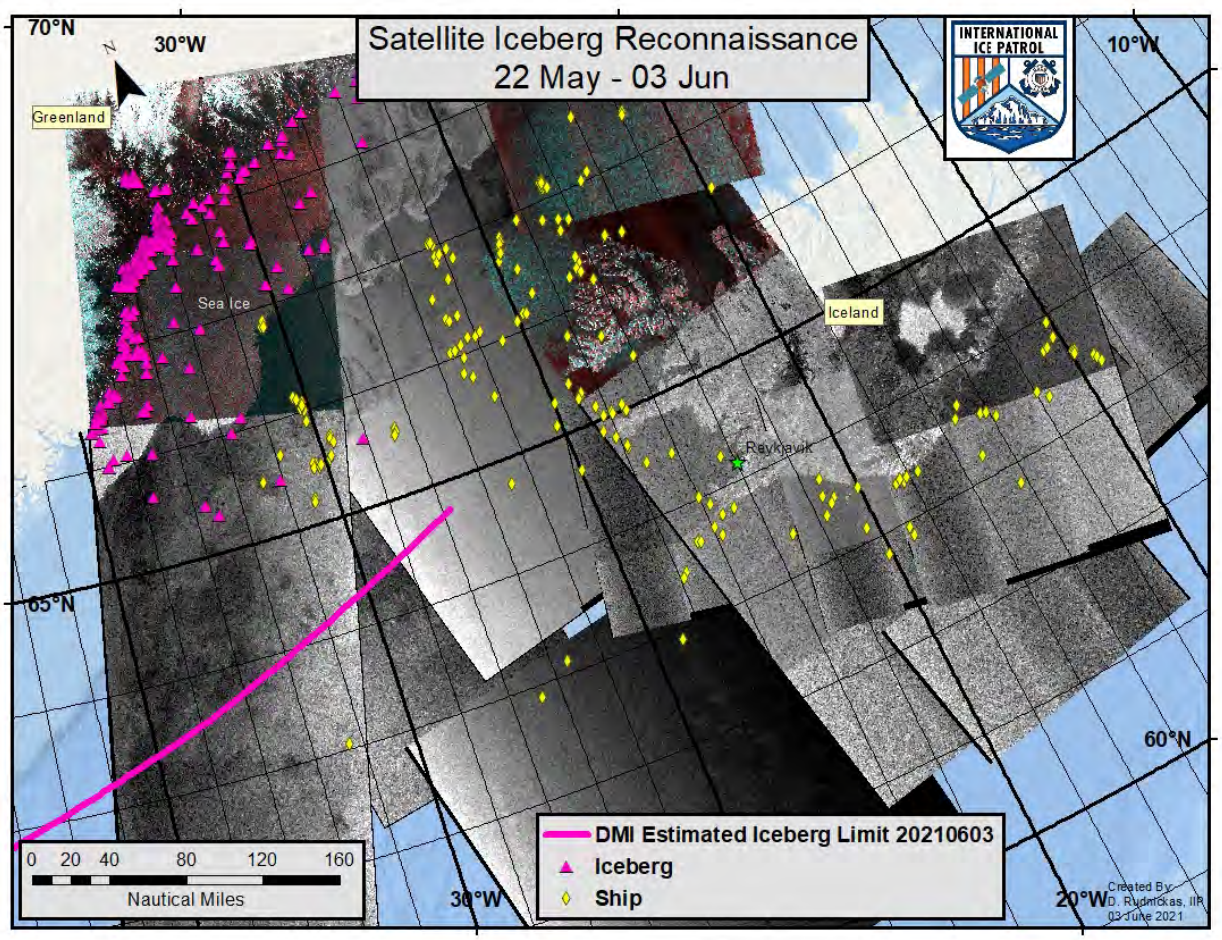

Figure B-8. Satellite imagery support for USCG Barque EAGLE.

B-2-C Satellite Reconnaissance

Throughout the course of the tailored support activities, with the exception of the satellite reconnaissance provided to Barque EAGLE, IIP did not conduct its own satellite reconnaissance of the areas where the supported units operated. DMI, a NAIS partner, routinely analyzes enough satellite imagery to cover the waters of Baffin Bay, and the east and west coasts of Greenland every 3-5 days. An automated process at DMI detects ("locates") icebergs in Synthetic Aperture Radar (SAR) imagery, classifies each located target (small, medium, large, etc.), and outputs the file of iceberg points used by IIP to create the product.

This partnership with DMI was the principal reason that IIP was able to provide supported units with products on a daily basis. For the CAMPBELL support in 2020, DMI was unable to maintain operations past the beginning of August and IIP was doing both the satellite imagery analysis and the product creation, which was a workload that allowed for delivery of products only every other day. Feedback from the cutters (discussed in detail later in this Appendix) consistently stated that a daily product was the right distribution pace, and, if anything, could be even more frequent.

B-3. Results and Effectiveness

B-3-A Feedback

Three of the deployed cutters (MAPLE, ESCANABA, and RICHARD SNYDER) were asked about their experiences with the tailored products, and the feedback was overwhelmingly and unanimously positive. Each unit requested/required different levels of support from IIP based on their assigned mission, experience, and structural strengthening against ice, but similar themes emerged between the feedback provided from each cutter:

(1) Products were indispensable for operating in iceberg-infested waters and were relied on heavily by commanding officers and navigators. Products were reviewed nightly by bridge teams, and the navigators used each product to plan the ship's movements for up to several days ahead. The Commanding Officer of MAPLE stated that he would not have brought the ship above the Arctic Circle without having he products in hand that he did (P. Howard, personal communication, August 3, 2021).

(2) Products were accurate and reliable. The density of the depicted iceberg populations showed a high correlation with the populations encountered. The navigator of CGC MAPLE described encountering isolated icebergs in the ship's path exactly when and where they expected to encounter them (J. Rendon, personal communication, August 3, 2021). The Commanding Officer of ESCANABA stated that the demarcation line between areas of "isolated" and "few" icebergs were accurately plotted, and that the crew could reliably expect to encounter a significantly more dense iceberg population after crossing from a green area to a yellow area as depicted on the Isolated/Few/Many product (B. Spector, personal communication, October 27, 2021).

(3) The Isolated/Few/Many product was preferred over the Drift Forecast product. In discussion with the navigator from CGC ESCANABA, he described using the product almost exactly as intended without prompting from IIP (P. Dixon, personal communication, October 27, 2021). When asked about how he used the Isolated/Few/Many chart, he stated that he would rely heavily on the shaded areas to plan the ship's movements, and focused less on the individual positions of icebergs. They were able to observe distinct changes in the density of the iceberg population after crossing from the "isolated" regime to the "few" regime, and confirmed that the "many" areas were quite hazardous to navigation. Similarly, the navigator onboard MAPLE stated that they encountered isolated icebergs almost exactly where and when expected based on their charted

track (J. Rendon, personal communication, August 3, 2021). None of the cutters reported unexpectedly encountering icebergs that were not charted or enclosed in the appropriate density contours.

(4) Products were simple to interpret, even for less-experienced bridge team members. The amplifying information included as text on each product was not explicitly needed. Furthermore, the products influenced the behavior of the lookouts and the bridge team. When icebergs were expected ahead, lookouts were more focused and knew where to search.

B-3-B Changes to Route Planning

Product distribution directly affected how navigators altered their routes. **Figures B-9** and **B-10** are examples of track adjustments made by MAPLE shortly after receiving updated iceberg products. In each figure, the green line represents the intended waypoints sent to IIP from the navigator, and the red dotted line indicates the path the ship actually followed after receiving products and making changes to the route. In both cases, the navigator recognized that the intended path would take the cutter through areas of high iceberg concentration, and made a course alteration to avoid those areas.

B-3-C Product Distribution to Partners

For Operation NANOOK, ESCANABA and RICHARD SNYDER spent much of the exercise interacting with naval units from Canada and Denmark. The naval forces from Canada and Denmark are understandably more acquainted with ice operations than the average U.S. Coast Guard crew, but nonetheless the iceberg products were also distributed to the Canadian Naval Vessels HMCS HARRY DEWOLF and HMCS GOOSE BAY to assist with their risk assessment and voyage planning.

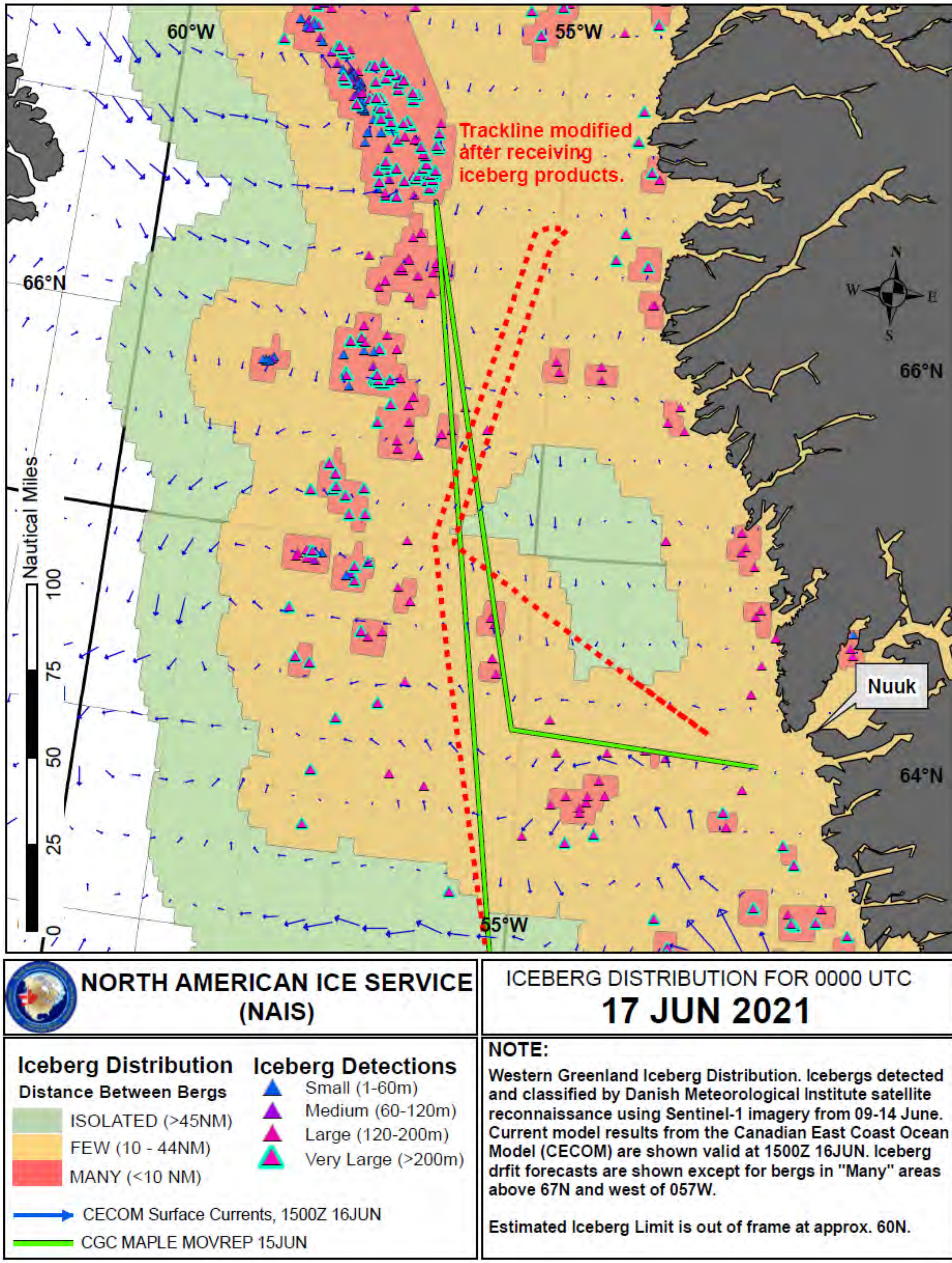

Figure B-9. Course alteration by USCGC MAPLE after receiving Isolated/Few/Many product.

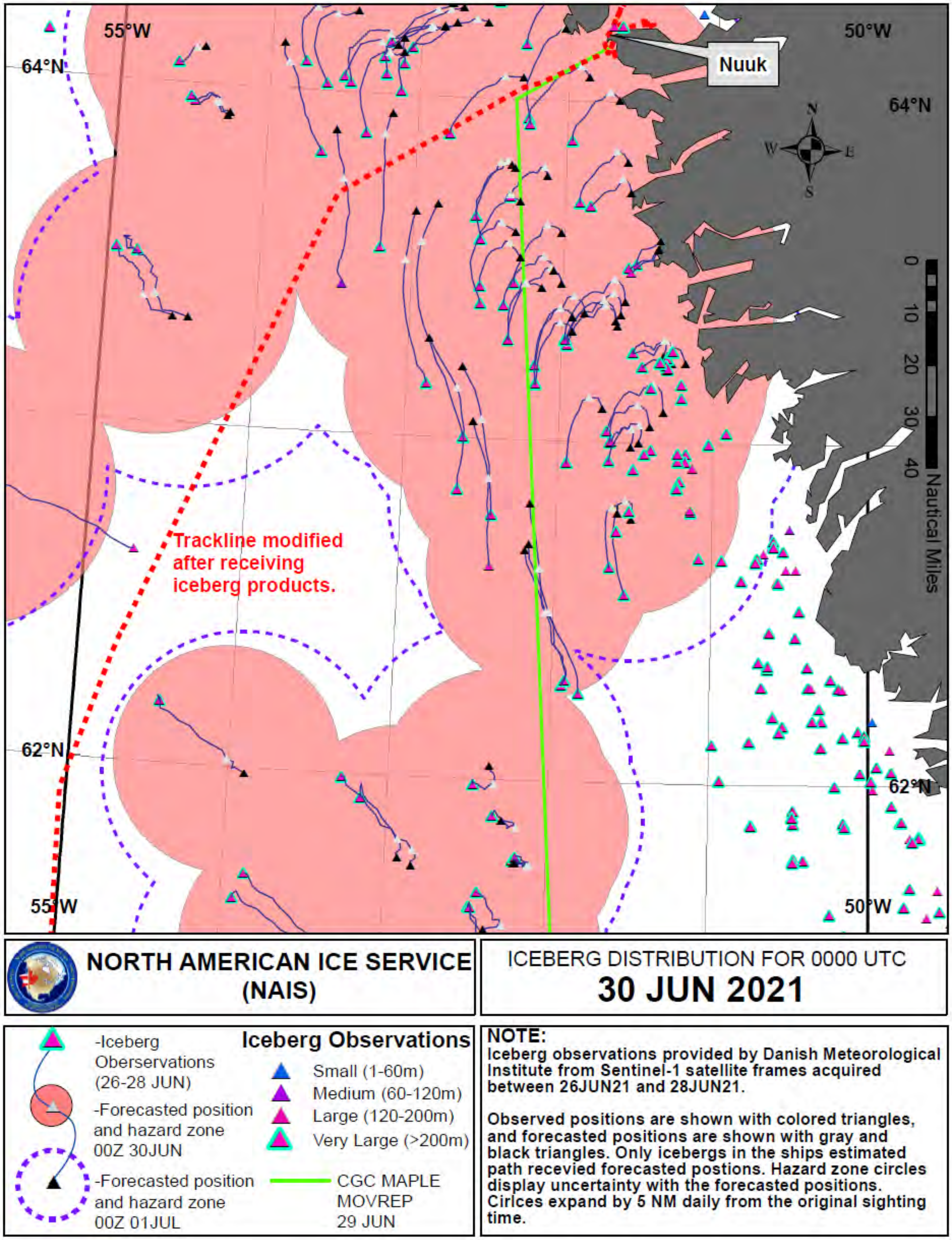

Figure B-10. Course alteration by USCGC MAPLE after receiving Drift Forecast product.

B-4. Future Work

B-4-A Product Improvements

Feedback from the supported units was overwhelmingly positive, but when asked for areas of improvement, several points emerged from the discussion with USCGC ESCANABA. The first point, which was an echo of similar feedback provided by her sister ship, CAMPBELL, in 2020, was that internet connectivity decreased in reliability as cutters transit north, and that an alternate method of product transmission could be investigated. Based on IIP's experience in distributing a standard daily Iceberg Limit product, this could take the form of a medium frequency radio NAVTEX transmission or a SafetyNET satellite broadcast of a text product. A radiofax broadcast of the graphic product could also be a method for transmission. While IIP does have experience with these types of transmissions, they are scheduled broadcasts that are available to every vessel that can receive them. This might have security implications, especially for showing the intended path of Coast Guard vessels. The transmissions are also executed by partner agencies like the National Geospatial Intelligence Agency (NGA), the National Weather Service (NWS), and the Marine Communications and Traffic Services of Canada (MCTS), all of which would add an intermediate step in any product distribution. Encrypted methods of transmission could also be investigated to mitigate security and transmission concerns.

The second point raised by ESCANABA was that it would useful to receive combined products for a range of environmental data. For example, one chart produced jointly by IIP and the US National Ice Center that showed sea ice and iceberg distribution in one image would streamline the display of all the data the cutter is considering when making voyage planning decisions. This could be further extended to other environmental data sets like wave height, wind speed, and sea level pressure.

B-4-B The Way Forward

The way forward for tailored iceberg ship support most imminently includes searching for methods to improve automation and computing times. While the current process for creating iceberg distribution products is already highly automated, it still requires several hours' worth of manual intervention for every product. The potential for reducing manual editing of features combined with upgrading software to reduce computing times for model runs would significantly expand IIP's capacity to support afloat units according to their specific needs.

As more and more cutters are expected to patrol the North Atlantic and Arctic waters, training more analysts on the production of these custom products will also be paramount. Currently only three IIP members can reliably produce all of the charts that the cutters receive. Along with increased automation, increased training will greatly expand IIP's capability for providing tailored products.

B-5. Conclusion

IIP's tailored iceberg support for Coast Guard Cutters in 2021 was a convincing success, and likely sets a precedent for changes to its role in the ever-expanding Arctic domain. While creating products exerts a measureable stress on the systems and personnel producing them, IIP has successfully demonstrated the capability to support afloat units that are highly dependent on the information contained in each chart.

Existing products are useful and informative for assisting with voyage planning while at sea. They were also reported to be highly accurate, and were used to make decisions on a daily basis for the units that received them. While the products currently being used for tailored support have proven useful, there always exists room for improvement. As these products are continuously evaluated by IIP, NAIS, and IICWG, alternate methods of transmission, increased automation and training, and dissemination to wider audiences are all areas for improvement for these custom products.

Providing custom support for vessels navigating in iceberg-infested waters is currently not within the mandated scope of responsibility for the International Ice Patrol. This venture, while likely to be part of any future mandates for IIP, is currently undertaken outside of the purview of IIP's general mandate. IIP exists to monitor the iceberg danger in the North Atlantic, and to provide relevant warning products to the maritime community by publishing the daily Iceberg Limit. That said, the demand for risk-based iceberg products and custom support continues to increase. IIP shall continue to assess its role within the Arctic and maritime safety domains, and equip the members assigned to this mission to be as effective as possible.

B-6. References

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Spector, B. (2021, October 27). Personal communication [phone interview].

Appendix C. Iceberg Limit Climatology (1991-2020)

Mr. Michael Hicks and Mr. Jack Cline

C-1. Introduction and Background

Under the Safety of Life at Sea (SOLAS) Convention, the International Ice Patrol (IIP) serves the North Atlantic mariner by monitoring iceberg danger and providing relevant warning products to the maritime community. Since its inception, IIP has communicated iceberg danger to transatlantic mariners by using the Iceberg Limit as its primary mechanism. IIP assumes that the primary users do not desire nor expect to see ice during their transit across the Atlantic. In most cases, a ship remaining outside of the published limit will not encounter an iceberg. The Iceberg Limit attempts to provide the mariner with an estimate of the location of icebergs observed from aerial, satellite and vessel sources by incorporating drift and deterioration modeling. In many cases, several days can pass between iceberg sightings so the uncertainty of the location of the Iceberg Limit increases with time and thus it is intended to be conservative in nature.

The goal of this Appendix is to document IIP's work to produce a year-round, bimonthly Iceberg Limit climatology during the 30-year period from 1991-2020. The scope of this work focuses on the Iceberg Limits issued on the 1st and 15th of each month to provide early and mid-month depictions of the Iceberg Limits. This results in a statistically derived "snapshot" of iceberg distribution at these discrete time periods. Since the Iceberg Limit is frequently established by a small number of isolated icebergs, a limitation of the "snapshot" approach is that reconnaissance (or iceberg modeling) can cause abrupt shifts in the limit over a short time period. For example, deletion of a single iceberg setting the Limit can cause a significant change in the Limit in a given snapshot. The 30-year climatology is intended to address this shortcoming and to provide the basis to compare present-year iceberg severity to the climatological period in terms of the area encompassed by the Limit.

Historically, IIP has conducted its reconnaissance and issued Iceberg Limit products during times when icebergs threaten the transatlantic shipping lanes – generally between February and July each year. Thus, prior Limit climatology studies (e.g., Viekman and Baumer, 1995) focused on these months only.

Until 2011, the Canadian Ice Service (CIS) also issued a daily Iceberg Limit separately for vessels operating in Canadian domestic waters. On 01 February 2011, the IIP and CIS began issuing a joint Iceberg Limit product as the North American Ice Service (NAIS). IIP and CIS divided responsibilities for creating and issuing these products temporally: IIP assumes this duty from February through August and CIS does so from September through January, when icebergs primarily threaten Canadian domestic shipping. With the transition to a joint, common-look NAIS product in 2011, IIP began including a western Iceberg Limit when icebergs drifted into the Gulf of St. Lawrence. However, with only 10 years of data, IIP chose to focus on the southern and eastern expanse of the Iceberg Limit for this study.

It is important to note that prior to 2011, IIP reported a Limit of All Known Ice (LAKI) as its daily warning product. CIS products reported an Iceberg Limit since icebergs were frequently located within sea ice during the early winter months. With potential isolated exceptions in early March while sea ice was still present over the Grand Banks, the LAKI and the Iceberg Limit are assumed to be identical. IIP and CIS agreed to use the Iceberg Limit as the basis for this product. For simplicity and clarity, this Appendix will refer to the Iceberg Limit (vice LAKI) for the entire 30-year climatology.

IIP and CIS staff create the Iceberg Limit daily by drawing a convex polygon enclosing the iceberg region. As a safety measure for shipping, watchstanders at both IIP and CIS apply a conservative buffer around the estimated locations of limit-setting icebergs to account for modeled drift error. For this climatology, IIP created raster images from these polygons on the 1st and 15th of each month, assigning a value of 1 for cells contained within raster boundaries and 0 for cells outside of the raster image. Cell values were summed by stacking the raster images bi-monthly for all years during which data were available. Final raster images were analyzed to identify extreme and median Iceberg Limit locations over the 30-year period. In addition to a count of the number of icebergs drifting south of 48ºN latitude, this climatology allows consideration of an additional season severity component for comparison purposes.

C-2. Data Collection and Preparation

C-2-A. Iceberg Limit Messages

IIP began this study by accumulating all Iceberg Limit messages in its archive. Since this climatology is intended to provide a broad overview of the temporal changes of the area affected by iceberg danger, IIP chose to use bi-monthly snapshots of the Iceberg Limit. To standardize this approach, this study selected the Iceberg Limit product issued as near in time to the 1st and 15th of each month to represent an early and mid-month depiction.

Latitude and longitude coordinates for daily Iceberg Limits are produced by IIP and CIS watchstanders using the iceBerg Analysis and Prediction System (BAPS). Although the IIP and CIS product had very different appearances prior to 2011, the basic formatted message structure describing Iceberg Limit coordinates are identical, facilitating the automation of data ingestion. **Figure C-1** provides examples of each center's product on 15 April 2001 (prior to the joint NAIS product). Formatted messages used to create the Limits are included as inset annotations. After 2011, IIP and CIS agreed on a common-look product that retained the underlying structure for Limit coordinates (**Figure C-2).**

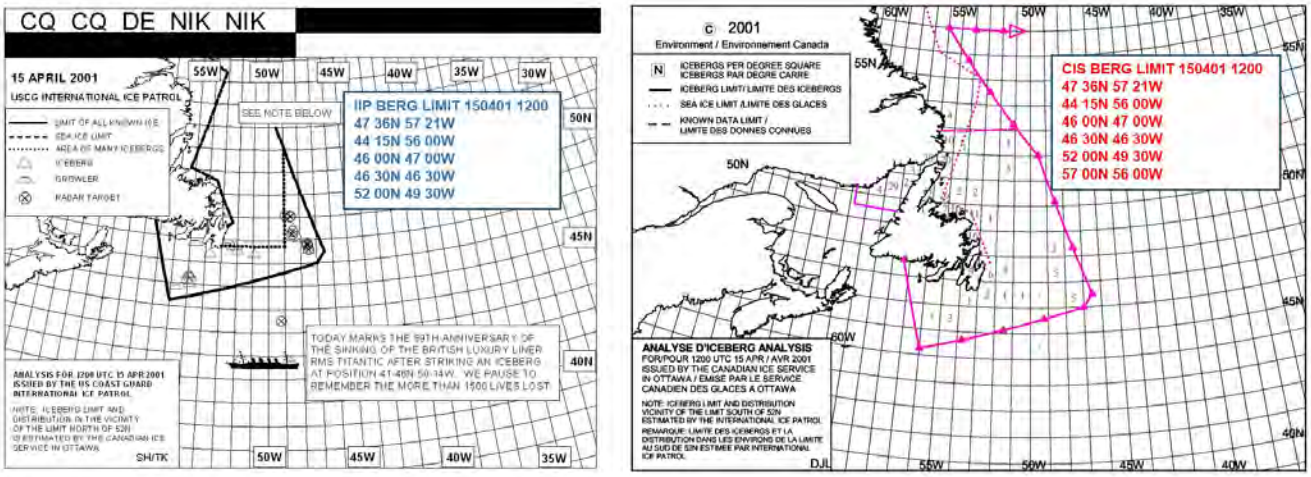


Figure C-1. Sample Iceberg Limit products from IIP (left panel) and CIS (right panel) prior to 2011. Standard formatted messages were the basis for graphical product development and are overlaid onto each Iceberg Limit product.

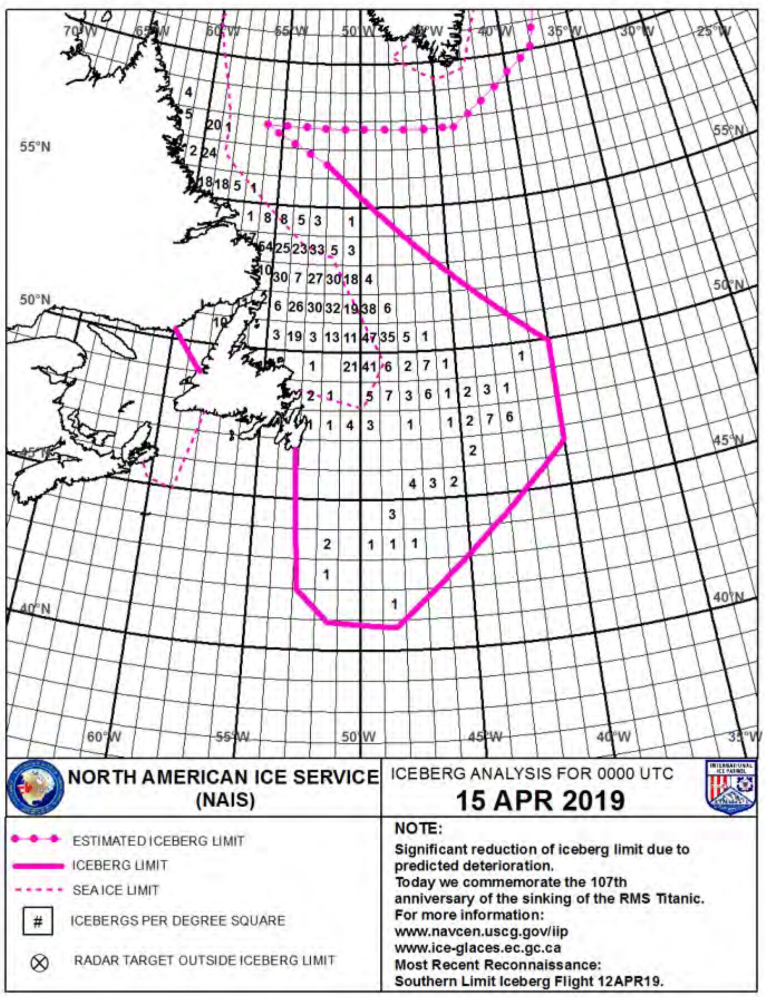


Figure C-2. Sample Iceberg Limit products from 2019. CIS and IIP adopted a common-look, joint product that depicts a similar display year-round. Message format remained consistent at both organizations throughout the entire climatology period.

C-2-B. Temporal Data Gaps

Temporal and spatial data gaps had the net result of reducing the total number of years that data were available for further analysis for any given Analysis Date. Prior to 2011, IIP based its decision to establish and publish an Iceberg Limit i.e., "open the iceberg season" on the number of icebergs that threatened the transatlantic shipping lanes. During 'Light' years, IIP began establishing a limit later in the spring. Notably, during four separate 'Light' iceberg years (1999, 2005, 2006, and 2010), IIP did not produce an Iceberg Limit at all. In turn, when the southward iceberg drift no longer posed a hazard to transatlantic shipping in late-summer, IIP stopped establishing a Limit and suspended issuing its warning product. As a result, the time period in which IIP generated products varied annually based on season severity. Since icebergs pose a year-round navigational hazard in Canadian domestic waters, CIS maintained an Iceberg Limit throughout the entire year. For this study, during times when IIP did not create a Limit, CIS provided Iceberg Limit data. Consultation and collaboration with CIS proved essential to minimize temporal data gaps in compiling a year-round dataset. With exception of 14 records in 1991, 1993, and 1994, the 30-year Iceberg Limit dataset contains a total of 706 Iceberg Limits, out of a maximum possible 720 records (bi-monthly over 30-year time period). A graphical depiction of the available data illustrates the sources of Iceberg Limit data and highlights the few temporal data gaps, when no Iceberg Limit data could be located in light-red (**Figure C-3**). Note that the time period after 2011 clearly shows the results of a more systematic, shared approach by using the joint NAIS product.

Figure C-3. Iceberg Limit data availability during the 30-year period from 1991-2020. With exception of 14 records in 1991, 1993, and 1994, IIP located 706 of a possible 720 records (30 years of bi-monthly data).

C-2-C. Spatial Data Gaps

Particularly during the early part of this dataset, spatial data gaps arose due to inconsistent practices at both IIP and CIS with respect to the northern terminus of the Iceberg Limit. For many years, IIP used 52ºN as its northernmost Limit point while CIS frequently chose a more northern point to reflect the northward movement of icebergs in late summer (see **Figure C-1** for example). For the purpose of this study, IIP chose 52ºN as the northern latitude for determining median and extreme Iceberg Limits. There were several instances during the early and late parts of the Ice Year that the entire area encompassed by the Iceberg Limit was north of 52ºN and were not considered in the analysis. The raw Iceberg Limit data for these cases were retained and are available for further study.

C-3. Iceberg Limit Assembly Process

The workflow was developed using some conceptual work previously completed by USCG Academy cadets performing a directed studies effort using a much earlier version of ArcMap. These conceptual steps formed the initial workflow skeleton, and were modernized and enhanced to work with ArcGIS Pro. Each step will be described in its own section.

At a high level there are three main steps to the process: Data Ingestion, Data Enrichment and GIS processing. The goal of the process is to take the data from 30 years of Iceberg Limit data, down-sample it to twice monthly on the first and fifteenth of each month (called Analysis Dates), then summarize the data for further statistical analysis (e.g., minimum, median, and extreme Limits) across the entire 30 year period.

C-3-A. Data Ingestion

To initiate this process, all Iceberg Limit messages created by BAPS were saved as text files into a series of folders for each year of this dataset. IIP used Python code, developed under a separate project with the USCG Research and Development Center (RDC) (Cline, 2020). This process involved automatically opening and reading the 706 text files using Python code in a Jupyter Notebook. To facilitate ArcGIS processing, the Python code then converted the BAPS text files from their native format into degrees and decimal degrees format, added an Order field, and created an Observed Date field from information in the file header. The code assembled all Iceberg Limit points into an Excel spreadsheet. (**Figure C-4**)

	A	B	C	D	E
1	Latitude	Longitude	Order	Observed Date	
2	49.25	53.46667	0	1991-01-03 00:00:00	
3	48.66667	49.5	1	1991-01-03 00:00:00	
4	49.5	46	2	1991-01-03 00:00:00	
5	52	46	3	1991-01-03 00:00:00	
6	55.75	48.83333	4	1991-01-03 00:00:00	
7	49.25	53.46667	0	1991-01-14 00:00:00	
8	50	45.5	1	1991-01-14 00:00:00	
9	51.66667	46.25	2	1991-01-14 00:00:00	
10	55.75	48.75	3	1991-01-14 00:00:00	
11	48.16667	52.83333	0	1991-01-31 00:00:00	
12	48.83333	47	1	1991-01-31 00:00:00	
13	55.75	48	2	1991-01-31 00:00:00	
14	48.1	52.88333	0	1991-02-14 00:00:00	
15	47	48.25	1	1991-02-14 00:00:00	
16	43	50.25	2	1991-02-14 00:00:00	
17	43	48.25	3	1991-02-14 00:00:00	
18	47.5	45	4	1991-02-14 00:00:00	
19	50	45	5	1991-02-14 00:00:00	
20	55.75	48	6	1991-02-14 00:00:00	
21	46.66667	53	0	1991-02-23 00:00:00	
22	43	46.5	1	1991-02-23 00:00:00	
23	48	42.58333	2	1991-02-23 00:00:00	
24	50	44	3	1991-02-23 00:00:00	
25	46.5	56	0	1991-02-28 00:00:00	
26	43.16667	45.16667	1	1991-02-28 00:00:00	
27	49.5	40	2	1991-02-28 00:00:00	
28	50	40.75	3	1991-02-28 00:00:00	

Figure C-4. Excerpt from Microsoft Excel file showing coordinates for January-February 1991, Order Field, and Observed Date.

C-3-B. Data Enrichment

The data enrichment process began with the data produced in the data ingestion phase and added additional columns to the dataset to serve as fields in an ArcGIS table. The data enrichment process again used Python code via Jupyter Notebook to update the Microsoft Excel spreadsheet. The process considered three types of dates: Observed Date – the actual date of observation in year-month-day format; the Plot Date – the date the value will be plotted which will always be the 1st or 15th of the month in year-month-date format; and the Analysis Date which will always be the 1st or 15th of the month in month-day format. The Analysis Date was used to select all dates across the years of the dataset for combined analysis.

In Excel, additional columns were added to break the Observed Date into its month, day, and year components. The Python code automated mapping of Observed Dates to Plot Dates, calculating Analysis Dates from Plot Dates, creating Label fields to assist the ArcGIS processing, and creating Value fields, assigned the numerical value of 1 to allow raster addition during the GIS processing phase (**Figure C-5**).

Additional processing was completed in a Jupyter Notebook to support the ArcGIS processing of the workflow. To complete the GIS processing accurately, an additional data point was needed for each Plot Date to close all polygons in a consistent manner. The new point used the same latitude as the last point for that Observed Date, and a common longitude point of 64.5ºW so that all polygons closed over land. The addition of this point allowed the Canadian coast to be used as a common boundary for all polygons.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Latitude	Longitude	Order	Observed Date	Month(obs)	Day(obs)	Year(obs)	Plot Date	Plot Month	Plot Day	Plot Year	Label	Value	AnalysisDate
2	49.25	-53.46666667	0	1991-01-03 00:00:00	1	3	1991	1991-01-01 00:00:00	1	1	1991	Limit_1991-01-01	1	01-01
3	48.66666667	-49.5	1	1991-01-03 00:00:00	1	3	1991	1991-01-01 00:00:00	1	1	1991	Limit_1991-01-01	1	01-01
4	49.5	-46	2	1991-01-03 00:00:00	1	3	1991	1991-01-01 00:00:00	1	1	1991	Limit_1991-01-01	1	01-01
5	52	-46	3	1991-01-03 00:00:00	1	3	1991	1991-01-01 00:00:00	1	1	1991	Limit_1991-01-01	1	01-01
6	55.75	-48.83333333	4	1991-01-03 00:00:00	1	3	1991	1991-01-01 00:00:00	1	1	1991	Limit_1991-01-01	1	01-01
7	55.75	-64.5	5	1991-01-03 00:00:00	1	3	1991	1991-01-01 00:00:00	1	1	1991	Limit_1991-01-01	1	01-01
8	49.25	-53.46666667	0	1991-01-14 00:00:00	1	14	1991	1991-01-15 00:00:00	1	15	1991	Limit_1991-01-15	1	01-15
9	50	-45.5	1	1991-01-14 00:00:00	1	14	1991	1991-01-15 00:00:00	1	15	1991	Limit_1991-01-15	1	01-15
10	51.66666667	-46.25	2	1991-01-14 00:00:00	1	14	1991	1991-01-15 00:00:00	1	15	1991	Limit_1991-01-15	1	01-15
11	55.75	-48.75	3	1991-01-14 00:00:00	1	14	1991	1991-01-15 00:00:00	1	15	1991	Limit_1991-01-15	1	01-15

Figure C-5. Sample excerpt from Microsoft Excel spreadsheet.

C-3-C. Geographic Information System (GIS) analysis

GIS processing represents the processing within the ArcGIS Pro software – either directly or using a Jupyter Notebook within ArcGIS Pro. GIS processing began by bringing the enriched data file into the GIS Environment as tables.

C-3-C.1. Creation of Points, Lines, and Polygons

The tables were then converted into points with the *XY Table to Points* tool in ArcGIS Pro. **Figure C-6 (left panel)** shows the result of the point creation step inside the GIS. Next, the points were converted into lines using the *Points to Line* tool. **Figure C-6 (right panel)** shows an example from 15 April for all years in the 30-year time period.

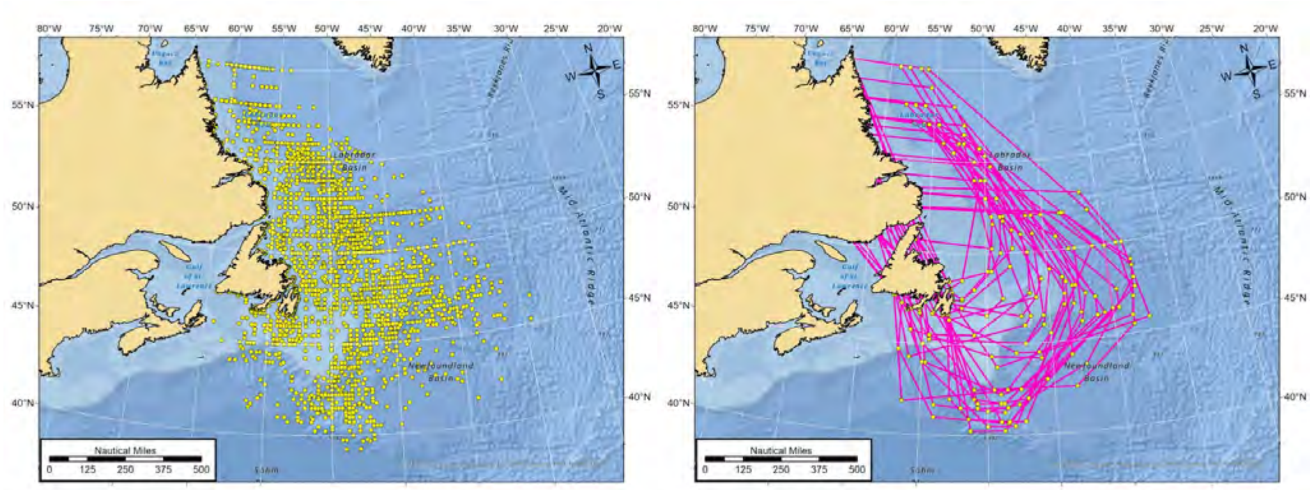


Figure C-6. GIS data table containing all points in the climatology dataset (left panel) with points and corresponding Iceberg Limit lines from 15 April (right panel).

The script then converted lines into polygons. **Figure C-7 (left panel)** shows a sample of all polygons from 15 April. To analyze a geographically consistent dataset, the polygons were truncated at 52ºN using the ArcGIS *Erase* tool (**Figure C-7, right panel**).

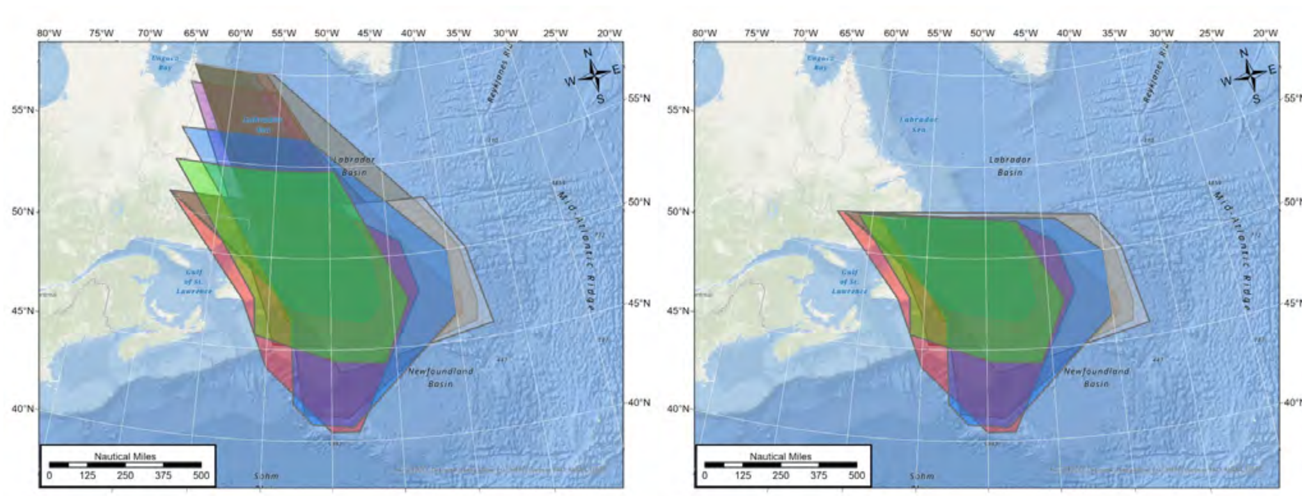


Figure C-7. Example for 15 April showing full polygon (left panel) and truncated portion of these polygons south of 52ºN (right panel).

C-3-C.2. Creation of Composite Raster Images

The Python code then converted the truncated polygons into raster images (rasters) using the *Polygon to Raster* tool. Rasters are required to accurately represent the area of the polygons representing the closed areas of the iceberg limits. As described in the Data Enrichment section, each pixel contained within the raster had a value of 1; pixels outside of the Limit had no value. Using raster functions within the ArcGIS, the code summed all raster images for each Analysis Date to enable further statistical analysis. **Figure C-8**, **left panel** shows an example from 15 April of the “stacked” rasters prior to summation. The final processing step required the creation of a mask containing the coastline and the area west of 56°W in the Gulf of St. Lawrence. The resulting composite raster image (**Figure C-8, right panel**) was the basis for creation of extreme, median, and minimum Iceberg Limits.

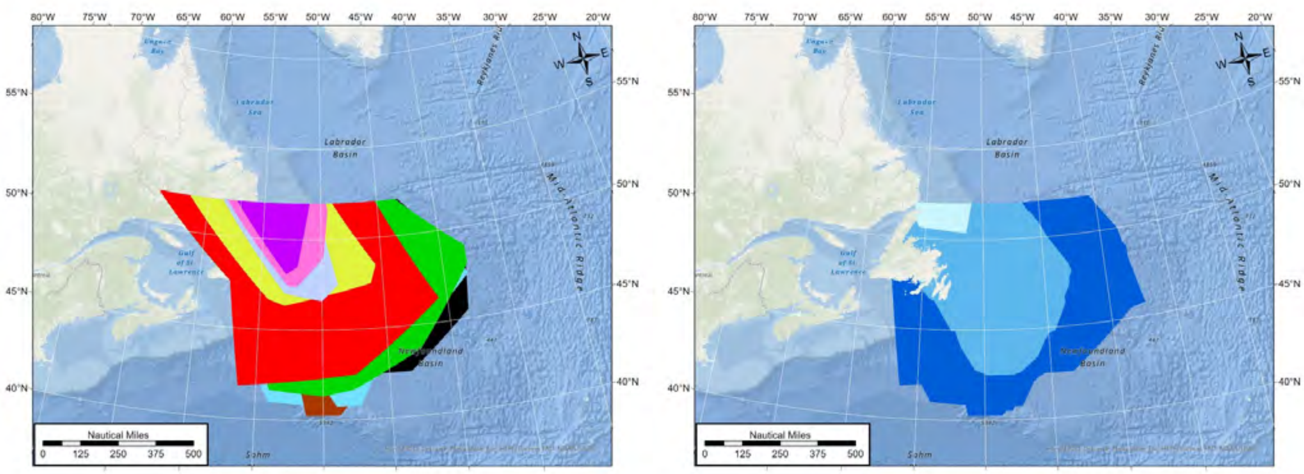


Figure C-8. Example “stacked” rasters for 15 April (left panel) and final composite raster after coast extraction (right panel). Final composite raster is displayed with manual intervals bounded by extreme, median, and minimum iceberg limits.

C-3-C.3. Creation of Extreme, Median and Minimum Iceberg Limits

Built-in statistical tools, were used to calculate and display extreme, median, and minimum Iceberg Limits. Extreme Iceberg Limits were determined as perimeters of the region bounded by the composite of all Iceberg Limits in the dataset. The outer boundary represents the Extreme Limit for the chosen Analysis Date (**Figure C-9**).

The first inner boundary represents the median Limit for the chosen Analysis Date. The median is automatically calculated by creating a histogram chart in ArcGIS Pro for each raster image, and displaying the median value on the chart. The example provided shows this histogram chart for 15 April (**Figure C-10**). The histogram represents the quantity of occurrences (vertical axis) plotted against the cell value – ranging from 1 (near the extreme when the Iceberg Limit was present in only one year) to the total number of years in the dataset (30 for the 15 April example) i.e., cells with a sum of 30 were contained by the Iceberg Limit in all 30 years of the dataset. The median for the example in **Figure C-10**, shown as a purple-colored vertical line, is 12 and represents the point where the sum of the count of pixels to the left of the median equals the sum to the right. In short, the median Limit can be interpreted as the boundary where the Iceberg Limit has occurred approximately 50% of the time over the 30-year period.

Minimum limits were created by examining the total number of years where the Iceberg Limit extended south of 52°N. The Minimum Limits show the position of the Limit where all seasons for the Analysis Date, south of 52°N, were contained within the boundary. It is important to note that there were several years where the Iceberg Limit did not extend south of this latitude. In these years, the maximum summed cell value was less than 30.

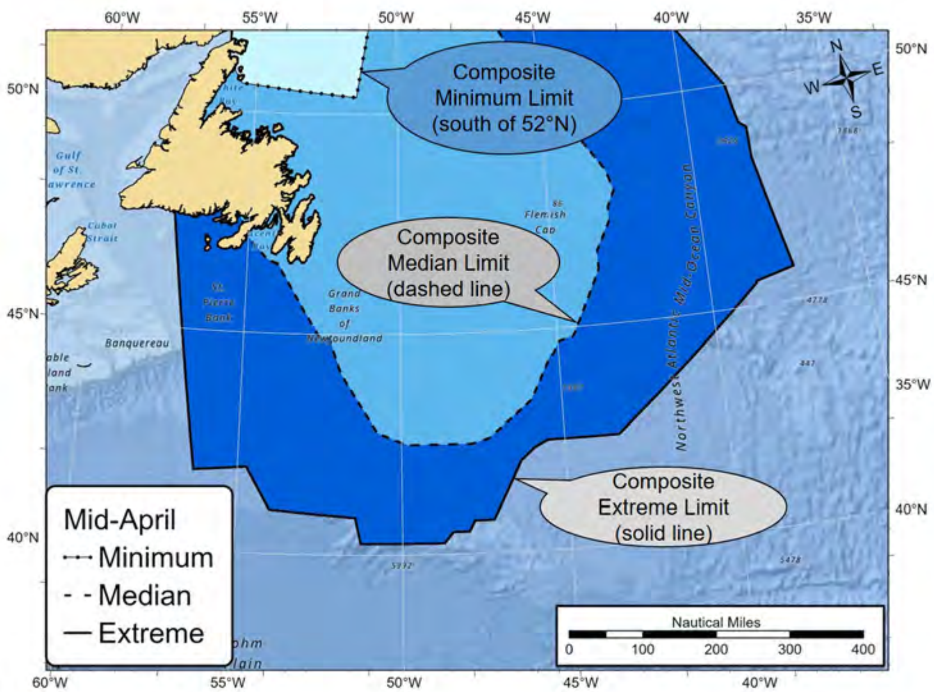


Figure C-9. Full polygons for 15 April (left panel) and polygons south of 52ºN (right panel).

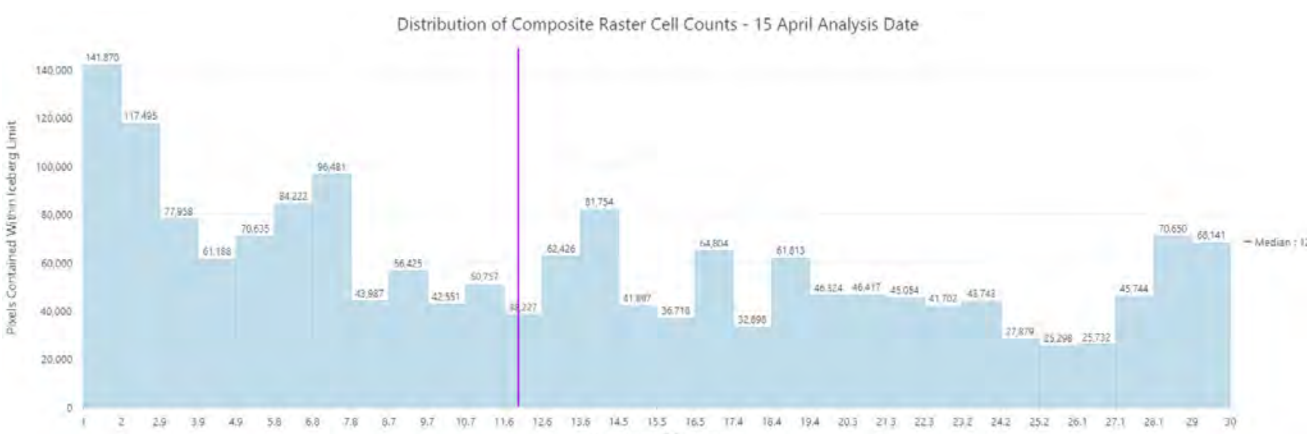


Figure C-10. Sample histogram for 15 April Analysis Date. The purple line shows the median value of 12. The sum of the number of cells within the composite raster to the left of the median is equal to the sum to the right.

C-4. Summary

This study involved the creation of composite raster images to represent the area encompassed over a 30-year time period for early and mid-month Analysis Dates. The use of raster analysis in ArcGIS Pro allows computation of key statistical metrics such as the extreme, median, and minimum to graphically display the Iceberg Limit climatology during the period from 1991 to 2020. The Iceberg Limit climatology serves as a comparison benchmark to yield additional insight on the severity of an iceberg season, beyond the count of icebergs south of 48°N. Viewing the composite raster images with extreme, median, and minimum Iceberg Limits (**Figures C-12 through C-22**) show the expected expansion of the Iceberg Limits during the months of April through June with contraction of the Limits during the late-summer and through fall. Interpretation of the extreme Iceberg Limit is straightforward as represents a composite of all Iceberg Limit perimeters over the time period. The median Iceberg Limit provides a more meaningful day-to-day benchmark to visualize developing season severity.

IIP has already incorporated elements of this climatology into a Seven-Day Iceberg Outlook comparing the location of the Iceberg Limit on a given date with the extreme, median, and minimum Iceberg Limits for the Analysis Date. A sample from 2021 shows this product with the Iceberg Limit for 13 April overlaid on top of the mid-April climatology (**Figure C-11**).

All data to include polygons, rasters, and minimum, median, and extreme Iceberg Limits are saved as geodatabases to facilitate data sharing. All data contain the Analysis Date field to facilitate the use of the Definition Query function within ArcGIS to examine any dates desired. Geodatabases are available on request.

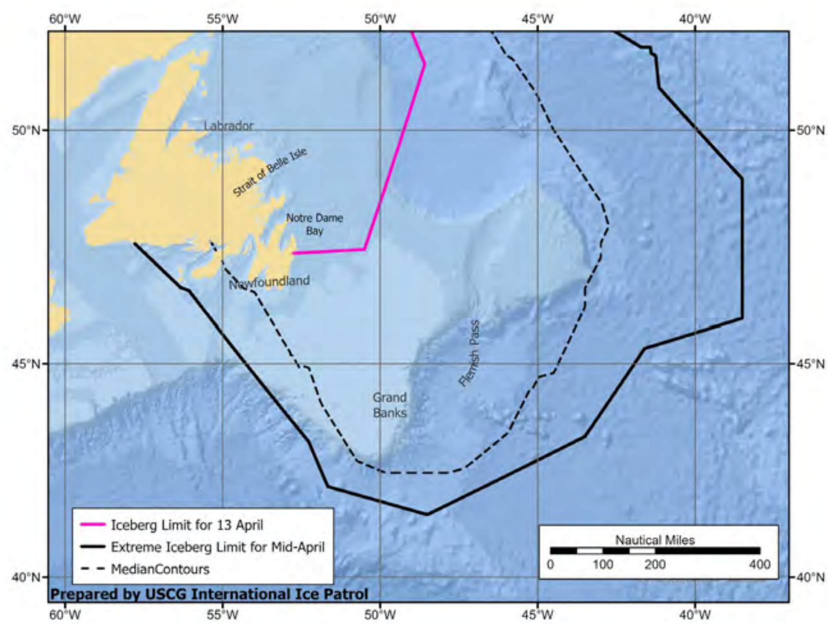
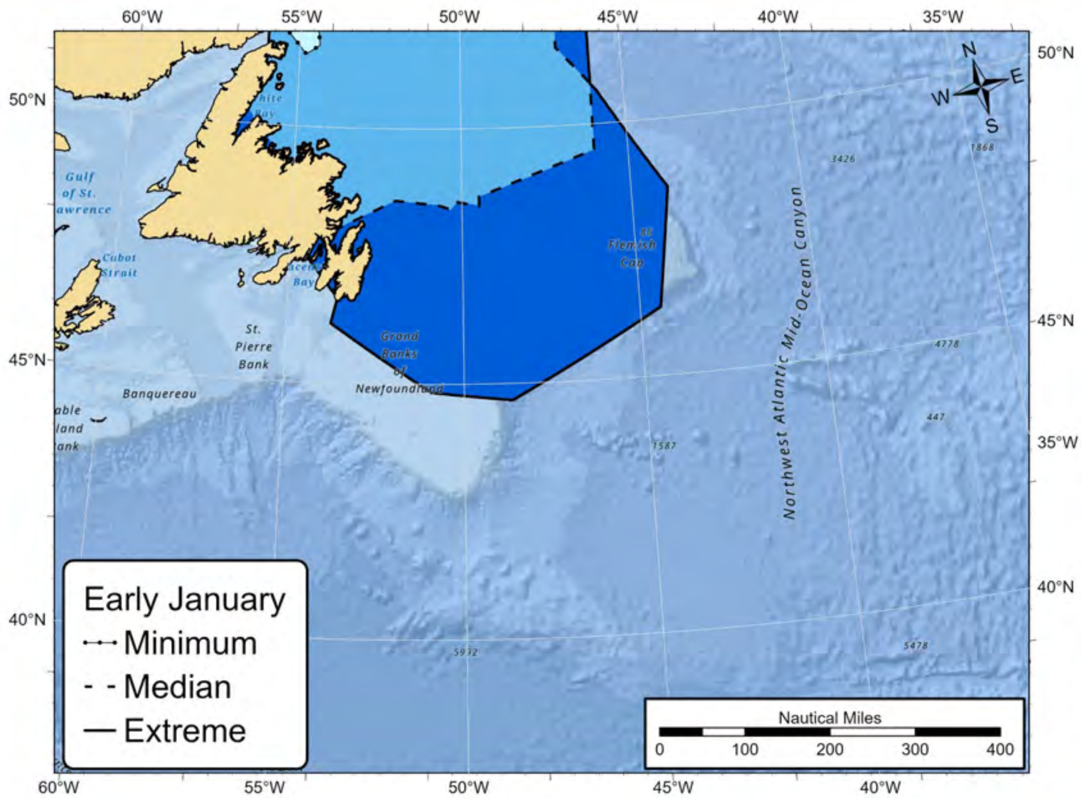


Figure C-11. Seven-Day Iceberg Outlook Product for 13 April 2021. The Iceberg Limit for 13 April is shown in magenta. This graphical comparison of the Iceberg Limit to the mid-April climatology highlights the light severity of the 2021 Ice Year.

C-5. Bi-Monthly Extreme and Median Iceberg Limit Plots for 1991-2020



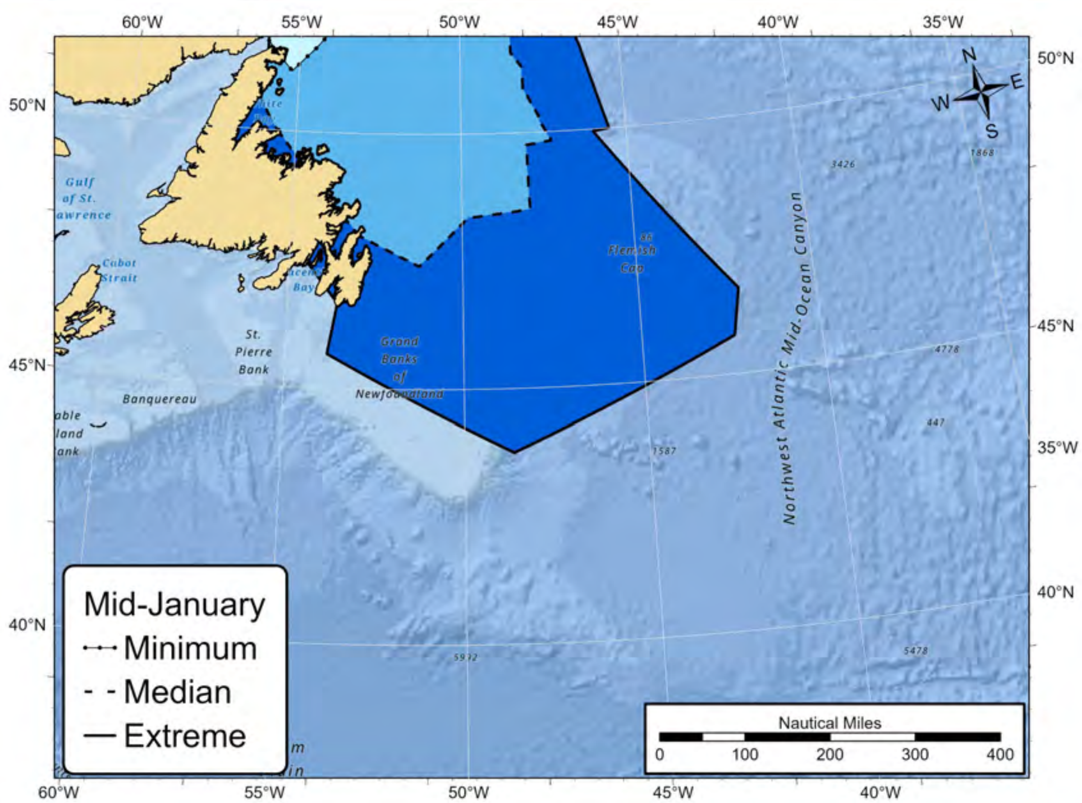
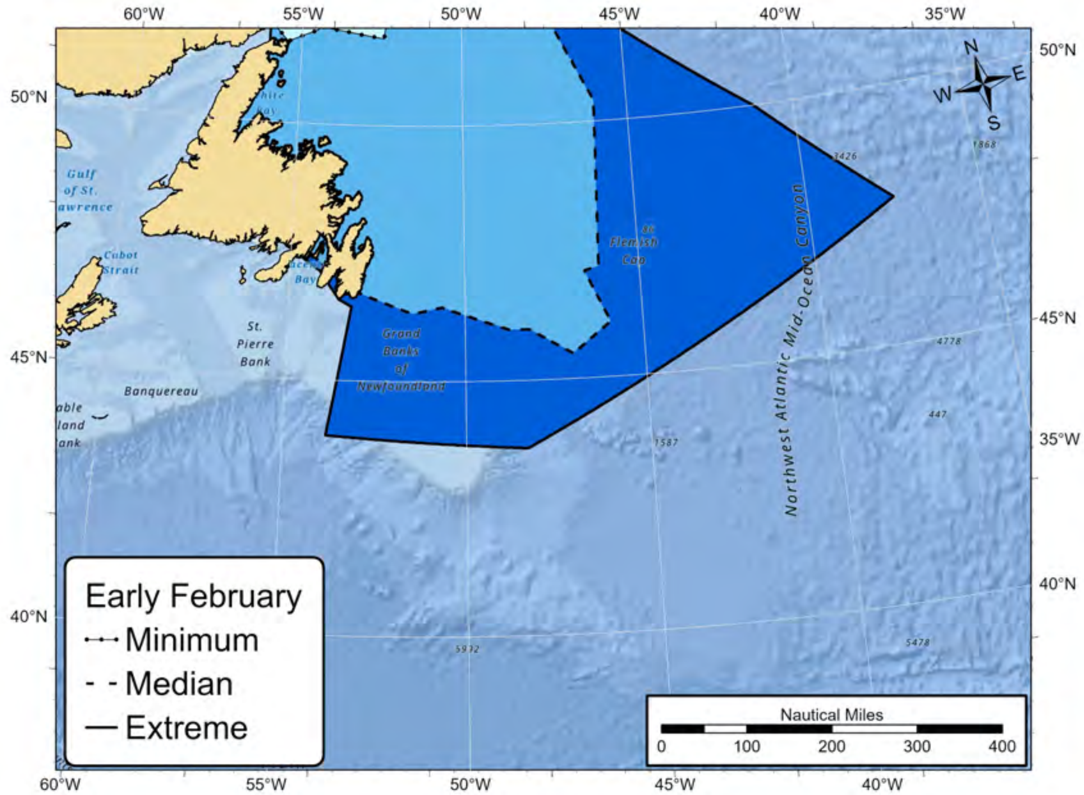


Figure C-12. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-January (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.



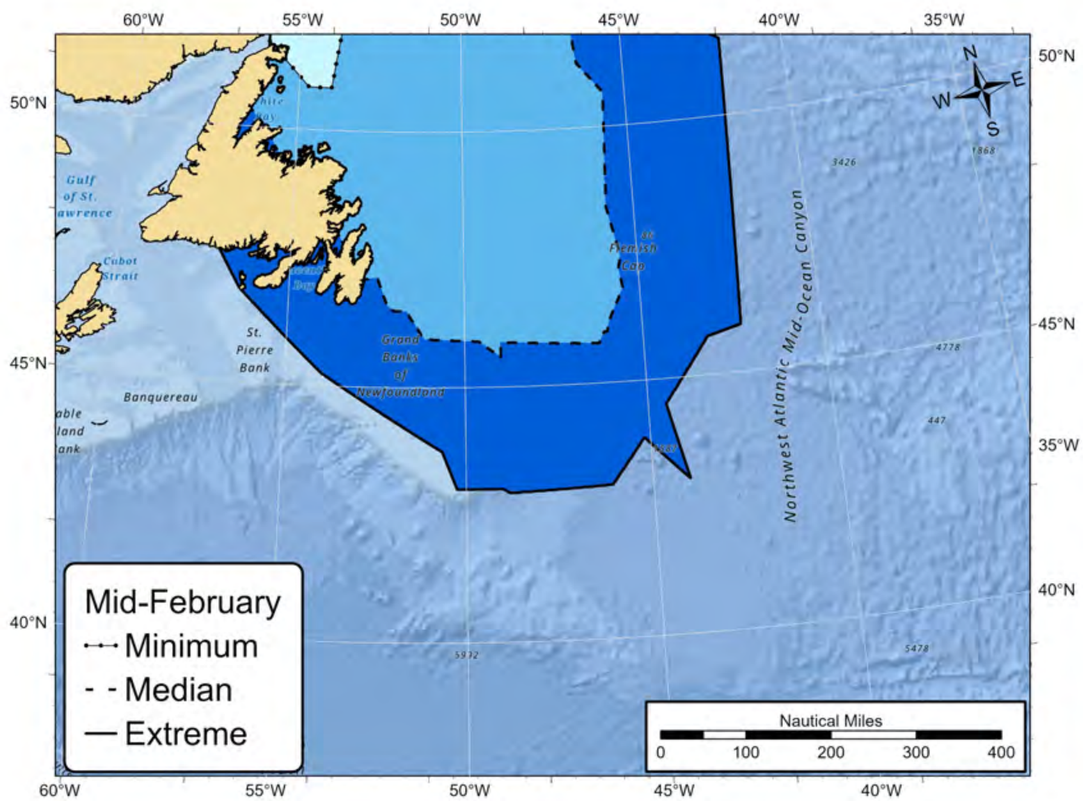
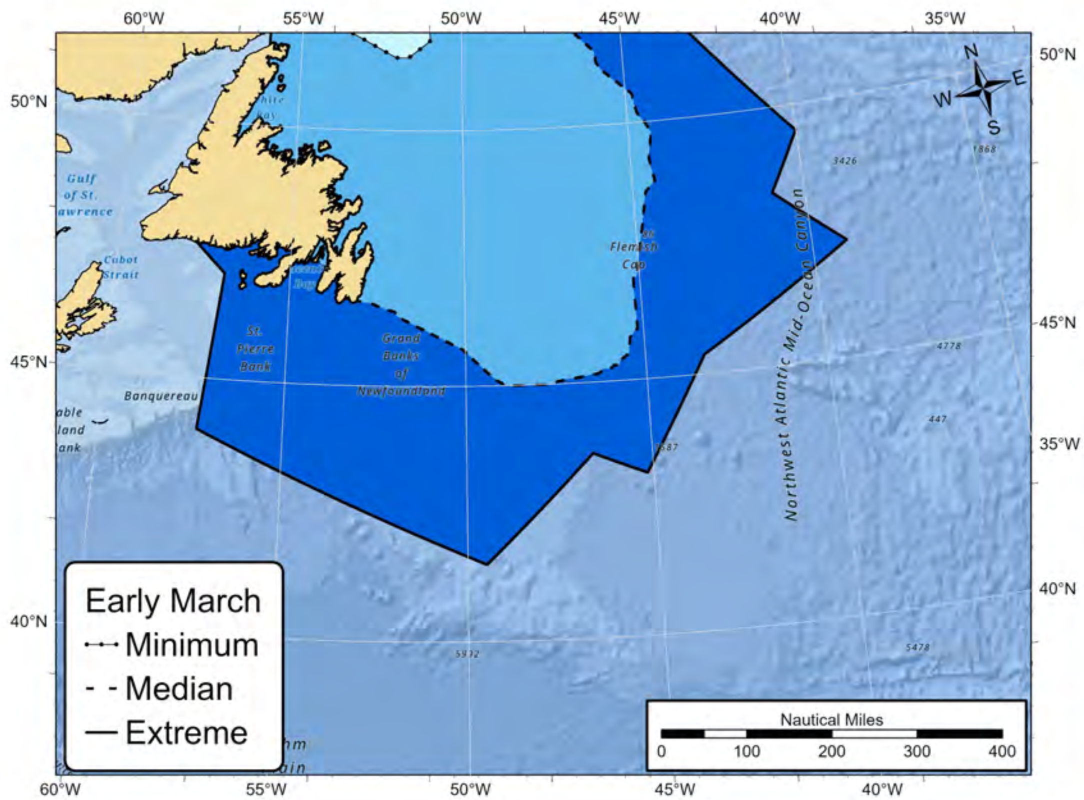


Figure C-13. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-February (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.



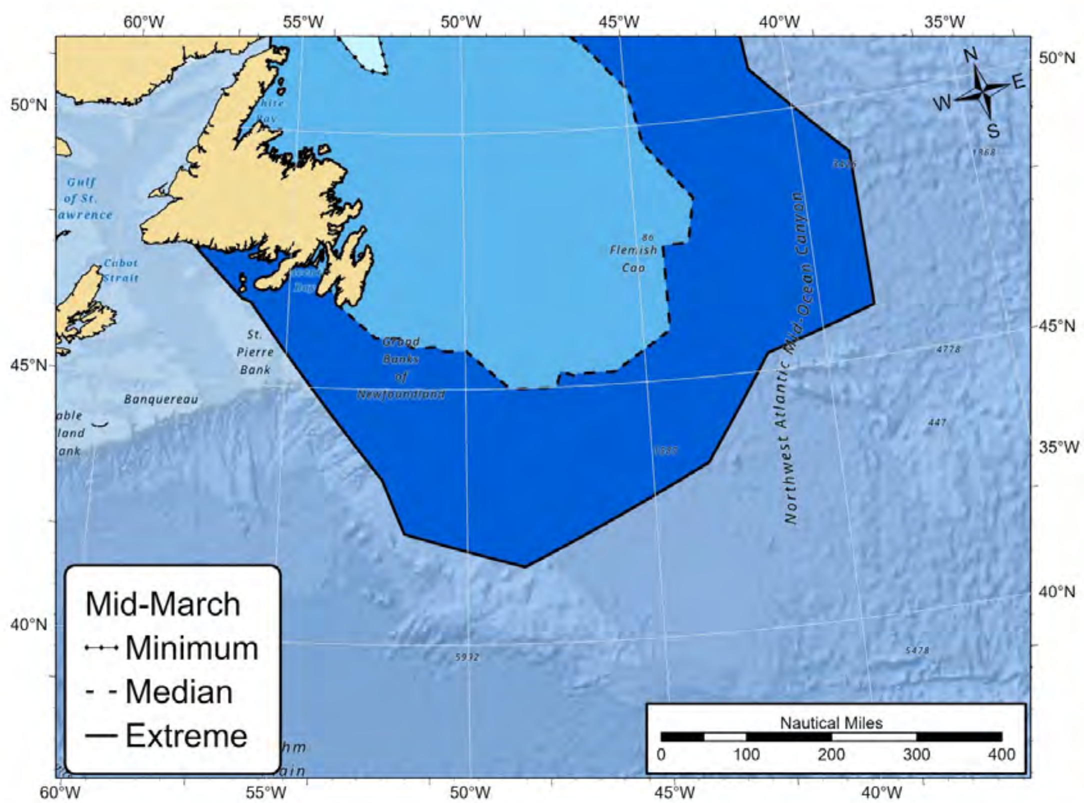


Figure C-14. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-March (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.

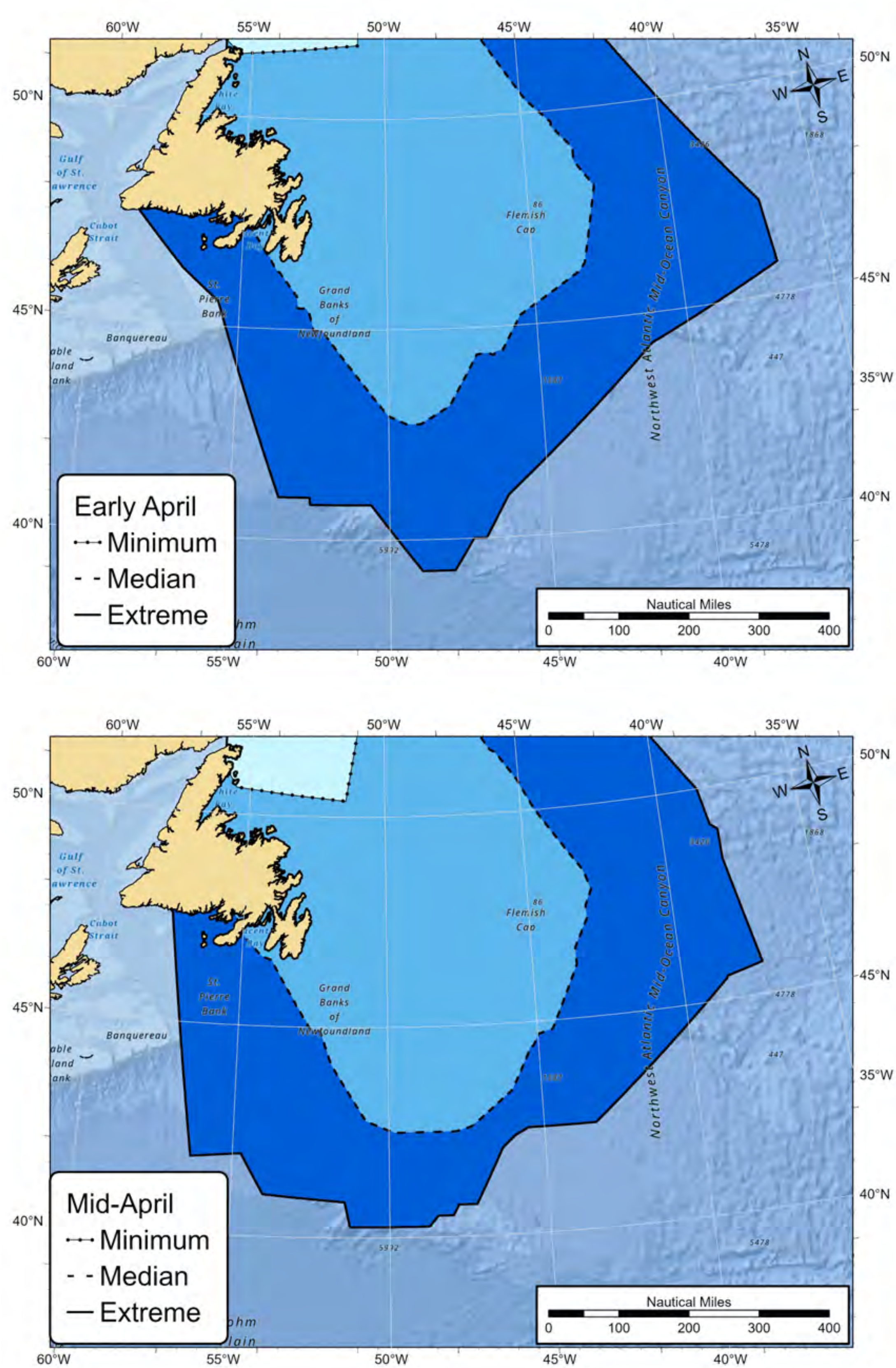
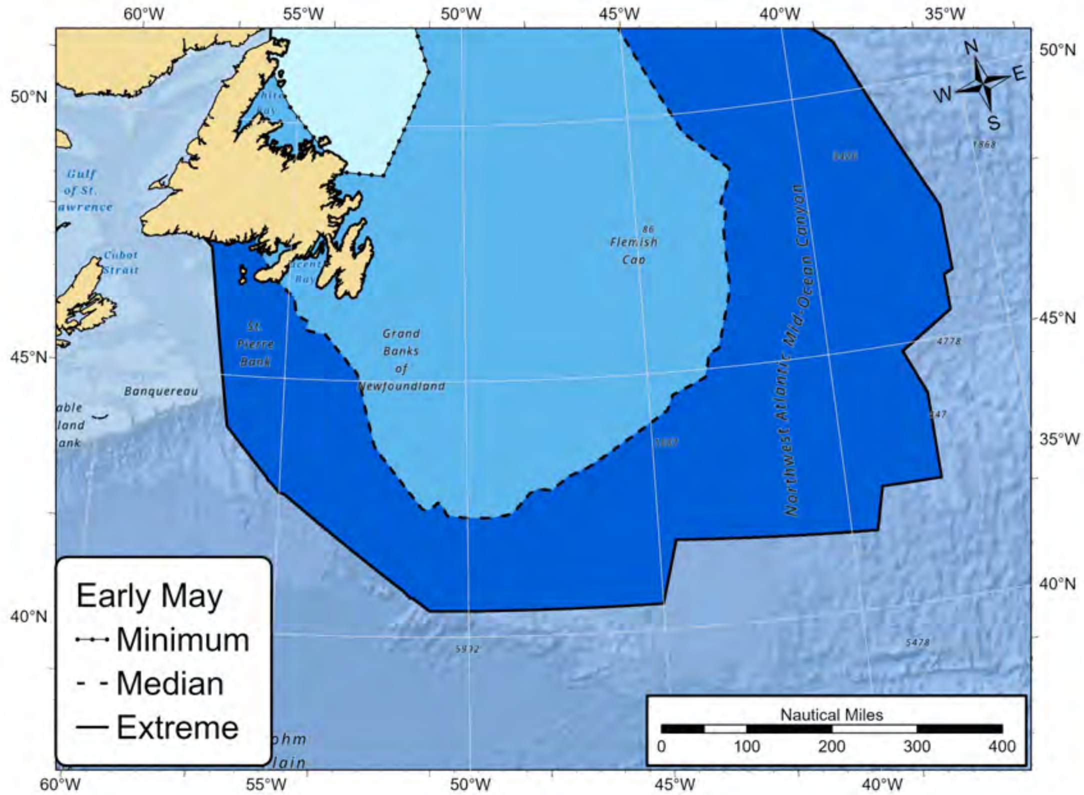


Figure C-15. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-April (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.



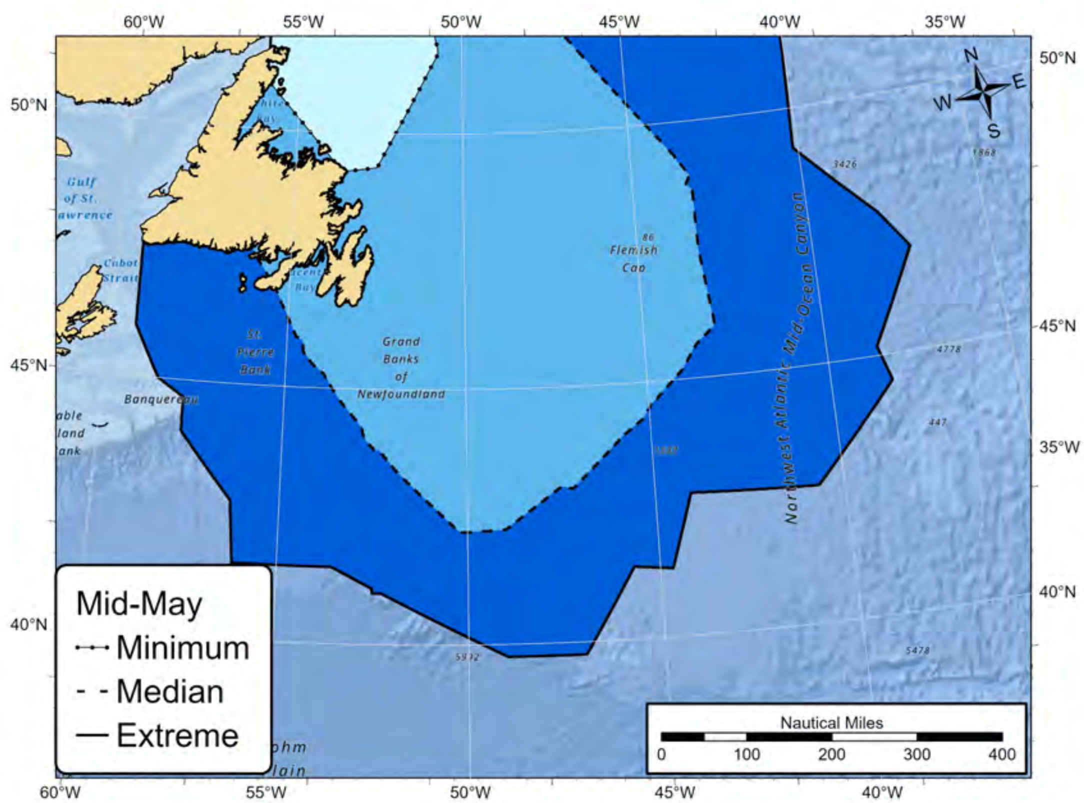
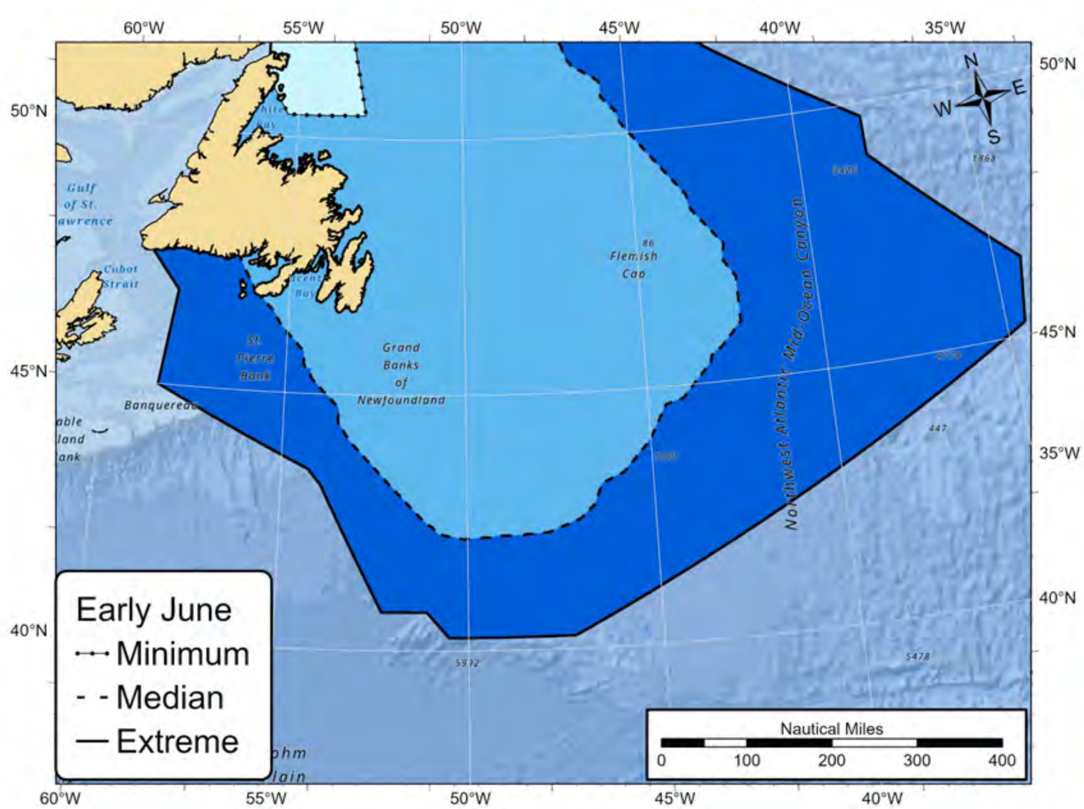


Figure C-16. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-May (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.



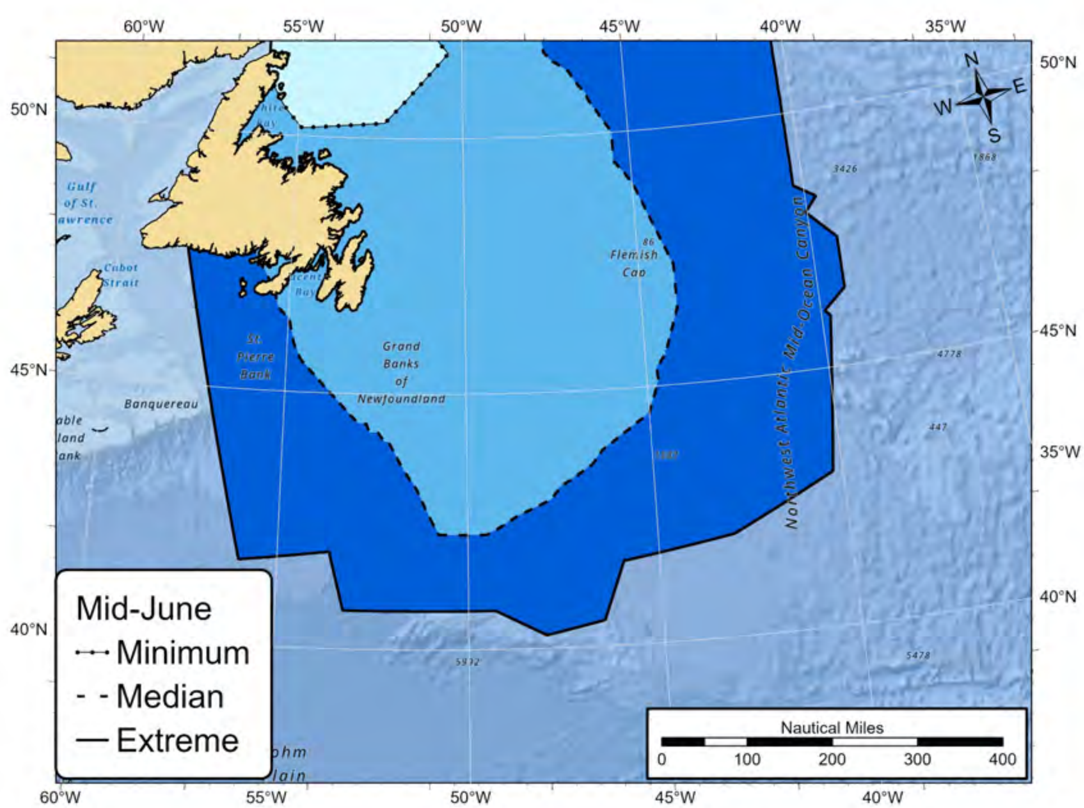
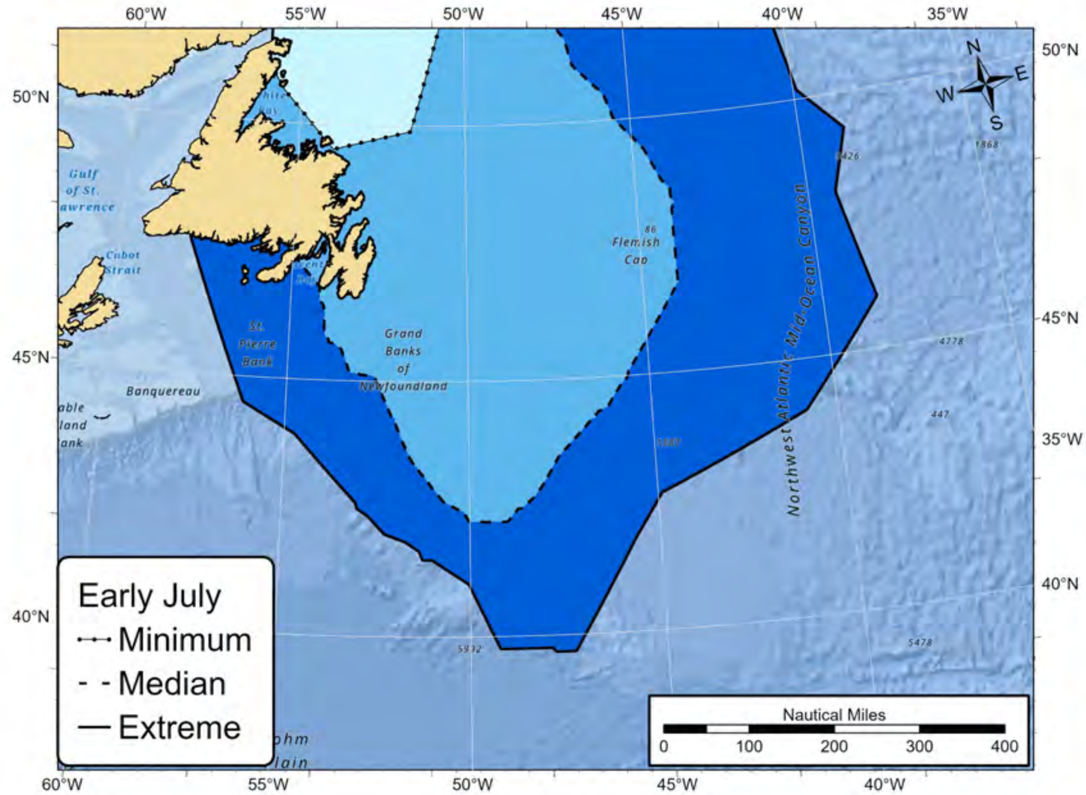


Figure C-17. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-June (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.



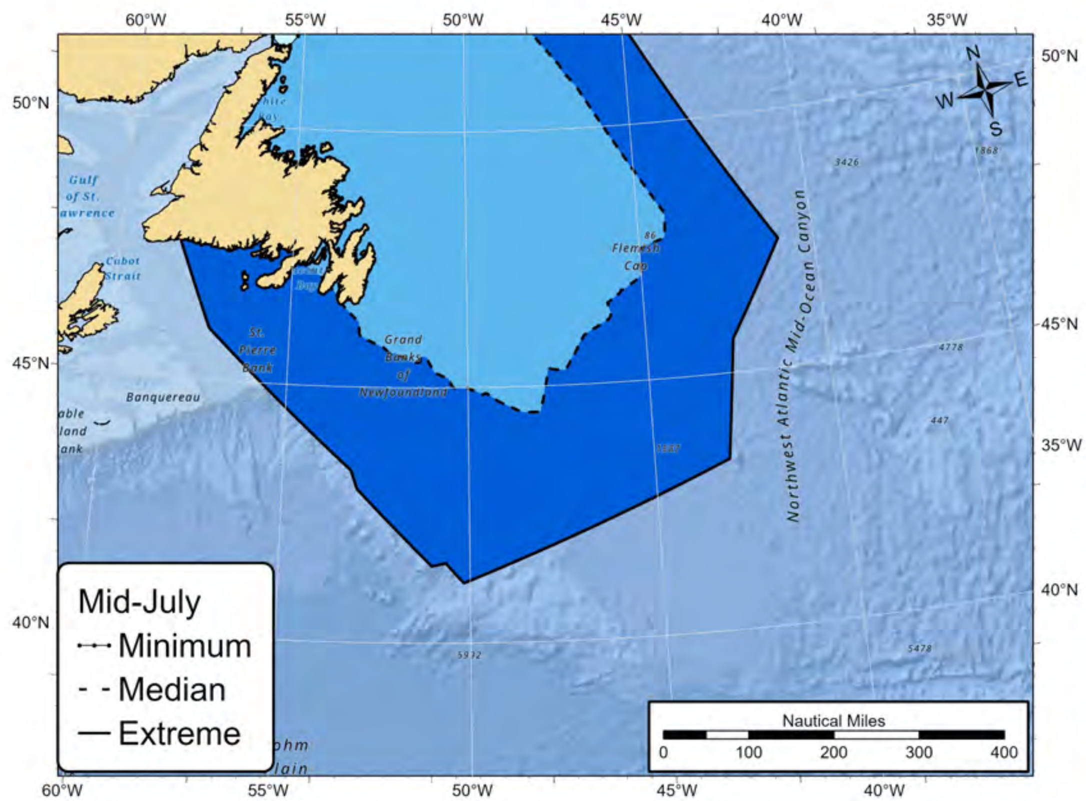


Figure C-18. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-July (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.

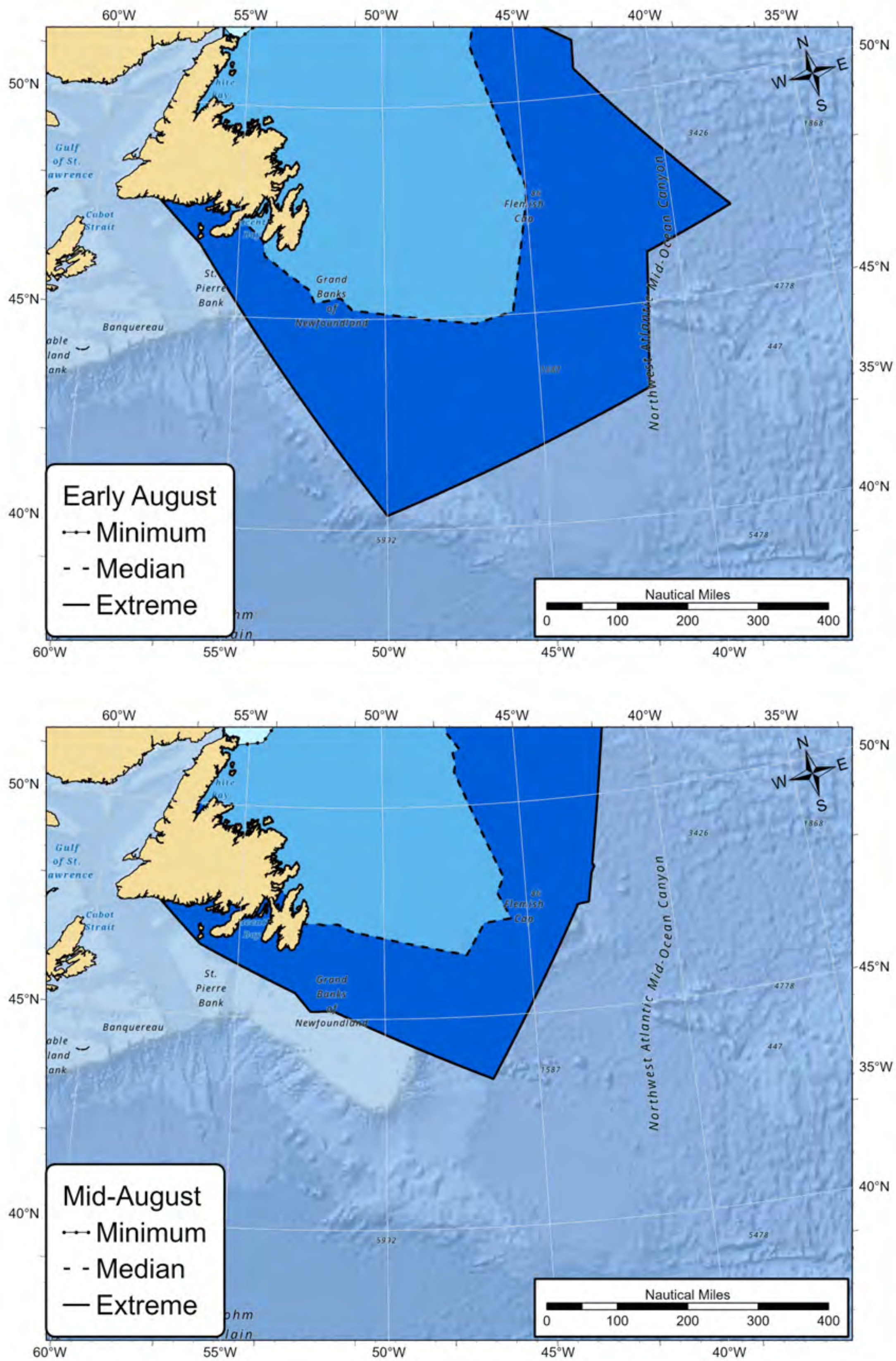
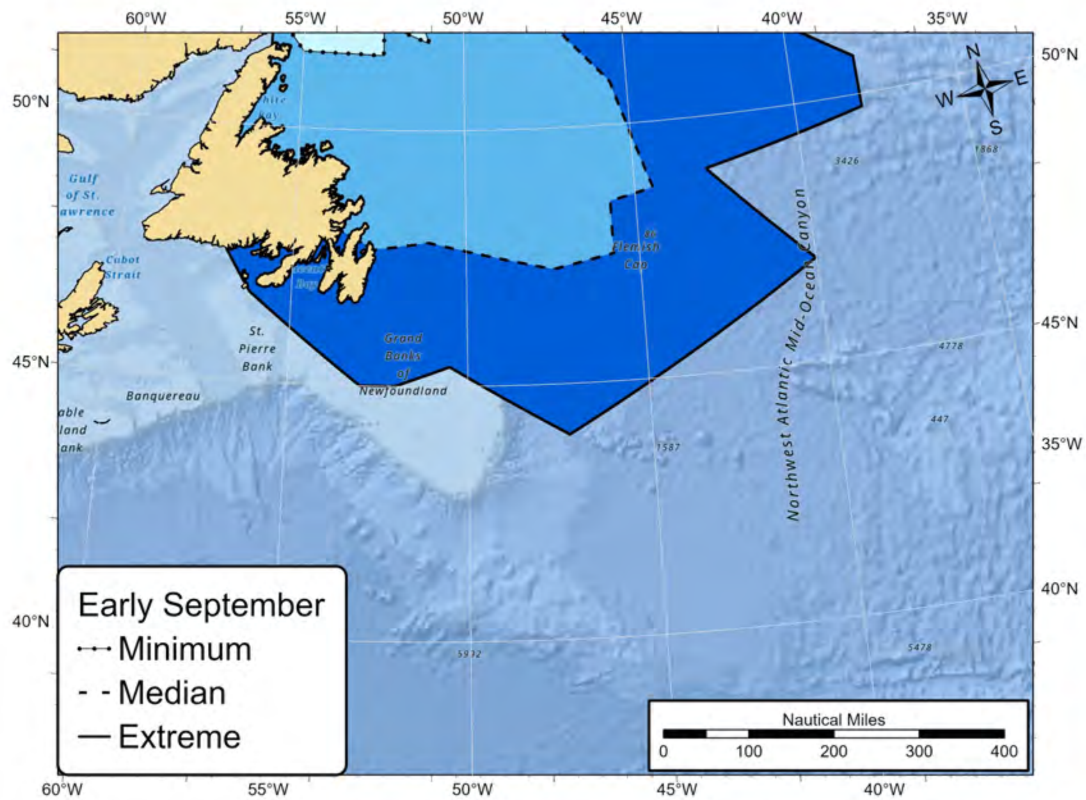


Figure C-19. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-August (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.



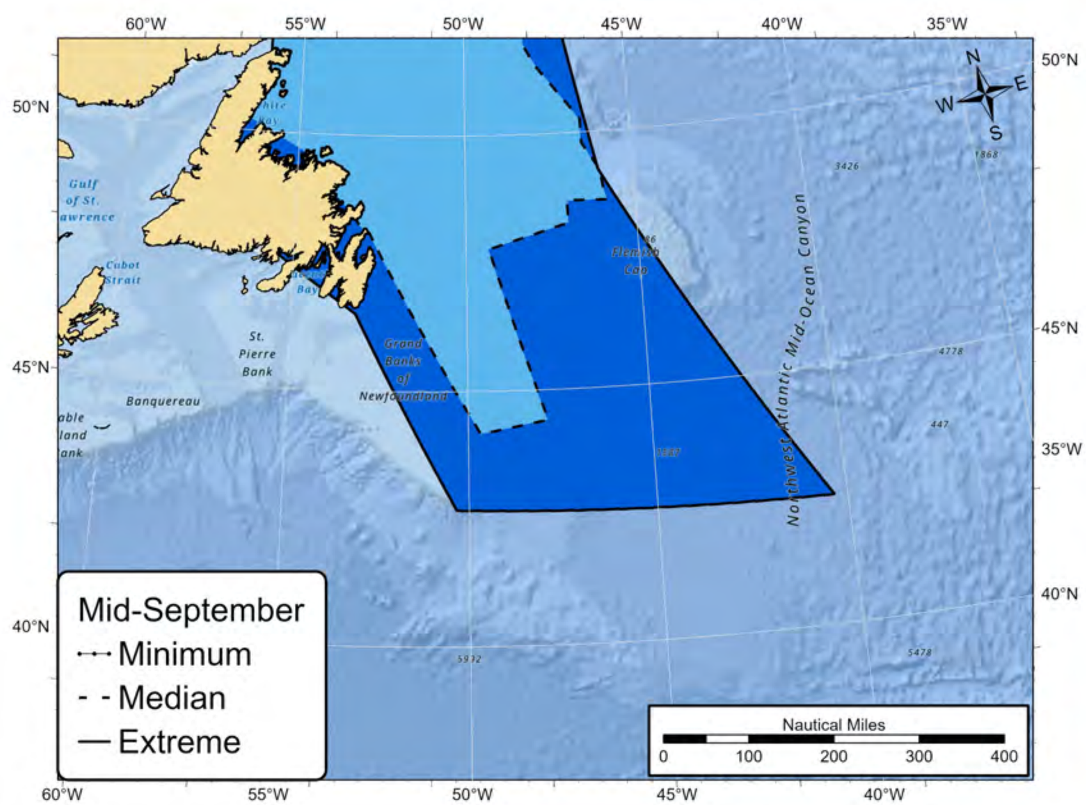
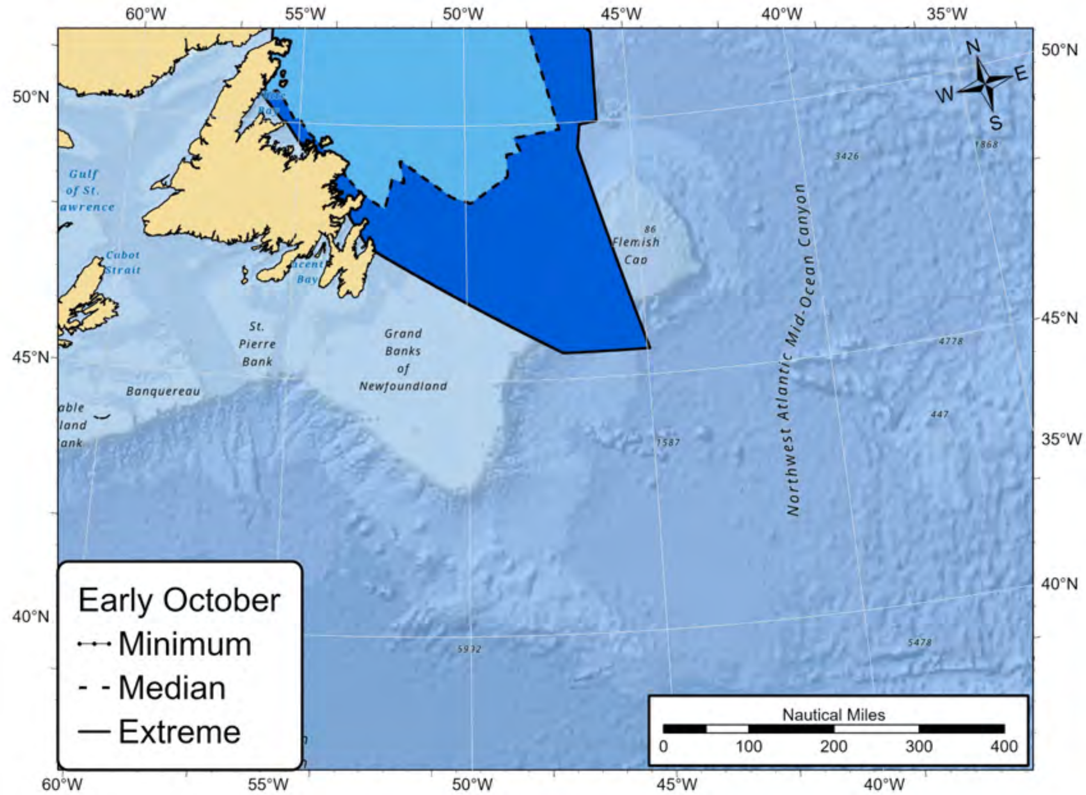


Figure C-20. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-September (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.



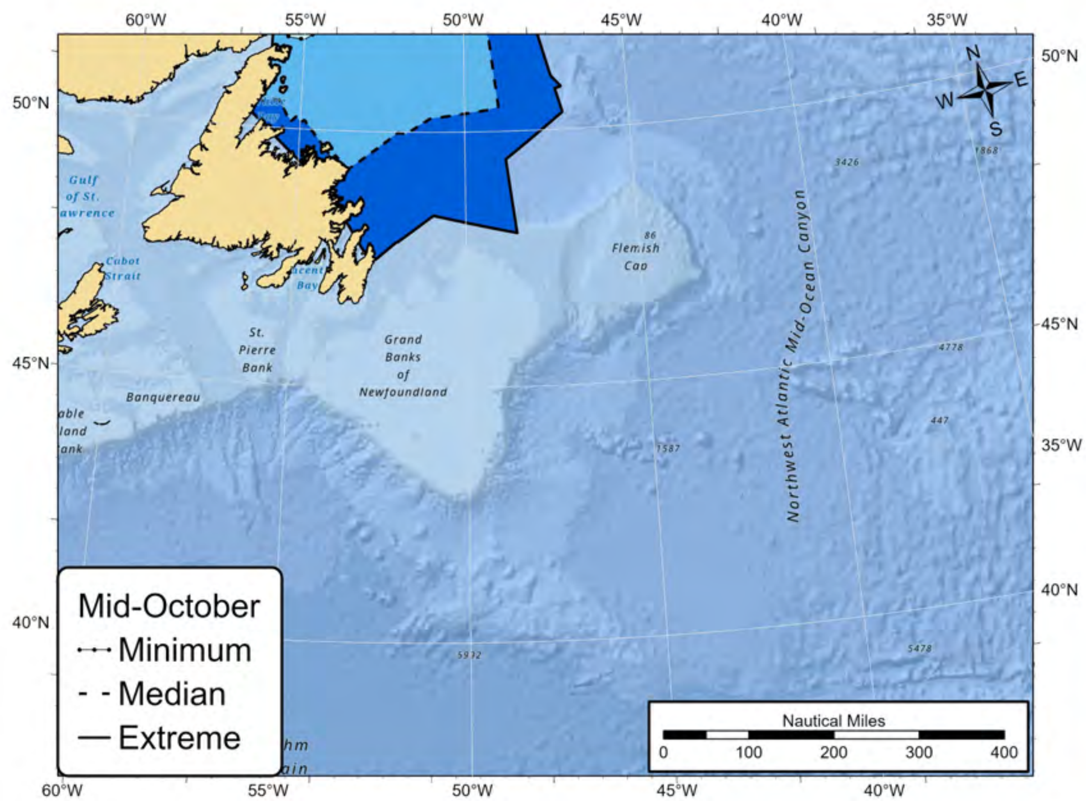
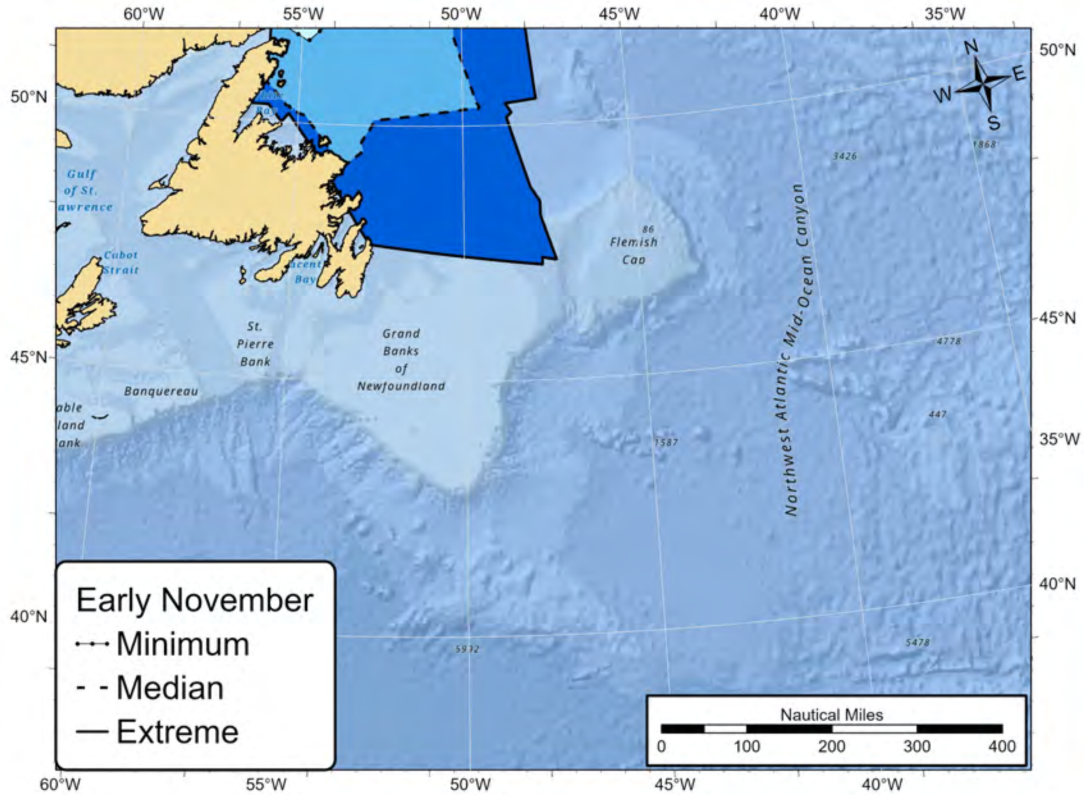


Figure C-21. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-October (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.



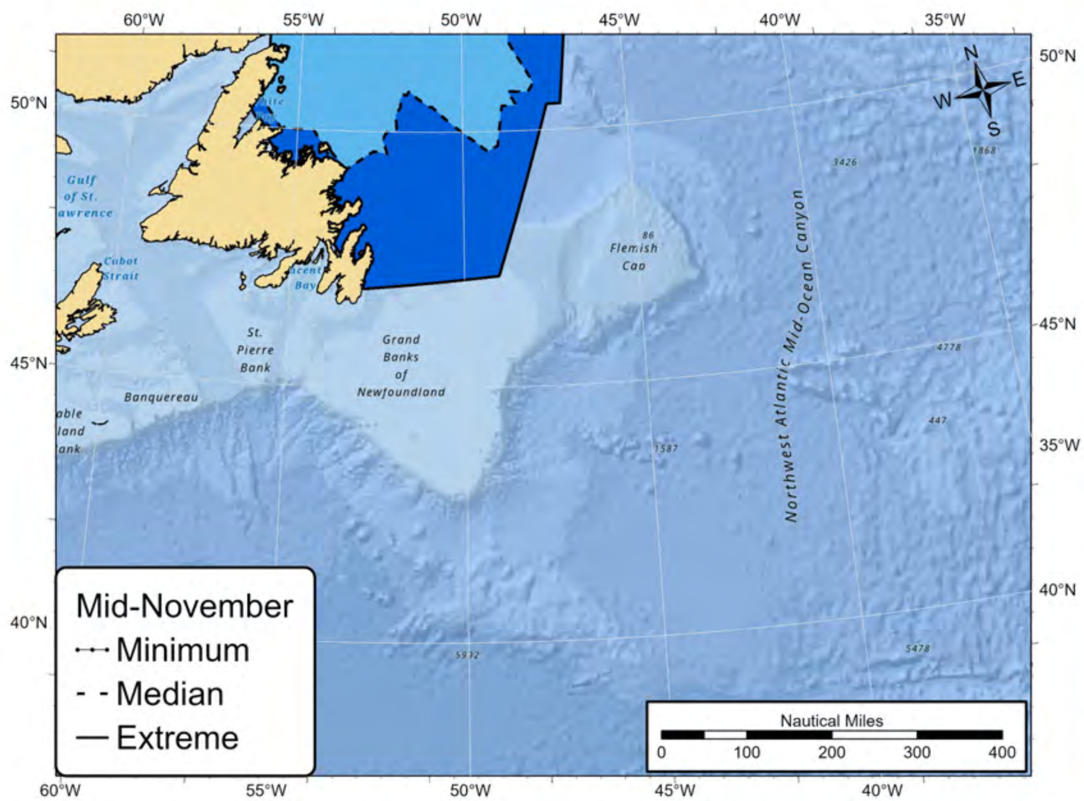
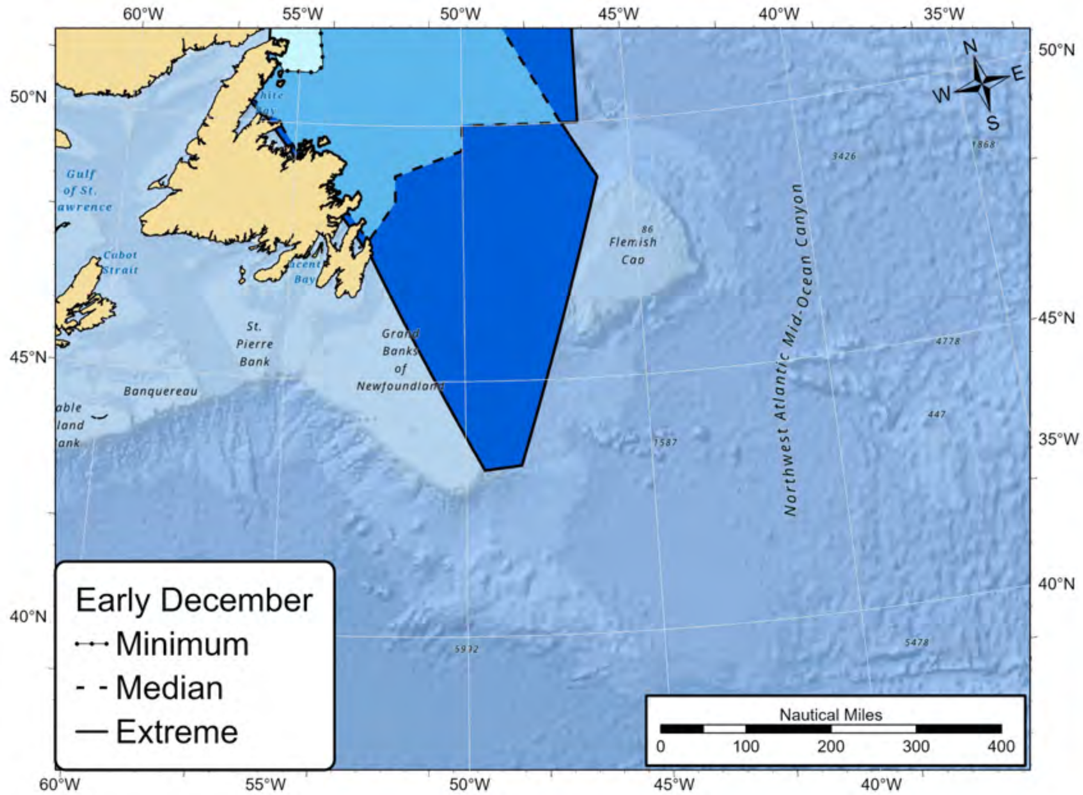


Figure C-22. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-November (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.



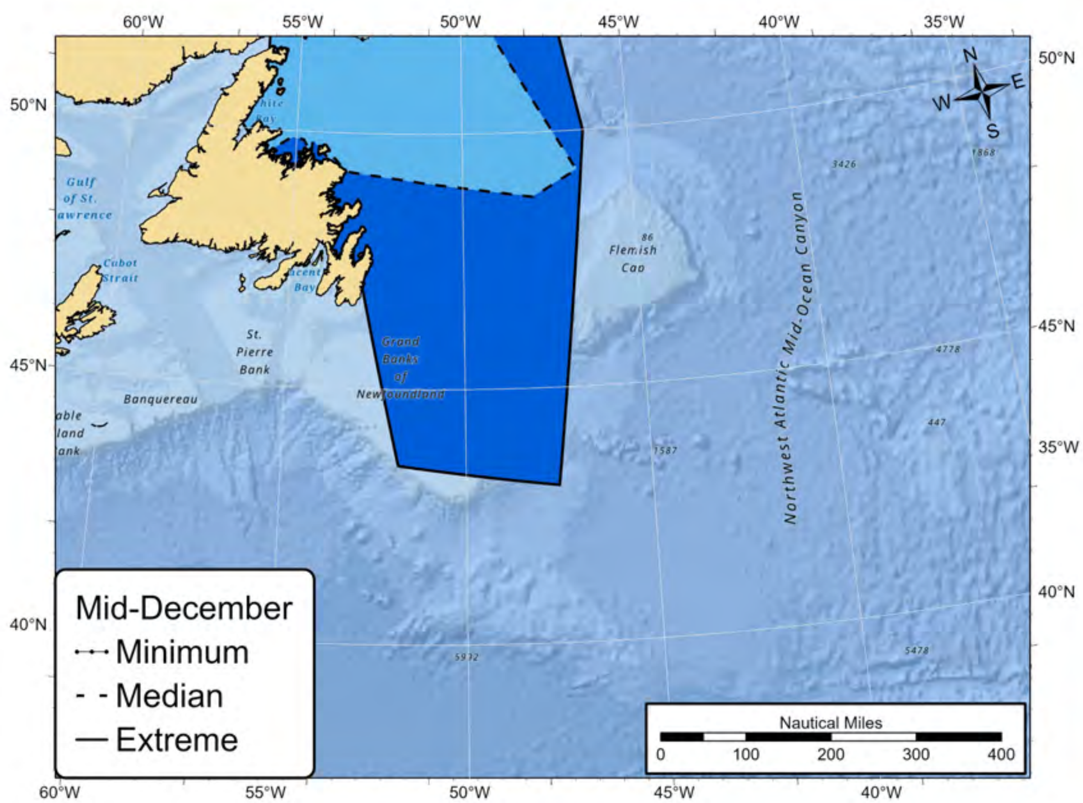


Figure C-23. Minimum, Median, and Extreme Iceberg Limit for Early (top) and Mid-December (bottom). Climatology based on IIP and CIS Iceberg Limit data from 1991-2020.

C-6. Acknowledgements

The authors acknowledge the dedicated work of Dr. Don Murphy (former IIP Chief Scientist) for his tenacious approach in collecting and organizing Iceberg Limit data; Luc Desjardins (former CIS iceberg analyst) for filling data gaps in the early years of this dataset and Angela Cheng (CIS) for her ArcGIS expertise.

C-7. References

Viekman and Baumer (1995). International Ice Patrol Iceberg Limits Climatology (1975-1995), Technical Report 95-03.

Cline, J. (2020). Technical Report: Iceberg Detection and Information Dissemination Methods. New London: USCG Research and Development Center.

Appendix D. The “Iceberg Gap” – Investigation of Iceberg Wave Erosion Deterioration Rates

LCDR Don Rudnickas

D-1. Introduction

During the summer of 2020, the International Ice Patrol (IIP) provided tailored iceberg warning products to vessels participating in an international exercise along the west coast of Greenland, outside of IIP’s typical reconnaissance area. While the vessels were transiting to the exercise area, the products predicted a region to the northwest of Nuuk, Greenland to be nearly iceberg-free, despite thousands of icebergs to the north and south. After several days of sending products similar to **Figure D-1**, one ship captain asked IIP about this apparent “Iceberg Gap.” Was it real or a function of the resolution of satellite imagery being used to produce the products? The IIP Analyst in communication with the vessel

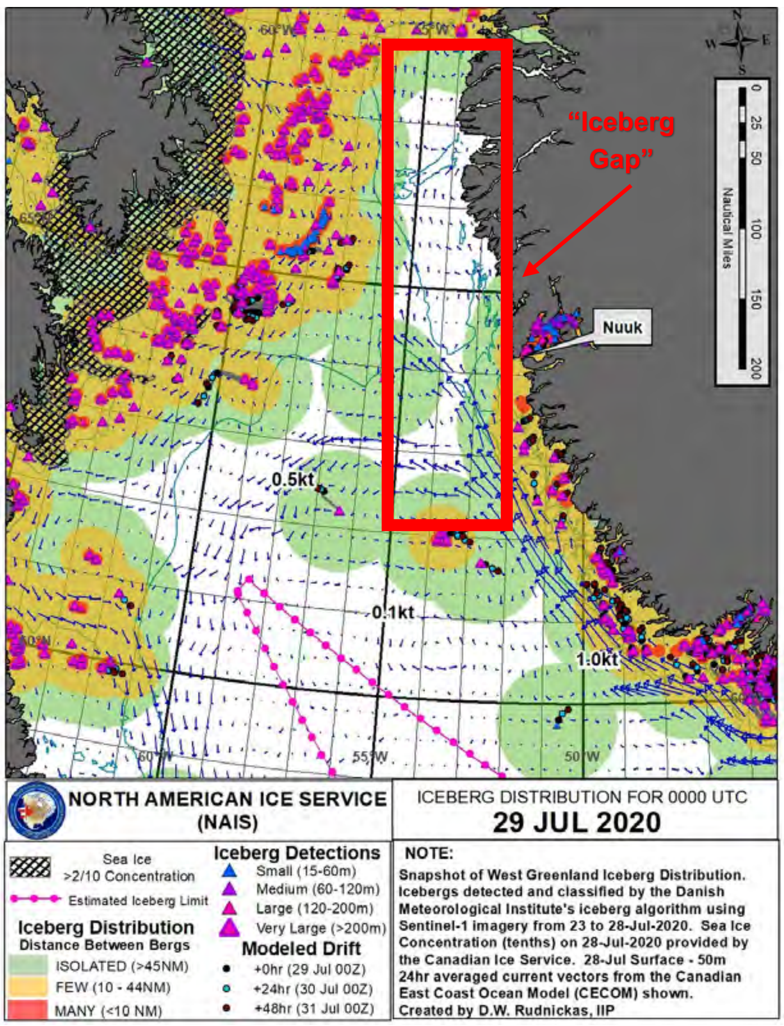


Figure D-1. Example of the products provided during July 2020 to vessels participating in exercises off the west coast of Greenland. This product was produced by the International Ice Patrol valid for July 29, 2020. The “Iceberg Gap” is denoted by the red box added for the reader’s benefit to this figure (not to the original product).

provided **Figure D-2** as a response, with the hypothesis that, given prevailing currents and winds, icebergs flowing north in the West Greenland Current were more likely to be well-deteriorated after a long journey from the east coast of Greenland or drifted aground before they could reach the area of Nuuk, while icebergs calved from the Jakobshavn Glacier on the west coast of Greenland, generally exit Baffin Bay on the western side of Davis Strait, leaving space for the "Iceberg Gap." Over the following months, frequent satellite reconnaissance of the area and shipboard observations, showed the "Gap" to be a legitimate feature, free of icebergs from the end of July through the end of September 2020.

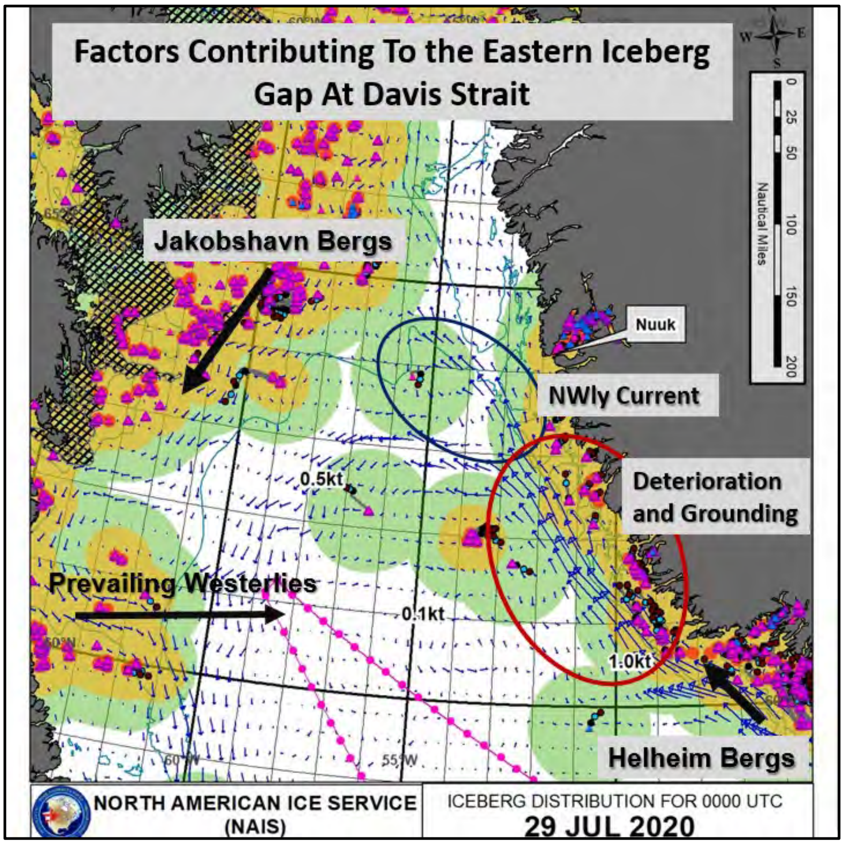


Figure D-2. Supplemental product provided to describe the initial hypothesis for the "Iceberg Gap". Given prevailing currents and winds, icebergs flowing north in the West Greenland Current were more likely to be well-deteriorated or aground after a long journey from the east coast of Greenland before they could reach the area of Nuuk, while icebergs calved from the Jakobshavn Glacier on the west coast of Greenland, generally exit Baffin Bay on the western side of Davis Strait, leaving space for the "Iceberg Gap."

This Appendix documents subsequent work to investigate the cause of this so-called "Iceberg Gap" through solving a daily rate of deterioration by wave erosion based on the dominant term in the IIP Iceberg Drift and Deterioration model resolved for the Irminger Sea, Labrador Sea, and Baffin Bay from 2018 through 2021. Considering idealized icebergs, stable current conditions, and model-derived wave height, wave period, and ocean temperature, a case is made for the "Iceberg Gap" existing year-round due to increased deterioration rates experienced by icebergs calved from the east coast of Greenland as they round Cape Farewell, making it less likely for all but the biggest icebergs to survive long enough to reach the latitude of Nuuk. Looking beyond the idealized icebergs at anomalies from a mean, components of the deterioration rate at different locations are tested for correlation to IIP's metric of Ice Season severity and a correlation is shown between the end-of-summer environmental conditions at Cape Dyer and the number of icebergs to pass south of 48°N the following year. The wave erosion deterioration rate is further compared to observed calving events of two icebergs in 2019: one was a Petermann Glacier Ice Island, originally calved in 2017, drifting in Baffin Bay and a second was the splitting of a GPS tagged iceberg along the coast of Newfoundland. Both calving events are shown to be linked to increases in the wave erosion deterioration rate, primarily from increases in the wave height.

D-2. Data and Methods

From the moment an iceberg calves from the glacier, it begins deteriorating. Each surface, each crack, each facet, absorbs some percentage of the sun's radiation and experiences melting as the relative heat of the air and ocean inexorably transfer. Shifts in the centers of buoyancy and gravity as the iceberg is rolled by the waves induces stress on the extremities and shape of the iceberg, perhaps leading to calving much of its mass in a sudden event. Of all the deterioration mechanisms acting on a drifting piece of glacial ice, wave induced erosion at the waterline is considered the most important (i.e. White et al., 1980; El-Tahan et al.,1987; Kubat et al., 2007). Wave erosion not only reduces the waterline length, but forms a "notch" at the waterline, changing the centers of buoyancy and gravity and increasing the stresses associated with overhanging ice that lead to calving. White et al. (1980) determined the rate of deterioration due to wave erosion (V_{we}) in units of m/s to be calculated as:

$$V_{we} = 0.000146\left(\frac{R}{H}\right)^{0.2}\left(\frac{H}{\tau}\right)\Delta T \qquad \textbf{Equation D-1}$$

Where R is the roughness height of the ice (typically 1 cm, (White et al., 1980)), H is the wave height (m), τ is the wave period (s), and ΔT is the difference between the ocean temperature and the temperature of the ice (℃).

To investigate the impact of deterioration by wave erosion in the IIP area of interest, a daily V_{we} was calculated throughout the area at 1/12 degree (0.083° by 0.083°) resolution. Ocean temperature, wave heights, and wave periods were downloaded from the Copernicus Marine Services data hub. Numerically modeled ocean potential temperature ("theta0") from the GLOBAL_ANALYSIS_FORECAST_PHY_001_024 dataset at daily (1200 UTC) temporal resolution and 15 m depth to approximate the mixed layer temperature below any sea ice was utilized. The ice temperature was set at a constant value of 0°C such that the ΔT term in **Equation D-1** was simply set equal to the theta0 value from the data. Numerically modeled spectral significant wave height ("VHM0") and the wave period at spectral peak/peak period ("VTPK") from the GLOBAL_ANALYSIS_FORECAST_WAV_001_027 data were used. These are provided in three-hour increments. For simplicity, a daily average was utilized and set at 1200 UTC to match the ocean temperature dataset. The roughness height value of 0.01 m was set as a constant, as in

White et al. (1980). Using these data, a daily V_{we} was calculated for the entire area of interest from October 1, 2017 through September 30, 2021. It should be noted that an "Ice Year" traditionally runs from October 1 through September 30 each year. Thus this study includes examination of the 2018, 2019, 2020, and 2021 Ice Years.

The input data sets handled grid cells modeled to have sea ice as "no data" cells. These values were set to 0 instead of "NaN" for the calculations. Similarly, when water temperature values were below 0°C this produced a negative value for deterioration, for the initial "Iceberg Gap" investigation, these values were set to 0 m/day deterioration in order to avoid the highly unrealistic appearance of accumulation due to wave erosion. For the case studies discussed later, **Equation D-1** was modified to remove the ΔT term so that only the wave height and wave period variables were considered.

Helheim Glacier, on the east coast of Greenland, and Jakobshavn Glacier, on the west coast of Greenland, are generally considered to be two of the largest iceberg producers of impact to the present study. An idealized route from each glacier was constructed (**Figure D-3**). The Helheim Route follows the 1,000m bathymetric contour which marks the East Greenland Current around Cape Farewell and the West Greenland Current north to Nuuk, Greenland. There, the route continues along the southern side of Davis Strait until it intersects with the Baffin Island Current and becomes the Labrador Current. The

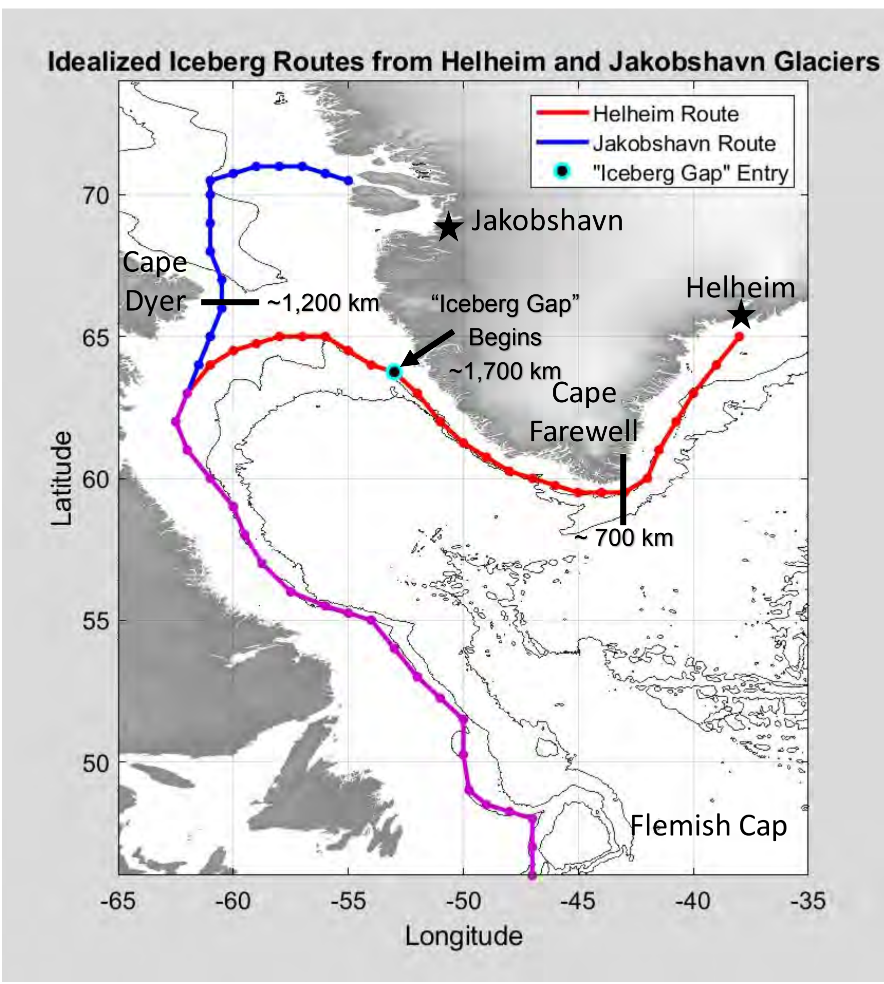


Figure D-3. The idealized iceberg routes created for icebergs coming from Helheim (red) and Jakobshavn (blue) glaciers used for testing the "Iceberg Gap" hypothesis. The two tracks join at 63°N 062°W in the Labrador Current (purple). The routes were created following the 1,000m bathymetric contour. The black/blue point marks the position (63.75°N 053°W) that is considered the beginning of the "Iceberg Gap", approximately 1,700 km along the Helheim Route.

Jakobshavn Route begins at the mouth of Vaigat Strait and flows across Baffin Bay before crossing Davis Strait near Cape Dyer and heading south to join the Labrador Current. There is much variability in the route icebergs take across Baffin Bay. The points picked here expose an iceberg to Baffin Bay's conditions before it is flushed out in the Baffin Island Current. This is an idealized route. In reality, Baffin Bay icebergs are exposed to lighter currents and their routes are much more variable than utilized here. Both routes meet at position 63°N 062°W and follow the Labrador Current toward the Flemish Pass.

To investigate the "Iceberg Gap", icebergs are assumed to be drifting at 1 kt, a reasonable value when compared with satellite and aerial observations as well as the typical current velocities in the Canadian East Coast Ocean Model currents. An idealized "Very Large" iceberg of 200 m waterline length was assumed to be drifting with the currents at a speed of 1 kt (1.852 km/hr) along each idealized route. Four start-times were considered in each year: the first day of January, April, July, and October in 2018, 2019, 2020, and 2021 to approximate icebergs beginning their journey at different seasons of different years. The position of the iceberg along the route on each day was approximated through a simple time, speed, distance calculation and the V_{we} value for that day and location was extracted. For each day of drift, the iceberg's waterline was reduced in accordance with the deterioration rate it was exposed to.

The "Iceberg Gap" was estimated to have begun at the 17th waypoint, approximately 1,700 km, along the Helheim route. At the idealized speed used for this study, that would take approximately 38 days for an iceberg to go along track and reach the "Iceberg Gap."

To spatially and temporally resolve the wave erosion deterioration rate for averaging and looking for anomalies, **Equation D-1** was calculated in each grid cell from 46°N to 76.5°N and 30°W to 70°W with daily values from October 1, 2017 through September 30, 2021.

The known life-history of two individual icebergs were also examined as case studies. The first of these was the 2,500 m long Petermann Ice Island 2017-A. This ice island was tracked by IIP's analysis of satellite imagery from its calving from the Petermann Glacier in July 2017 through its catastrophic deterioration near Sisimiut along the west Greenland coast in March 2020. A detailed treatment of the satellite detection and tracking of this ice island is provided by Rudnickas (2020). For this case study, the iceberg's track was determined daily from satellite imagery analysis. If there was a day's gap in the dataset, the position was linearly interpolated between the two most recent observations. For each day's position, the V_{we} value was extracted.

The second case study utilized an iceberg tagged with a GPS tracker (B1005) from the 2019 Department of Homeland Security Science and Technology Branch funded Iceberg Tagging Campaign. The tagging campaign is described by IIP (2019). The 135 m B1005 was the longest-lived tag of the campaign transmitting from May 1-13, 2019. After the tag stopped transmitting, an IIP HC-130J aerial reconnaissance flight identified the remains of the iceberg on May 14 and confirmed that it had broken in half, estimating the approximate time of calving to be 0700 UTC on May 13, 2019. For this case study, the position of B1005 was received approximately every 30 minutes while the tracker was active. For each known position, the V_{we} was extracted from the daily mean calculation. It was not temporally resolved in greater detail for this study, though future work could look to utilize the three-hour wave information to make a more finely resolved analysis.

D-3. Results and Analysis

D-3-A. The 2020 "Iceberg Gap"

Figure D-4 shows the calculation of the wave erosion deterioration rate along the Helheim Route during 2020. The results show that icebergs leaving Helheim Glacier in 2020 experienced deterioration rates from wave erosion that exceeded 4 m/day (**Figures D-4** and **D-5**). For an iceberg to reach the geographic region of the "Iceberg Gap", it would have to drift approximately 1,700 km, taking 38 days given this study's parameterizations. **Figure D-6** shows that, in 2020, the average, hypothetical 200 m iceberg would have been completely deteriorated by the 33rd day, thus supporting the hypothesis that, in 2020, environmental conditions around southern Greenland deteriorated all but the largest icebergs (more than 215 m) before they could reach the colder, calmer safety of the Davis Strait along western Greenland, leaving the observed "Iceberg Gap."

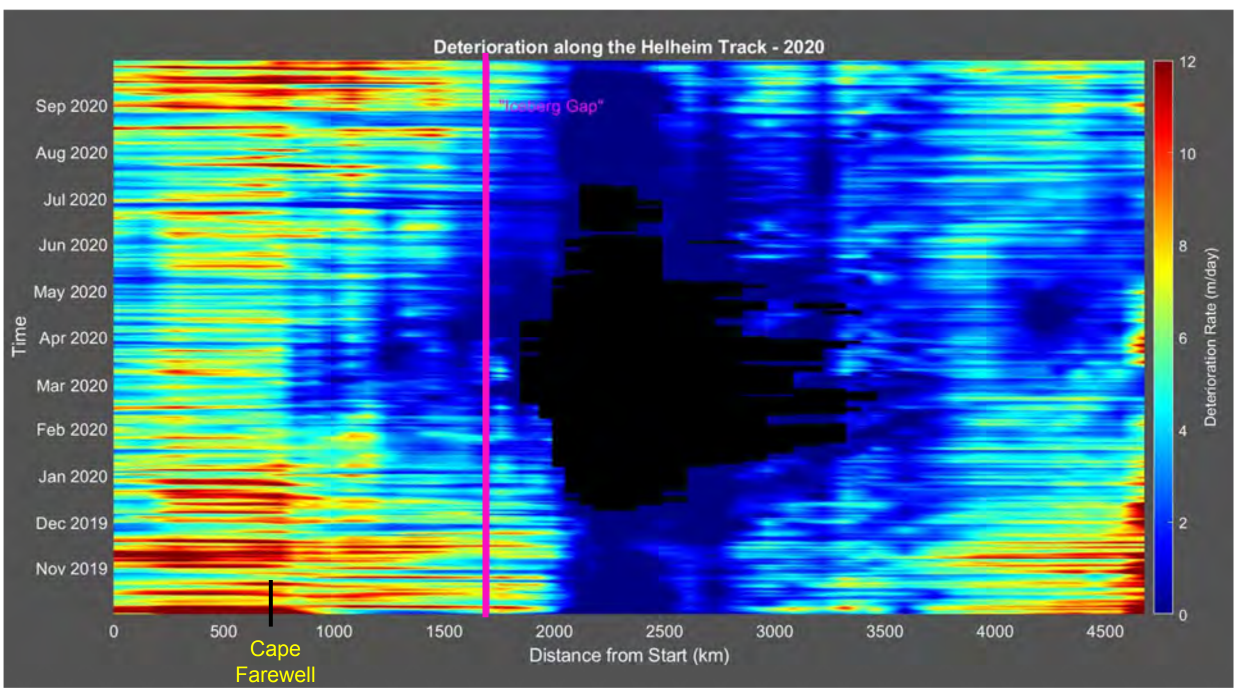


Figure D-4. Wave Erosion Deterioration Rate (m/day) along the Helheim Route during the 2020 Ice Year. The vertical magenta line demarks the entry point to the "Iceberg Gap" and the black bar at approximately 700 km denotes the approximate position of Cape Farewell At any point in the year, icebergs along this route experienced deterioration rates of greater than 4 m/day, though between February and May the extent of these conditions was more constrained to the east coast of Greenland prior to Cape Farewell. The black area in the center denotes areas of sea ice encountered near Davis Strait and the Labrador Coast.

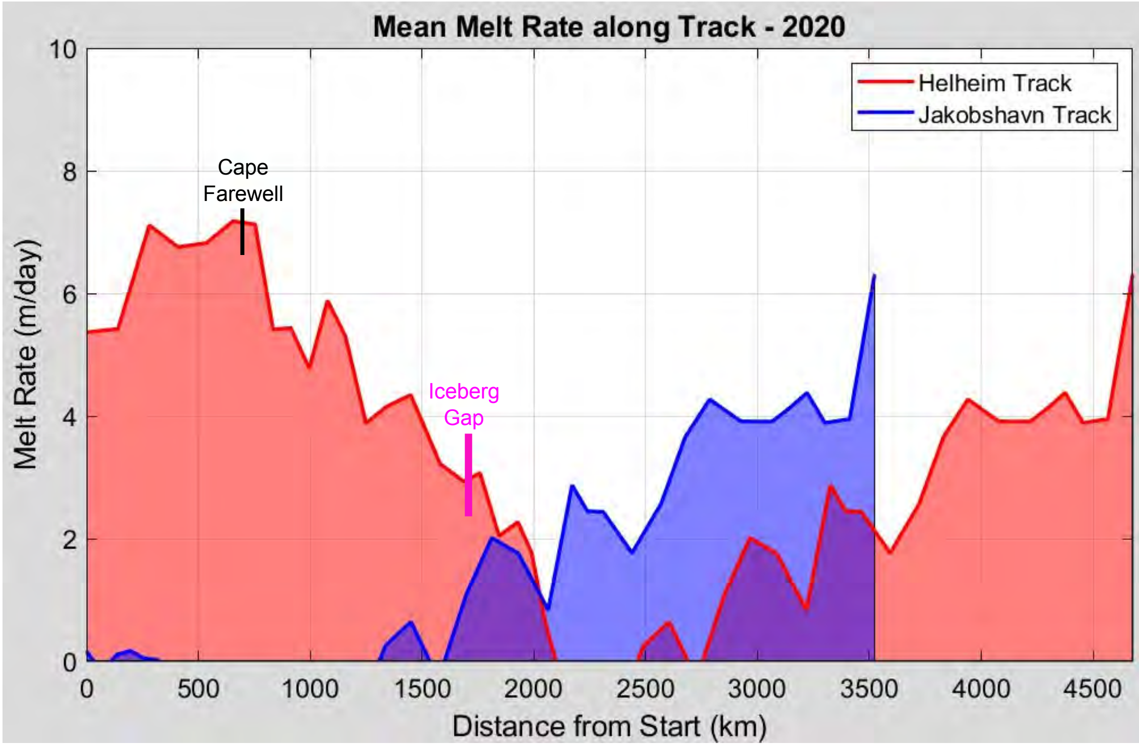


Figure D-5. Mean melt due to wave erosion (m/day) along the Helheim (red) and Jakobshavn (blue) Routes during the 2020 Ice Year. The vertical magenta line demarks the entry point to the "Iceberg Gap" and the black line denotes Cape Farewell. The amount of deterioration an iceberg is subjected to prior to entering the "Iceberg Gap", exceeds that experienced afterwards. Note the minimal melt experienced by an iceberg along the Jakobshavn route prior to joining the Labrador Current, at which point the two melt rates match (after 1,400 km (2,500 km) for the Jakobshavn (Helheim) Route).

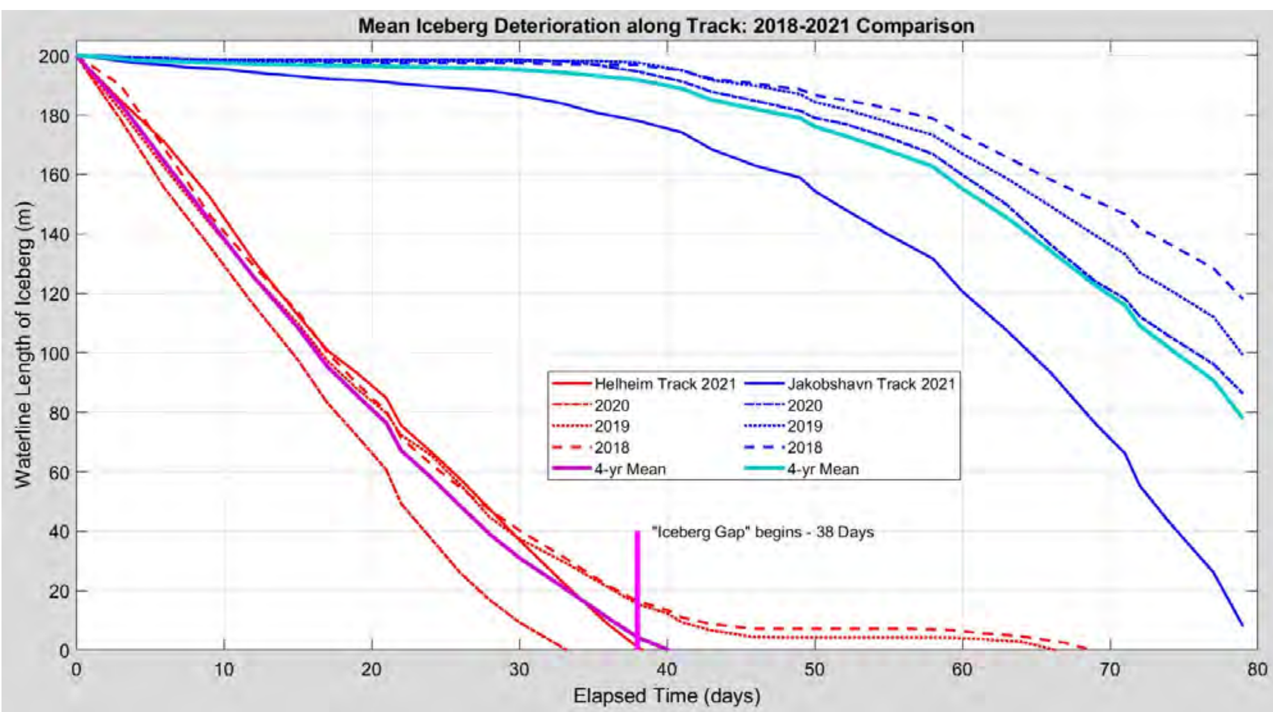


Figure D-6. Mean deterioration of an idealized 200 m iceberg along the Helheim (red) and Jakobshavn (blue) Routes over time during each year and combined for a four-year mean. The vertical magenta line demarks the entry point to the "Iceberg Gap" at 38 days on the Helheim Route. Note that in 2020, the average 200 m iceberg would have been completely deteriorated by day 33. The four-year average iceberg and those in 2019 and 2020 make it into the "Iceberg Gap" but at waterline lengths of less than 15 m (as a bergy bit or growler).

D-3-B. Annual Variation

The difference between iceberg longevity in different ice years is apparent in **Figure D-6.** A review of satellite iceberg reconnaissance from the Danish Meteorological Institute (DMI) during these years confirmed that the "Iceberg Gap" of one size or another persisted. Future work could examine the geographical extent of the Gap. **Figure D-7** shows a comparison of the conditions from 2018 – 2021. The deterioration rate by wave erosion that icebergs on the Helheim Route would have experienced during the first 1,700 km of their journey averaged 5.41 m/day (4.92 in 2018, 4.98 in 2019, 5.63 in 2020, 6.11 in 2021.) **Figure D-7** shows that the majority of the deterioration occurred prior to the Cape Farewell (approximately 700 km along the Helheim Route). Along just the first 700 km of the Helheim track, the four-year average deterioration was 5.50 m/day (4.87 in 2018, 4.74 in 2019, 6.58 in 2020, 5.82 in 2021). Indeed, **Figure D-6** shows that the idealized 200 m iceberg drifting from Helheim during any of these years was likely to be completely deteriorated or reduced to the size of bergy bit or growler (<15 m waterline length) before reaching the "Iceberg Gap" (magenta vertical line). 2018 and 2019 had the smallest average deterioration rate.

Examination of the Jakobshavn Route over the four years (**Figure D-8**) shows that barely any deterioration occurred prior to exiting the Davis Strait (at approximately 1,200 km along track). Considering only the portion of the route (starting at 1,500 km) where

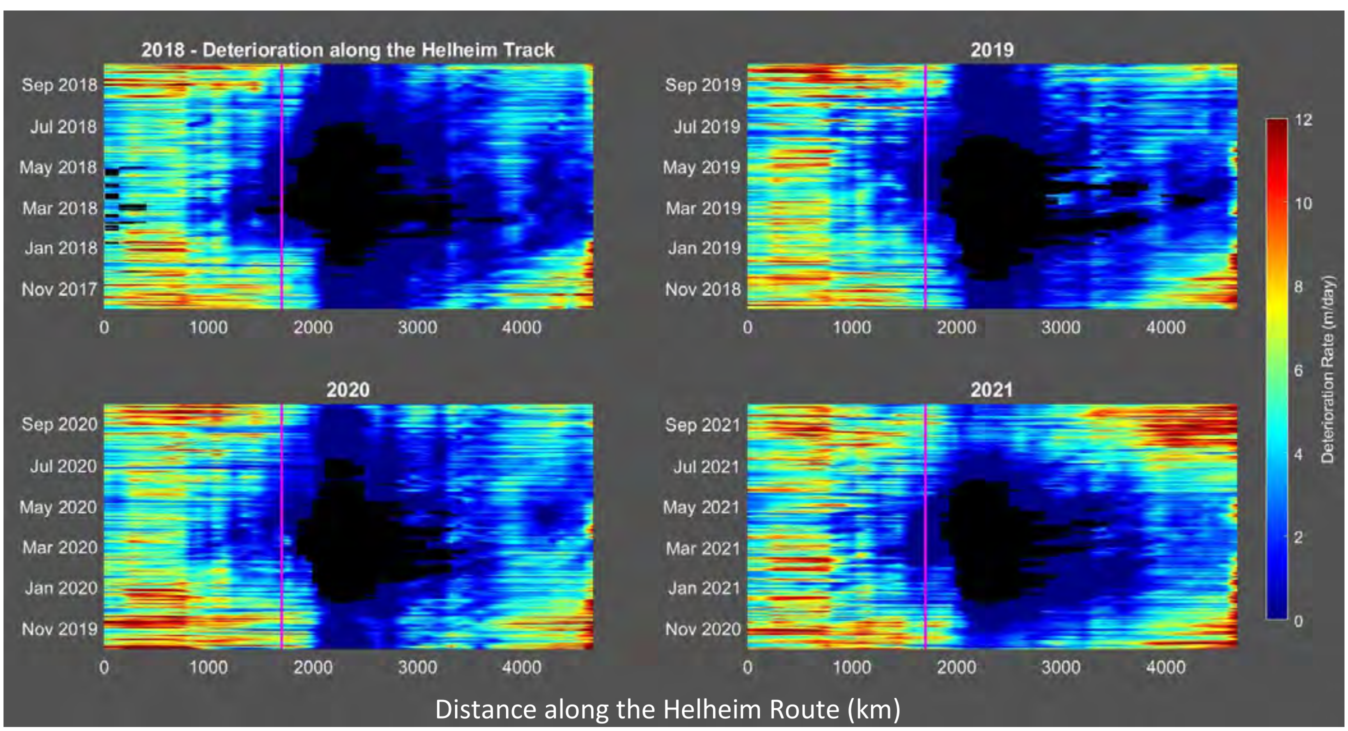


Figure D-7. Wave Erosion Deterioration Rate (m/day) along the Helheim Route during from 2018 - 2021. The vertical magenta line demarks the entry point to the "Iceberg Gap." The prevalence of deterioration rates exceeding 4 m/day early on the route supports the persistence of the "Gap" throughout these four years. The black area in the center denotes areas of sea ice encountered near Davis Strait and the Labrador Coast.

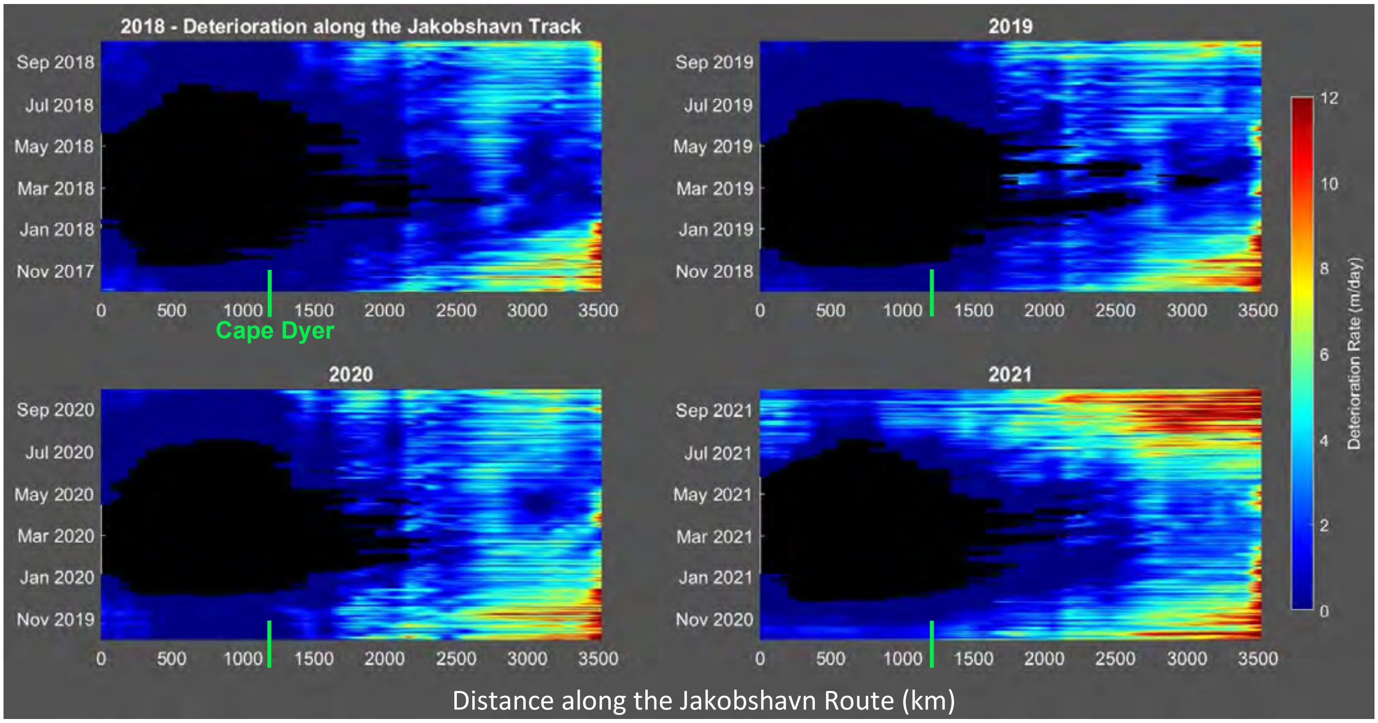


Figure D-8. Wave Erosion Deterioration Rate (m/day) along the Jakobshavn Route during from 2018 - 2021. Note that almost no deterioration occurred during the first 1,200 km (in Baffin Bay), except for during the summer of 2021. The green bar denotes the approximate position of Cape Dyer, the exit from Baffin Bay. The black area in the center denotes areas of sea ice encountered near Davis Strait and the Labrador Coast.

Year	I48N	V_{er} (m/day)
2018	208	0.72
2019	1515	0.99
2020	169	1.35
2021	1	2.23

Table D-1. Comparison of the number of icebergs sighted or modeled to drift south of 48˚N (I48N) and the Wave Erosion Deterioration Rate (V_{er}, m/day) along the Labrador Coast from 2018 – 2021.

both the Helheim and Jakobshavn Routes joined until they end at the Flemish Pass, we see a mean deterioration rate over the four years of 1.33 m/day (0.72 in 2018, 0.99 in 2019, 1.35 in 2020, and 2.23 in 2021). A loose negative correlation (r = -0.45) with the metric that IIP utilizes to quantify Iceberg Season Severity – the count of icebergs sighted or modeled to drift south of 48°N each year (I48N) (208 in 2018, 1,515 in 2019, 169 in 2020, and 1 in 2021; **Table D-1**). If the 2018 year is removed from the correlation calculation, the negative correlation increases to r = -0.78. Rudnickas and Serumgard (2018) provide an in-depth treatment of the challenge of relating season severity to other metrics due to significant changes in reconnaissance capability over the years of IIP's operations. There are many factors: environmental, technological, and human, that impact the I48N number. This work in no way asserts that wave erosion is the sole key to predicting season severity, but future work could continue to investigate a longer-term correlation.

Stepping away from the idealized routes used to examine the "Iceberg Gap" to look at the entire IIP area of interest, this study calculated a yearly mean deterioration rate (**Fig-**

ure D-9) and examined the standard deviation from it (**Figure D-10**). This again highlighted the differences between "Light" Iceberg Seasons like 2021 that showed a higher average deterioration rate and increased deviation from the mean in Baffin Bay and along the Labrador Coast, and an "Extreme" Iceberg Season like 2019 that showed lower deterioration rates in these areas and less deviation.

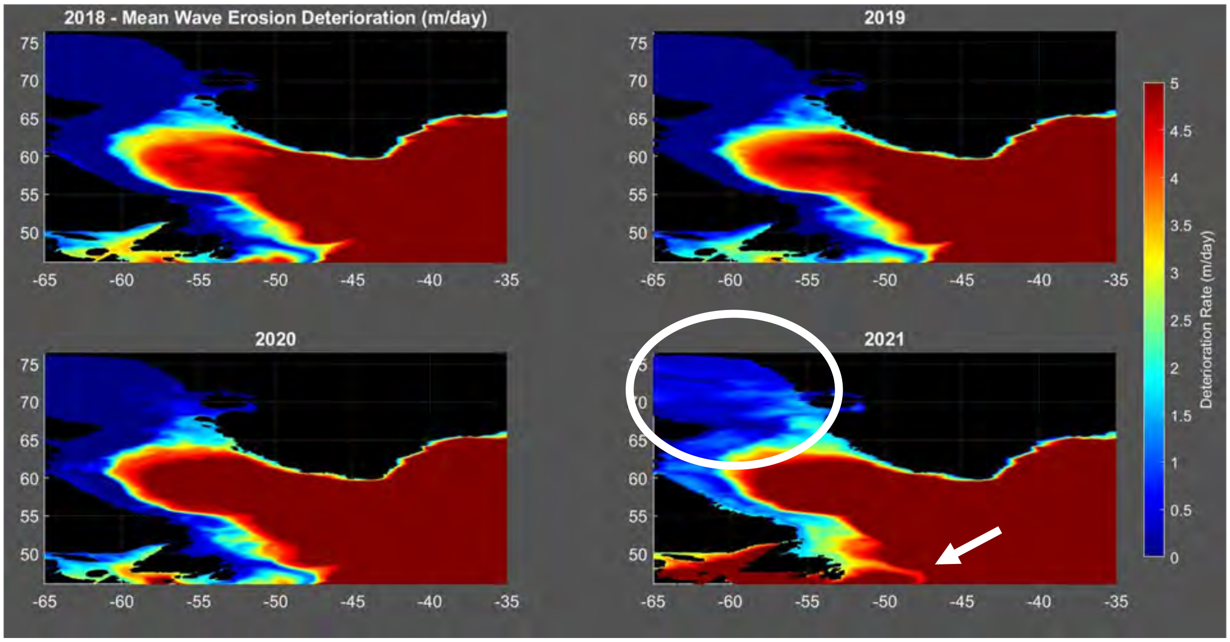


Figure D-9. Yearly Mean Wave Erosion Deterioration Rate (m/day) throughout the International Ice Patrol area of interest. The white circle and arrow highlight noticeably higher deterioration rates in Baffin Bay and in the southern portion of the Labrador Current (respectively) in 2021. Note that the color scale is deliberately set low here in order to best visualize areas of small variation.

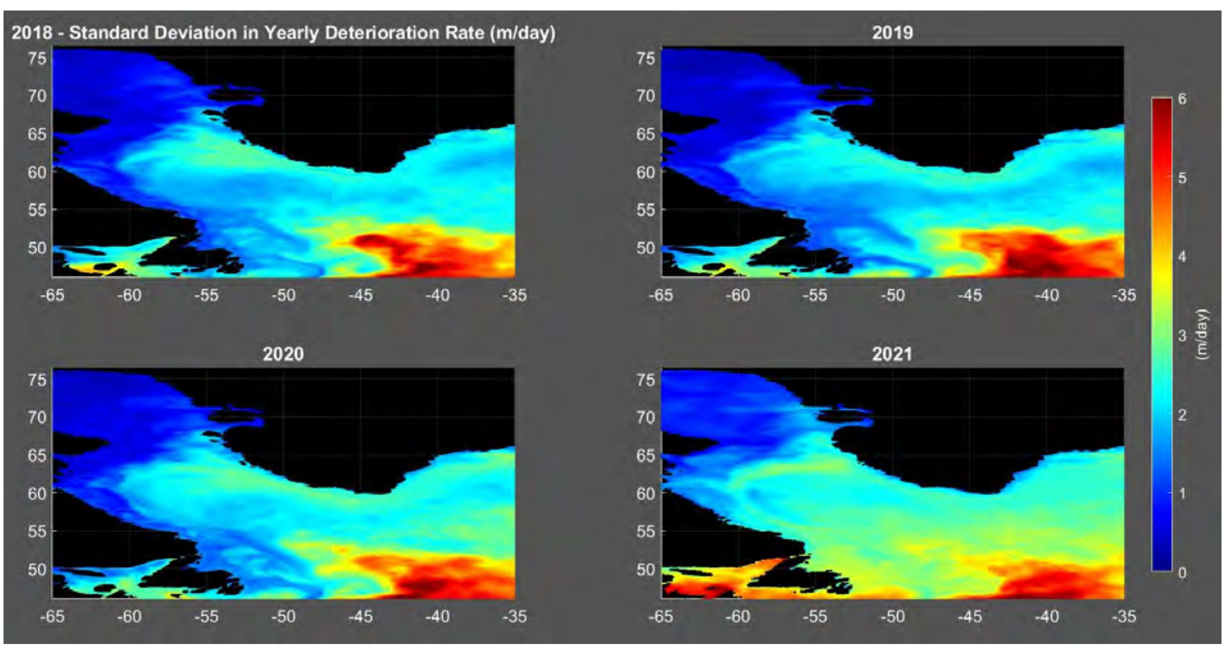


Figure D-10. Standard Deviation in Yearly Mean Wave Erosion Deterioration Rate (m/day) throughout the International Ice Patrol area of interest. Note the higher variation throughout the Labrador Coast in 2021, a light iceberg season (1 iceberg south of 48˚N), compared to 2019, an extreme iceberg season (1,515 icebergs south of 48˚N.)

By calculating a 4-year average deterioration rate for the entire region and the yearly anomaly from it, (as yearly mean – 4-year mean; **Figure D-11**), we see different geographical areas in each season that are anomalous from the mean, highlighting the interannual variability associated with this metric. The overall higher than average deterioration rates during 2021 that saw only one iceberg cross south of 48˚N and especially the higher deterioration rates in Baffin Bay, are of special note. **Figure D-12** shows the time series of all the variables considered in the wave erosion deterioration rate for a point in central Baffin Bay (72˚N 063˚W). When comparing conditions in this position to the severity of the Iceberg Season, it is important to consider the time lag between an iceberg being in Baffin Bay and making its transit down the Labrador Coast toward 48˚N. In the summer leading up to the "Extreme" (1,515 icebergs south of 48˚N) 2019 season (July to September 2018), we see wave heights in Baffin Bay that do not exceed 2 m and ocean temperatures that barely come above 0˚C. In contrast, the summer before the "Light" (1 iceberg) 2021 season (July to September 2020), we see slightly higher waves and markedly warmer ocean temperatures (peaking near 2˚C). The summer before the "Light" (169 icebergs) 2020 season (July to September 2019), was characterized by colder ocean temperatures but more variable wave heights (reaching 3 m).

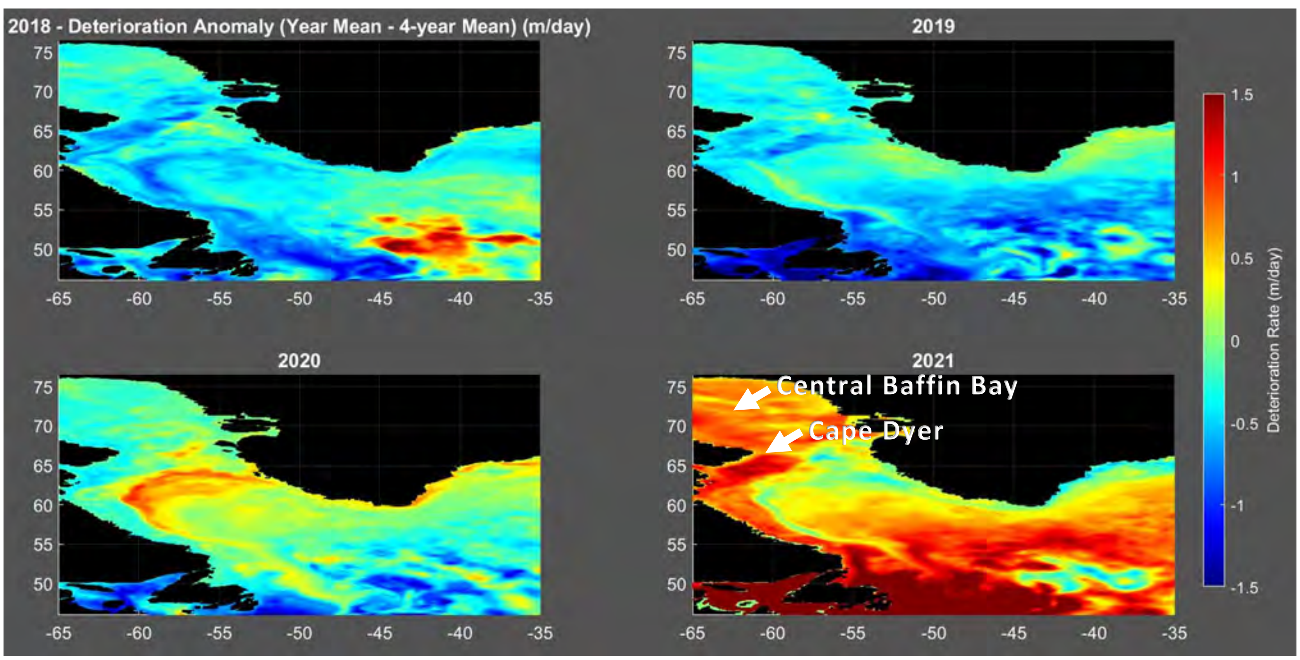


Figure D-11. Wave Erosion Deterioration Rate Anomaly from 2018 – 2021 (taken as the yearly mean – 4-year mean). Note the variation between years, but the overall higher than average deterioration rates during 2021 (a Light Iceberg Season) and lower than average deterioration rates in 2019 (an Extreme Iceberg Season.)

To further expose the reasons for the interannual variability, a similar analysis was conducted of the Cape Dyer region (66.5°N 060.5°W). This is the point at which icebergs are ejected from Baffin Bay to drift south toward the Labrador Coast and Newfoundland. As such, deterioration of icebergs here likely plays a direct role in the number that could reach the transatlantic shipping routes each year. **Figure D-13** and **Table D-2** show that

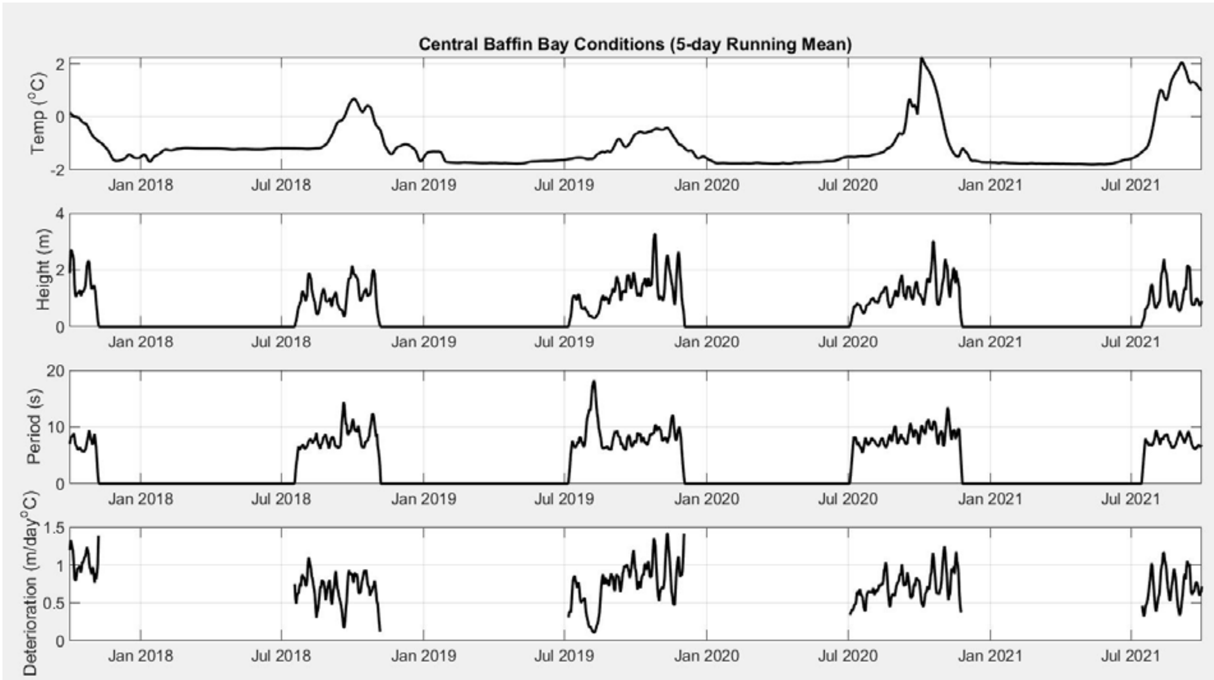


Figure D-12. Time series of conditions in central Baffin Bay (72˚N 063˚W) during the study time period. All data shown as a 5-day running mean. Note the large spikes in temperature at the beginning and end of the 2021 Ice Year. Because of the typically negative ocean temperatures in this area, the deterioration rate here is decoupled from the ocean temperature by calculating it without the ΔT term in Equation D-1, so that the units are actually m/day per ˚C.

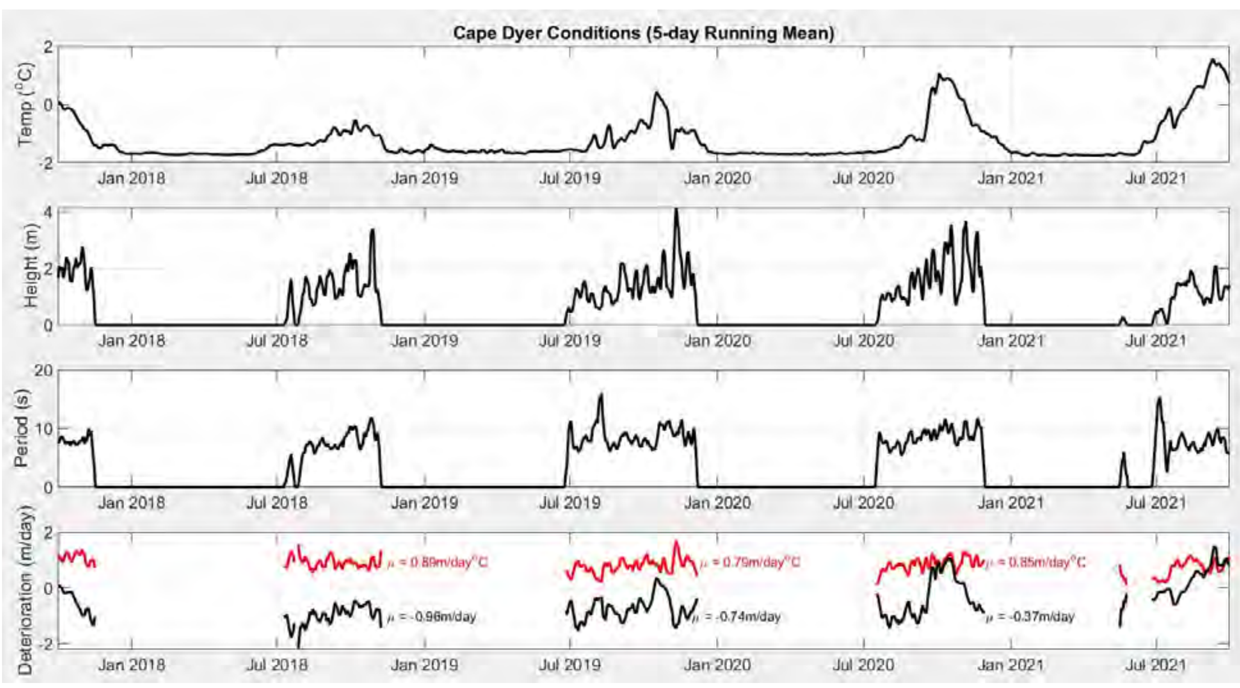


Figure D-13. Time series of conditions near Cape Dyer (66.5˚N 060.5˚W) during the study time period. All data shown as a 5-day running mean. The bottom plot shows both the deterioration rate when considering the ocean temperature (black line) as well as the deterioration rate per ˚C (red line), decoupled from the ocean temperature because of negative ocean temperatures making the value negative.

Conditions at Cape Dyer (66.5°N 60.5°W) By Calendar Year													
Calendar Year	μ_{Ver} (m/day°C)	σ_{Ver}	μ_{Ver} (m/day)	σ_{Ver}	μ_T (°C)	σ_T	μ_H (m)	σ_H	μ_τ (s)	σ_τ	Days with Temp >0°C	Beginning Date of Temps >0°C	Max Temp
2018	0.89	0.32	-0.96	0.42	-1.47	0.31	0.44	0.84	2.27	3.78	0	N/A	-0.55°C on 06-Oct-18
2019	0.79	0.36	-0.74	0.50	-1.32	0.47	0.63	0.92	3.85	4.68	13	13-Oct-19	0.39°C on 16-Oct-19
2020	0.85	0.36	-0.37	0.81	-1.24	0.77	0.61	1.05	3.14	4.37	45	20-Sep-20	1.08°C on 03-Oct-20
2021*	0.72	0.35	0.26	0.62	-1.00	1.05	0.38	0.62	2.86	4.22	53+	8-Aug-21	1.53°C on 09-Sep-21

Table D-2. Statistical values taken from the time series of wave erosion deterioration rate and all input variables for Equation D-1 at Cape Dyer (66.5°N 60.5°W). Here, values are calculated for the calendar year (01 Jan – 31 Dec) instead of the Ice Year in order to examine the seasonal trends observed in Figure D-13. Values associated with the μ are the mean and the σ immediately to the right is the standard deviation associated with that mean. * Note: for 2021, only values up to 30-Sep-2021 were utilized. The first column includes wave erosion deterioration rates per °C, decoupled from the ocean temperature, while the third column is that value multiplied by the ocean temperature value as in Equation D-1. This was done in order to first, examine the terms in the equation just associated with wave height and period in order to gauge the relative importance of waves vs. temperature, and second, to avoid negative numbers in the result that could give the impression of accumulation of ice on icebergs, and unrealistic condition. Note that the mean and standard deviation of the deterioration rate apart from the ocean temperature (first two columns) remain relatively consistent throughout the study period, while the mean and standard deviation of the ocean temperature increase.

between 2018 and 2021, the wave erosion deterioration rate remained fairly consistent when decoupled from the ocean temperature. When ocean temperature was considered, the annual variation and ice season variability become more apparent.

Table D-2 and **Figure D-13** show that the yearly average ocean temperatures (15 m depth) at Cape Dyer increased by 0.47°C from 2018 to 2021. The maximum temperature increased by nearly 2°C over the four years: from -0.55°C in 2018 to 1.53°C in 2021. Further, the number of days with temperatures greater than 0°C increased from 0 in 2018 to more than 53 (as of September 30, 2021 the ocean temperature was still above 0°C). The onset of ocean temperatures greater than 0°C got earlier as well, from October 13 in 2019, September 20 in 2020, to August 8 in 2021.

Increasing ocean temperatures will certainly melt icebergs more quickly regardless of the impact of wave action that leads to erosion and the yearly means do not clearly expose a trend in the wave heights or periods that can easily explain variations in iceberg season severity. Again, the importance of timing comes into focus.

Though a small time-series, cross-correlations between the I48N dataset and the input variables at the Cape Dyer location were analyzed. A moderately strong correlation was observed when comparing the I48N count to some variables directly year to year (highest was a positive correlation to wave period with $r = 0.80$ ($p = 0.20$), wave height was second with $r = 0.67$ ($p = 0.33$)), but when a one-year lag was applied such that the mean conditions in **Table D-2** were correlated with the I48N count of the following iceberg year, a stronger correlation is revealed. The strongest correlation was between the I48N count and the wave height ($r = -0.98$; $p = 0.13$). Ocean temperature was the second highest and only slightly lower ($r = -0.97$; $p = 0.16$). The wave erosion deterioration rate, itself was less strongly correlated ($r = -0.84$; $p = 0.36$).

D-3-C. Case Studies

While the previous section showed the importance of trends in ocean temperature in examining seasonal variation, two case studies highlight the importance of high wave events in iceberg deterioration.

Using satellite imagery, IIP tracked Petermann Ice Island 2017-A (PII2017A) from when it calved from the Petermann Glacier in July 2017 through its catastrophic destruction after grounding along the coast of Greenland near Sisimiut at the end of March 2020. A full record of the ice islands track is detailed by Rudnickas (2020). Two calving events are examined here. **Figure D-14** shows satellite images of August 13, 2019 (before) and August 31, 2019 (after) when the island lost 2.2 km^2 of area. PII2017A had been aground and in sea ice along the southeastern coast of Ellesmere Island for much of the preceding two years, and this calving event around August 31, 2019 appears to have shed enough mass that the island began drifting again. **Figure D-15** shows the second calving event that occurred on the morning of October 25, 2019, and resulted in a 1.4 km^2 reduction in area. **Figure D-16** shows the conditions along the PII2017A track surrounding the two calving events. The August event does not show a clear signal in either of the variables as the island was surrounded by sea ice and there were no modeled wave heights or periods available, however, **Figure D-12** shows a corresponding increase in wave action in the center of Baffin Bay during that timeframe, and shortly after the calving event, once the data became available closer to PII2017A, we see potential evidence of the wave heights came

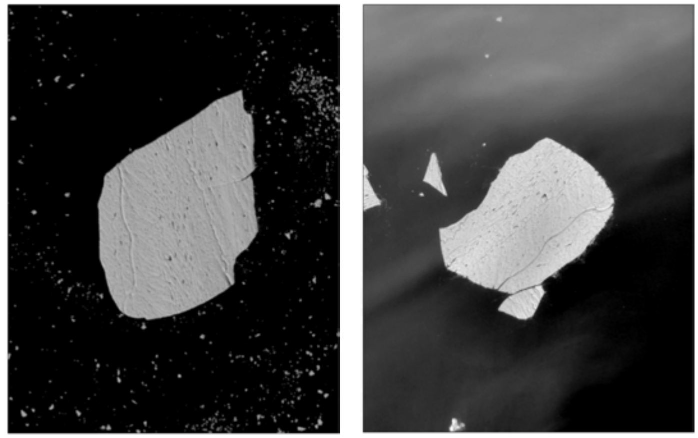


Figure D-14. Petermann Ice Island 2017-A before (left) and after (right) a 2.2 km^2 calving event. Landsat-8 imagery courtesy of the US Geological Survey. Sentinel-2 imagery from Copernicus Marine Services, 2020.

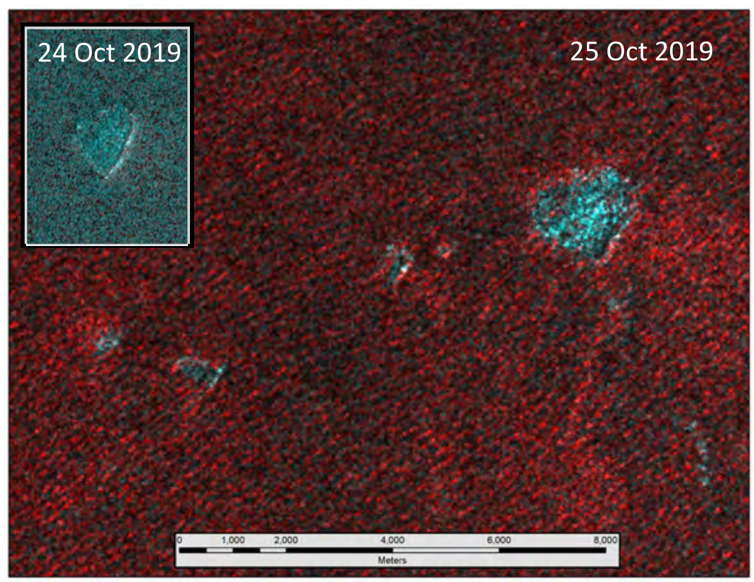


Figure D-15. Petermann Ice Island 2017-A on 25 October 2019 after a 1.4 km^2 calving event. The inset shows the ice island on 24 October, before the event. Both images from Sentinel-1 Extra Wide Swath synthetic aperture radar, shown with HH-HV-HV in R-G-B. Imagery from Copernicus Marine Services, 2020.

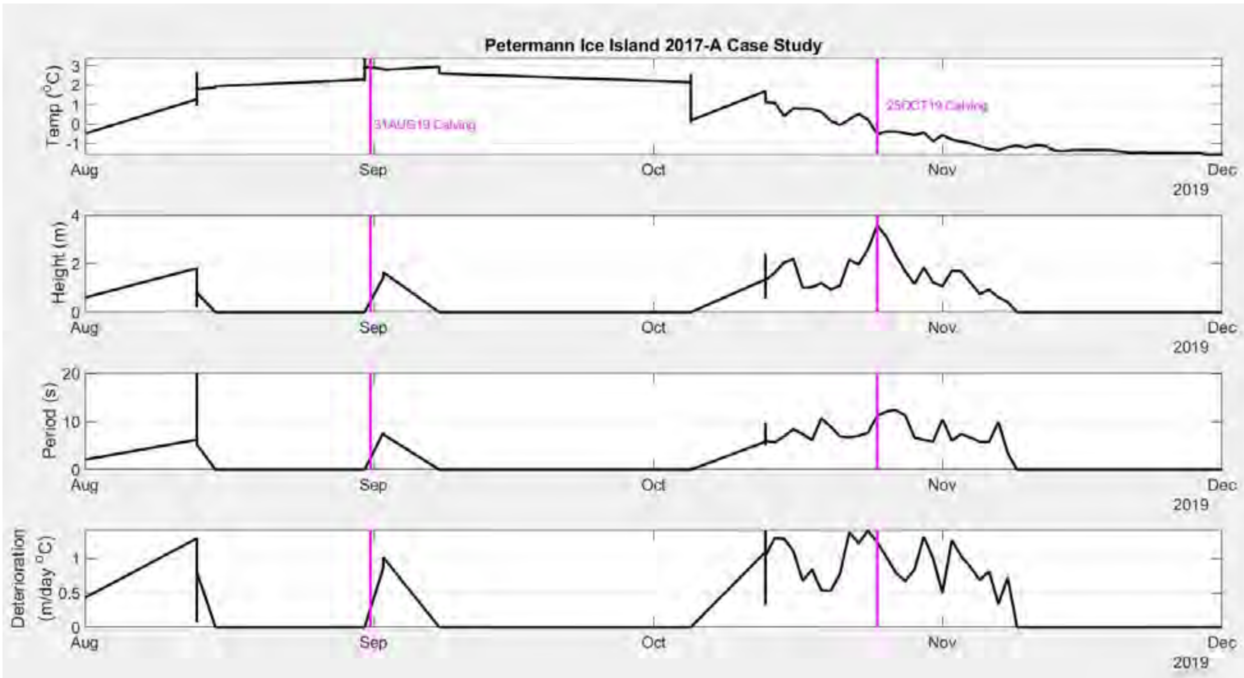


Figure D-16. Time series of conditions along the Petermann Ice Island 2017-A track line from 01 August to 01 December 2019. Ocean temperature, wave heights, wave periods, and the wave erosion deterioration are shown from top to bottom. The pink lines mark the 31 August calving event (left) and 25 October calving event (right). Note that the last half of August had the iceberg surrounded by sea ice, so the wave heights and periods, and thus the deterioration rate went to 0. Due to the amount of time in which the temperature was below 0°C, the deterioration rate is decoupled from the ocean temperature and is shown as m/day per °C. Note the peak in wave heights at the same time as the 25 October calving event.

down from a peak in mid-August. The October calving event, however, is clearly coincident with a major spike in wave erosion deterioration rate driven by wave heights exceeding 2 m for the only time during the observed timeframe shown here.

The second case study of B1005 was from May 2019. A GPS transmitter was placed onto B1005 on May 1 and it provided positions approximately every 30 minutes until 0700 UTC on May 13, 2019. An IIP aerial reconnaissance flight located the remnants of the iceberg the following day, confirming that it had split in half. **Figure D-17** shows pictures of the iceberg before and after the May 13 calving, and **Figure D-18** shows the conditions along the GPS track of the iceberg. The ocean temperature steadily increased as B1005 drifted south which is reflected in the deterioration rate steadily increasing over time, but there was a notable increase in wave heights of nearly 2 m on the afternoon of May 12 that preceded the calving event.

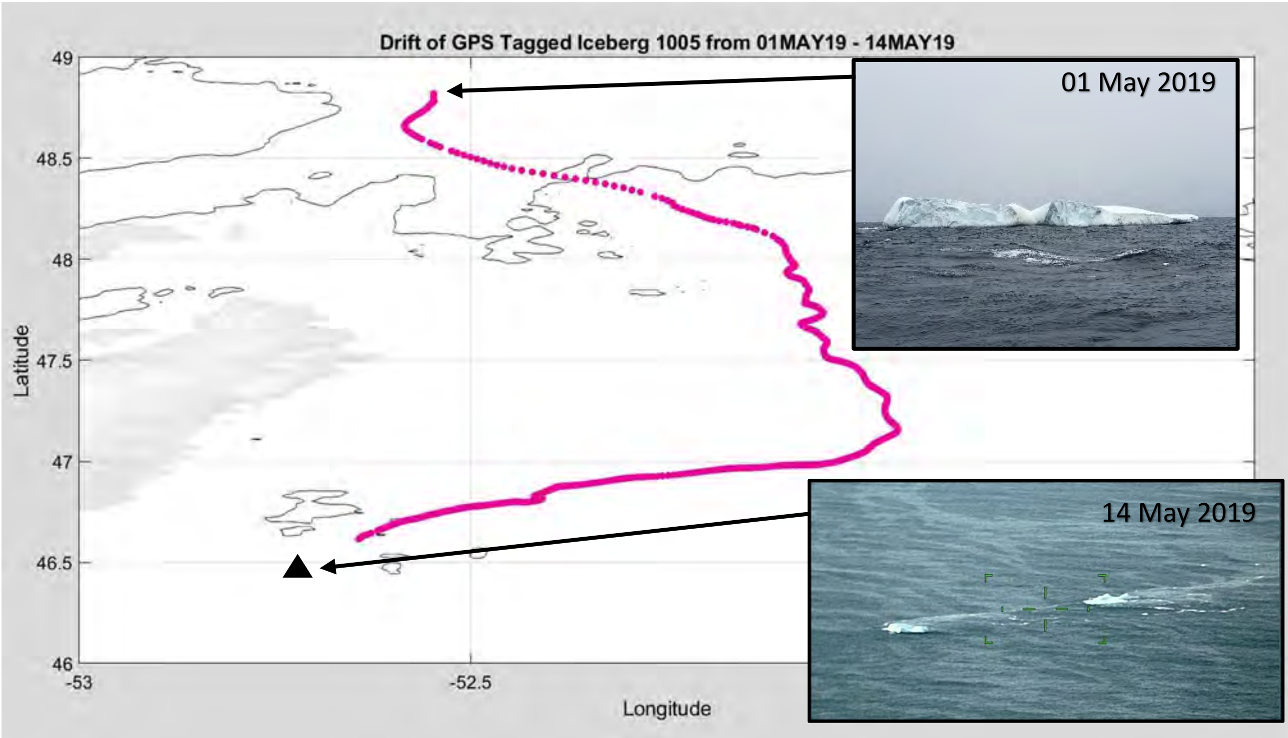


Figure D-17. Drift track of GPS tagged Iceberg 1005 from 01-14 May 2019 near the Avalon Peninsula of Newfoundland. The top inset is a picture taken by the author of Iceberg 1005 just prior to deploying the GPS tag on 01 May. The pink line is made up of every GPS position received from the tag, ending at 0700 UTC on 13 May. The bottom inset is a picture taken by the author during an HC-130J ice reconnaissance flight on 14 May in the position marked by the black triangle.

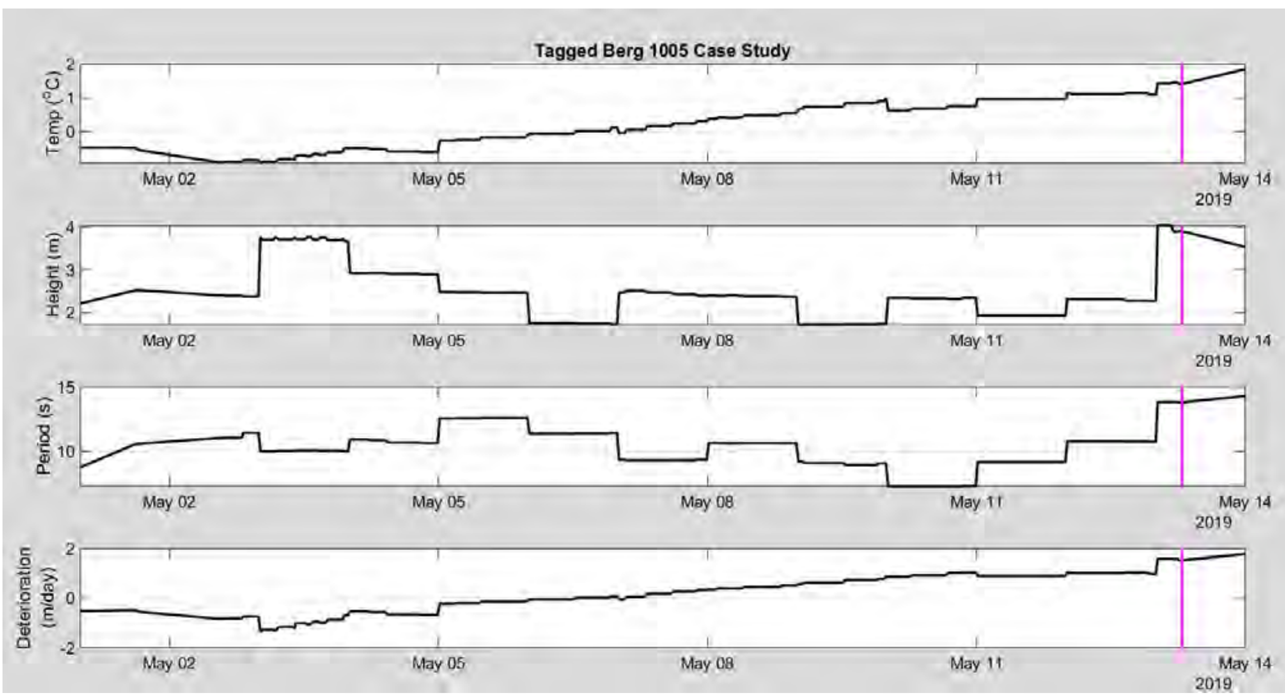


Figure D-18. Time series of conditions along the Tagged Iceberg 1005 drift route from 01-14 May 2019. Ocean temperature, wave heights, wave periods, and the wave erosion deterioration are shown from top to bottom. The pink line marks the time of last GPS transmission on 13 May, most likely associated with the calving event. Note the peak in wave heights and periods that drove the increased deterioration rate just prior to the last transmission.

D-4. Conclusion

Using hypothetical icebergs drifting along idealized routes that follow the major ocean currents, this study showed increased deterioration rates along the southern coast of Greenland, especially prior to reaching Cape Farewell. Due to the effects of waves and ocean temperature, icebergs coming from Greenland's east coast glaciers experience significant deterioration as they drift in the major currents such that all but the biggest icebergs are likely to have been completely deteriorated before they can reach the latitude of Nuuk, Greenland on the west coast. This increased deterioration can explain the occurrence of an "Iceberg Gap" on the eastern side of the Davis Strait.

Ocean temperature appears to be the main factor in the interannual variability of the spatially resolved wave erosion deterioration rate. Geographic regions that noticeably differ from the average (i.e. Central Baffin Bay) were seen to have warmer temperatures. Temperatures in Baffin Bay and Cape Dyer were shown to have increased and stayed warmer longer from 2018 to 2021.

The results showed a strong negative correlation (over a very short, four-year time-series) between the average wave heights in the Cape Dyer region and the number of icebergs to pass south of 48°N the following year. The ocean temperature at Cape Dyer was also strongly negatively correlated with the following year's count. Future work should extend this time-series to test the correlation over more of the I48N dataset.

Trivers (1994) and Marko et al. (1994) showed a strong correlation between sea ice concentration and the I48N count. It should be no surprise that warmer temperatures and higher waves will also deteriorate or prevent the growth of sea ice. Though this study examined the correlation in terms of iceberg wave erosion, the correlation could just as easily be related to the amount of sea ice in a season. This dynamic has a component of feedback as well. Colder temperatures lead to more sea ice that dampens wave action. But, if the waves are already high outside of the sea ice edge, they will deteriorate the sea ice from the outside in. Less sea ice allows for waves to grow, and higher waves reduces the amount of sea ice. The Ice and Environmental Conditions Section (**Section 1**) of this Annual Report showed that the last four years have seen decreasing sea ice in the region. In some ways, we find ourselves in a "chicken vs. the egg" scenario. Did reduced sea ice allow for higher waves or did higher waves reduce sea ice? This author posits that it is likely that the trend of higher ocean temperatures reported in this Appendix resulted in lower sea ice extents that allowed for higher waves that, in turn, cause increased iceberg deterioration by wave erosion.

It is important to consider the cumulative effects of deterioration over time. While this study began with examining the creation of the "Iceberg Gap" by deploying hypothetical icebergs that drifted straight from the glacier toward the Flemish Pass, the reality is that icebergs are subject to the dynamics of nature and do not necessarily take the most direct route. Some may spend years in Baffin Bay before finally being ejected into the Labrador Current. All the while, they are being deteriorated. Surviving one season's deterioration leaves the icebergs smaller for the next season. Many high-deterioration seasons in a row, as has been observed since the summer of 2019, could then result in very few icebergs capable of making it to the transatlantic shipping lanes.

It is also important to consider long time scales (erosion) vs. short time scales (calving). The theory behind the wave erosion deterioration rate calculated here is that wave action erodes the waterline of the iceberg, promoting calving and rolling over time, a long time scale. While the case studies examined here showed signals of wave height induced calving, what could be called catastrophic deterioration at a short time scale, it is impossible to discern from the observations how significantly the calving events were impacted by long time scale erosion. This is an area of study that future work could address to better understand the physics and dynamics associated with iceberg deterioration.

What began as a thought experiment to examine the "Iceberg Gap," has turned into a serious investigation of iceberg season severity with a foundation rooted in observations. This work is far from over. Specifically, a historical record of the conditions at Cape Dyer should be correlated with the I48N dataset and, if the correlation remains strong, the conditions should be monitored by IIP throughout each summer. The size of icebergs in southern Baffin Bay compared to the environmental conditions there could provide solid clues as to the operational requirements and tempo of the coming Ice Year.

D-5. References

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Landsat-8 imagery courtesy of the U.S. Geological Survey.

2019 Sentinel-1 and Sentinel-2 imagery downloaded from Copernicus Sentinel data.

Appendix E. Automated Iceberg Detection in Sentinel-2 Imagery by Spectral Reflectance Thresholding

LCDR Don Rudnickas

E-1. Introduction

On March 7, 2020, the International Ice Patrol (IIP) used Sentinel-2 (SN2) multispectral imagery to create a standard iceberg message for the first time (i.e. **Figure E-1**). Thereafter, under cloud-free conditions, SN2 imagery quickly became the favorite of IIP's satellite analysts because optical imagery makes sense to the human eye, reducing the challenge of classifying targets detected in Synthetic Aperture Radar (SAR) imagery. However, with relatively small scene sizes and without an established automated detection process, compared to IIP's SAR imagery analysis, the entirely manual process of SN2 analysis was time consuming and tedious. To make the best use of analyst time, increase the number of frames processed daily, and standardize analysis among watchstanders, IIP developed an Iceberg Detection Script (IDS) to automate target detection. The IDS compares the pixel-by-pixel spectral reflectance to a series of thresholds identified with the known spectral reflectance of icebergs. This Appendix details the determination and utilization of the spectral reflectance thresholds and provides an accuracy assessment of the IDS using ground truth data collected during a 2021 iceberg tagging campaign in Disko Bay. This campaign was conducted under the International Cooperative Engagement Program for Polar Research (ICE-PPR).

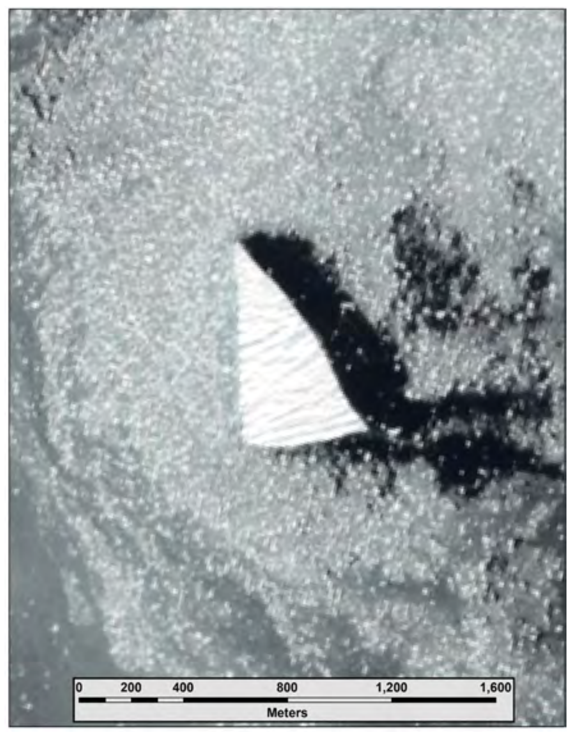

Figure E-1. The first sighting of "Pizza Berg", Ice Island Fragment 2020-001, from Sentinel-2 True Color Imagery on March 7, 2020 in position 56.81˚N 059.93˚W along the Labrador coast. Sighting this ice island fragment occurred during the first operational use of Sentinel-2 imagery and paved the way for development of the Sentinel-2 Iceberg Detection Script. Copernicus Sentinel data 2020.

E-2. Spectral Reflectance Curve Determination

The basis for the IDS is the spectral reflectance curves (**Figure E-2)** extracted from SN2 Level 2A imagery. These were created by identifying 20-30 pixels associated with each of 10 classes: Iceberg, the Underwater Portion of an Iceberg, Thin Cloud, Thick Cloud, Land, Ocean, Sea Ice, New Ice, Snowy Land, and Iceberg Through Thin Cloud. Once identified, the Bottom Of Atmosphere (BOA) reflectance was extracted from the raster datasets at each of the 13 SN2 spectral bands (including Band 8A). The mean and standard deviation of each sample data set was then calculated (**Table E-1**). Analysis of the curves focused on bands and values that could distinguish icebergs from the other classes.

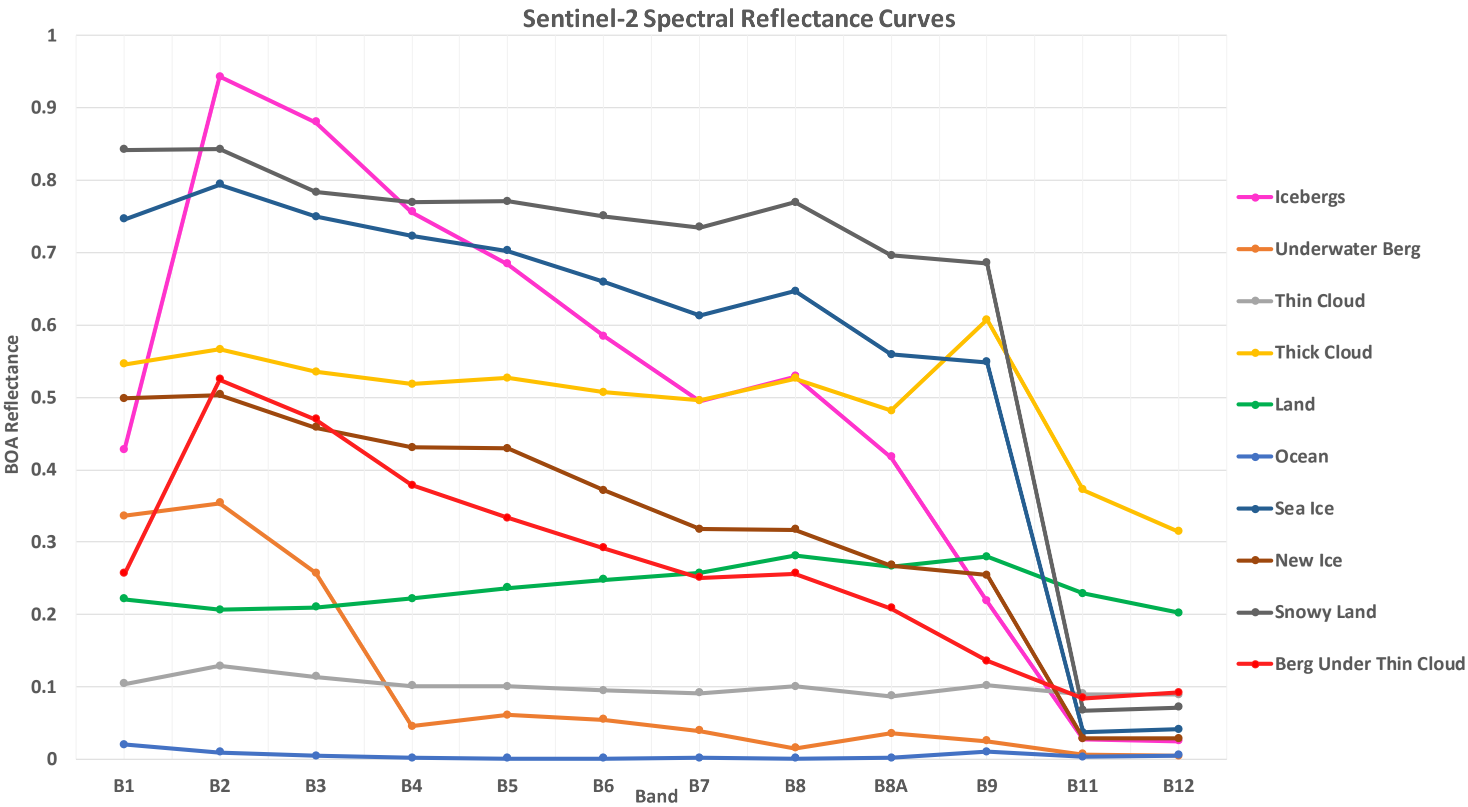

Figure E-2. Mean spectral reflectance (bottom of the atmosphere) curves created from Sentinel-2 multispectral imagery. For the Sentinel-2 Iceberg Detection Script, each pixel in an image was compared spectrally to thresholds derived from this curve. The basic procedure followed was to find threshold values at different bands that help to segregate iceberg pixels (pink line) from all of the others. Band 2 (Visible Blue), Band 5 (Near Infrared), Band 8 (Near Infrared), and Band 11 (Shortwave Infrared) as well as the difference between Band 8 and Band 2 and Band 5 and Band 2 are currently used.

Class	B1	B2	B3	B4	B5	B6	B7	B8	B8A	B9	B11	B12	B8 - B2	B5 - B2
Iceberg	0.4281	0.9429	0.8799	0.7557	0.6844	0.5845	0.4950	0.5290	0.4173	0.2187	0.0281	0.0250	-0.4139	-0.2586
Underwater Berg	0.3363	0.3539	0.2576	0.0459	0.0614	0.0546	0.0391	0.0152	0.0360	0.0254	0.0070	0.0048	-0.3387	-0.2925
Thin Cloud	0.1045	0.1290	0.1143	0.1014	0.1010	0.0948	0.0919	0.1006	0.0877	0.1021	0.0899	0.0892	-0.0284	-0.0280
Thick Cloud	0.5460	0.5663	0.5354	0.5185	0.5266	0.5068	0.4955	0.5263	0.4813	0.6076	0.3722	0.3143	-0.0399	-0.0397
Land	0.2214	0.2062	0.2100	0.2223	0.2367	0.2484	0.2575	0.2810	0.2663	0.2797	0.2294	0.2024	0.0748	0.0305
Ocean	0.0202	0.0099	0.0050	0.0016	0.0016	0.0014	0.0020	0.0015	0.0020	0.0106	0.0037	0.0052	-0.0084	-0.0083
Sea Ice	0.7460	0.7941	0.7497	0.7227	0.7024	0.6595	0.6132	0.6467	0.5589	0.5488	0.0374	0.0415	-0.1474	-0.0916
New Ice	0.4989	0.5034	0.4585	0.4309	0.4293	0.3719	0.3181	0.3169	0.2678	0.2544	0.0288	0.0291	-0.1864	-0.0741
Snowy Land	0.8420	0.8427	0.7835	0.7695	0.7712	0.7505	0.7351	0.7695	0.6960	0.6852	0.0677	0.0716	-0.0732	-0.0715
Berg Under Thin Cl	0.2565	0.5246	0.4700	0.3789	0.3336	0.2916	0.2510	0.2565	0.2089	0.1358	0.0846	0.0922	-0.2682	-0.1911

Table E-1. Values used to make the spectral reflectance (bottom of the atmosphere) curves shown in Figure E-2. These are the mean values of the datasets for each target class. The columns highlighted in blue are the primary ones utilized for the spectral thresholding.

The most challenging of the distinctions between classes is identifying icebergs from cloud and from sea ice. In visible imagery, all three of these classes look white, so wavelengths beyond the visual spectrum were utilized. Specifically, near infrared (Bands 5 ($B5$, 704 nm) and 8 ($B8$, 833 nm)) and short-wave infrared (Band 11 ($B11$), 1610-1614 nm).

The SN2 IDS was primarily based upon the distinction between icebergs and the other classes in Bands 2 ($B2$, visible blue, 492 nm), $B5$, $B8$, and $B11$. The difference between bands was also extremely useful. The script utilized $\Delta B8 = B8 - B2$ and $\Delta B5 = B5 - B2$, capitalizing on the slope of the Iceberg spectral signature observed in **Figure E-2**.

Several different threshold schemes were tested. The one that proved the most accurate (qualitatively) was based on identifying Iceberg pixels with the following spectral reflectance thresholds:

$$B2 > 0.3$$
$$B11 < 0.1$$
$$\Delta B8 < -0.1$$

This regime is termed "Normal" processing and is designed to capture both the Iceberg and the Berg Under Thin Cloud classes while excluding the Thin Cloud and Thick Cloud classes in **Figure E-2**. This relied on the slope of the line from visible to infrared wavelengths, the brightness in the visible bands, and the minimal shortwave infrared signature of ice compared to cloud.

Icebergs in sea ice pose an additional challenge and a different set of thresholds were selected. For imagery with sea ice, the spectral reflectance thresholds were:

$$B2 > 0.8$$
$$\Delta B5 < -0.1$$
$$\Delta B8 < -0.125$$

This regime is termed "Sea Ice" processing and relies mainly on the steeper slope of spectral reflectance of an iceberg between the infrared bands and the visible as well as the brighter white typically seen with an iceberg.

E-3. Iceberg Detection Script

The SN2 IDS was created within the Python 2.7 coding environment to interface with ArcGIS in order to process SN2 imagery. It first asks the analyst for inputs such as date, time, and source of the imagery. Then it asks whether the analyst would like to utilize the "Normal" or "Sea Ice" spectral threshold regime. Once processing begins, the script:

1. Locates the file pathways for each raster dataset of the required SN2 bands.
2. Resamples all rasters to be used in the calculations to 10m resolution "analysis rasters".
3. Identifies pixels above or below the designated thresholds in the "analysis rasters". Pixels meeting the threshold in each "analysis raster" are assigned a value of "1"; pixels not meeting the threshold are assigned a value of "0".

4. Conducts raster math to generate a sum of the “analysis rasters”. Pixels that meet all conditions will have the maximum value and are extracted as the “result raster”.
5. Converts the “result raster” to polygons in order to group adjacent pixels together as one target.
6. Converts the polygons to points centered inside the polygon.
7. Extracts the latitude and longitude of each point and prepares the point dataset for analysis by adding all required fields for the analyst.
8. Creates a True Color composite image in .tif format to assist with accurate classification using $B4$-$B3$-$B2$ in R-G-B.

It should be noted that the IDS is not a classification tool - it does not predict the class of each pixel in the image for the analyst. Instead, it finds only the pixels that have a spectral signature closest to that of an iceberg, groups adjacent pixels together, and recommends them for analysis.

E-4. Accuracy Assessment

IIP utilized the SN2 IDS throughout the 2021 Ice Season with excellent qualitative results, but had yet to conduct a quantitative assessment of its accuracy. A quantitative accuracy assessment was conducted utilizing the imagery collected during the ICE-PPR 2021 Iceberg Tagging Experiment in the vicinity of Disko Bay, Greenland. This area was selected because there were thousands of icebergs of varying sizes in varying conditions within a confined area, providing a large sample size. For the assessment, IIP satellite analysts ran 20 SN2 images through the IDS with the “Normal” spectral thresholds. Each frame was examined to classify all detected targets and locate any additional, undetected targets. Only targets of waterline lengths greater than 30 m were considered as missed targets (false negatives), as smaller icebergs are difficult to discern with confidence, especially within sea ice, near cloud, or on windy days, with the 10 m resolution.

These 20 frames had no sea ice and very little wave action, two environmental conditions that can add thousands of false positive targets, but there were areas of dense mélange (chunks of ice and snow as a byproduct of iceberg calving) from the Jakobshavn Glacier. These areas were excluded from the accuracy assessment so as not to skew the results in an area of minimal interest to IIP analysts. Even though they included thousands or tens of thousands of chunks of ice that were successfully identified by the script, nearly every pixel within the fjord was ice of some characteristic and was identified as a potential target by the IDS. Typically, IIP does not conduct reconnaissance this close to the glacier and does not have to analyze mélange.

For the Disko Bay dataset, there were a total of 19,417 verified icebergs within the 20 frames. The IDS detected 19,138 of them correctly using the “Normal” spectral threshold regime resulting in 99% detection accuracy. The 279 (1%) that were missed were all observed through thin cloud. Examples of these missed icebergs are in **Figure E-3**. The thin cloud changes the spectral signature of the iceberg. Though the thresholds are set to identify icebergs through thin cloud, no two days or two icebergs or two cloudbanks are the same. For now, IIP analysts must continue to visually scrutinize areas around thin

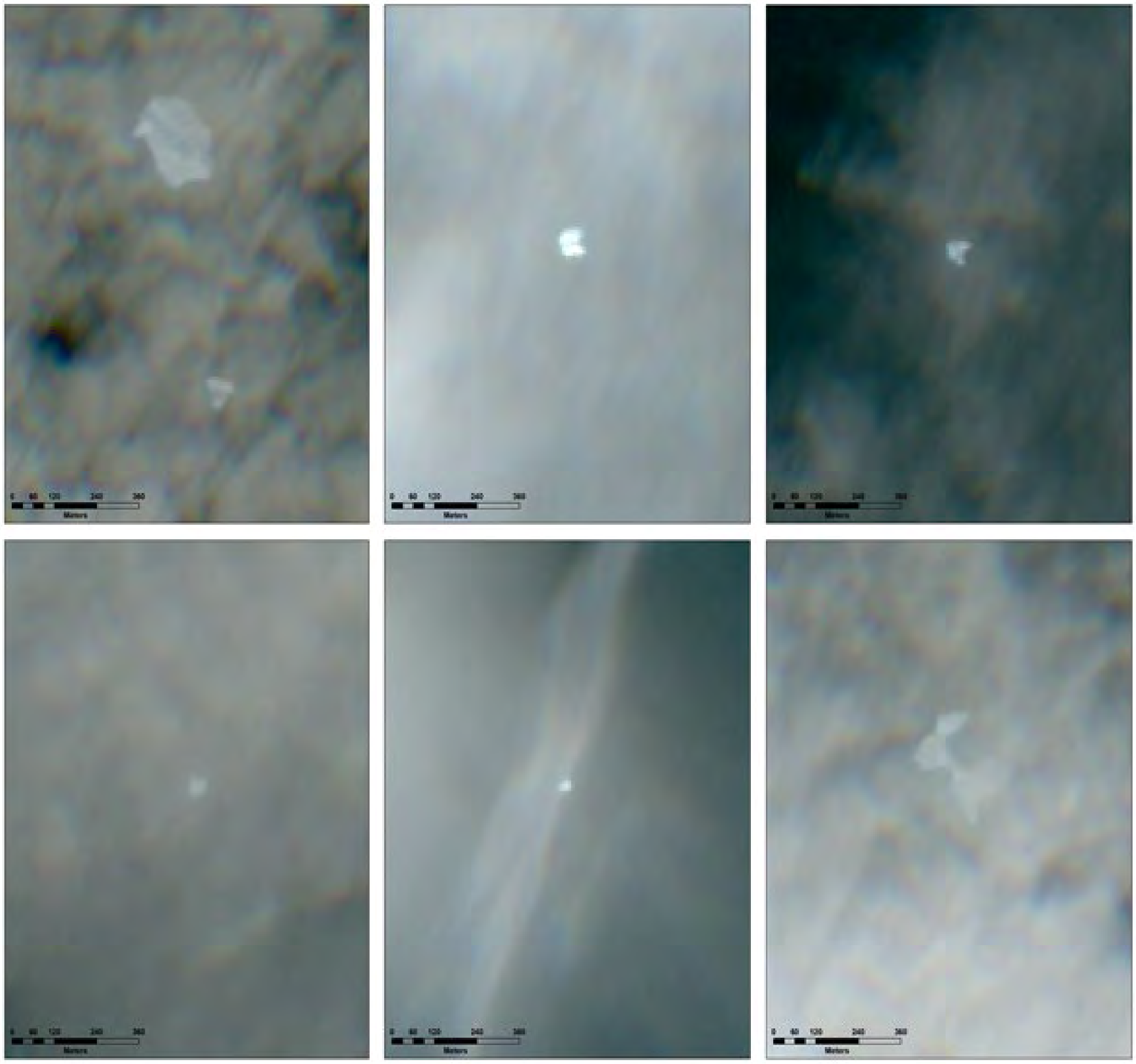

Figure E-3. Examples of icebergs under thin cloud that were not detected by the Sentinel-2 Iceberg Detection Script. All target chips are precisely the same scale. The scale bar ranges from 0 to 360 m. Copernicus Sentinel data 2021.

cloud for missed detections that must be manually added to the reconnaissance. Future development of the IDS will be aimed at improving detectability through thin cloud.

Though 99% of icebergs were detected by the IDS, the IDS also detected an additional 19,038 targets. These were false-positive detections that the analyst is required to sort through and delete from the analysis. 5,613 of these were cloud and especially the shadowed edges of cloud banks, the remainder were isolated areas of mélange not excluded from the analysis. In this regard, the targets were spectrally similar to icebergs, but not of a size or quality of interest. Though the process of reviewing these targets is time-consuming, it is not as challenging as the classification of SAR imagery and significantly less time-consuming than manually scanning the entire SN2 image.

Two frames with sea ice were also analyzed for accuracy using the “Sea Ice” spectral thresholding regime. 176 verified icebergs were present in the two sea ice frames. Of these, the IDS correctly detected 151 of them, yielding an 86% detection accuracy in sea ice. Analysis of sea ice frames produced many more false positive targets due to the similarity of sea ice and icebergs. The two frames had a total of 1,636,788 false positive targets, all were sea ice. It should be highlighted that these two frames are only a small sample size, and, similar to thin cloud, the characteristic of the sea ice in a frame plays a major role in the ability to discriminate icebergs. Different concentrations and types of ice will be spectrally different, so there remains work to be accomplished in this area. Identifying a spectral signature for every ice type and development of a supervised classification scheme would be a useful path forward.

Figure E-4 shows examples of the 25 icebergs (14%) in sea ice that were not detected correctly by the IDS. Investigation has revealed that each of the pixels were correctly spectrally identified as icebergs, but so were many of the surrounding sea ice pixels. During the creation of polygons from the raster datasets (Step 5), the resulting polygon included the surrounding sea ice pixels that were of similar enough spectral characteristics to be called iceberg pixels. This created an overly large polygon. When the point for

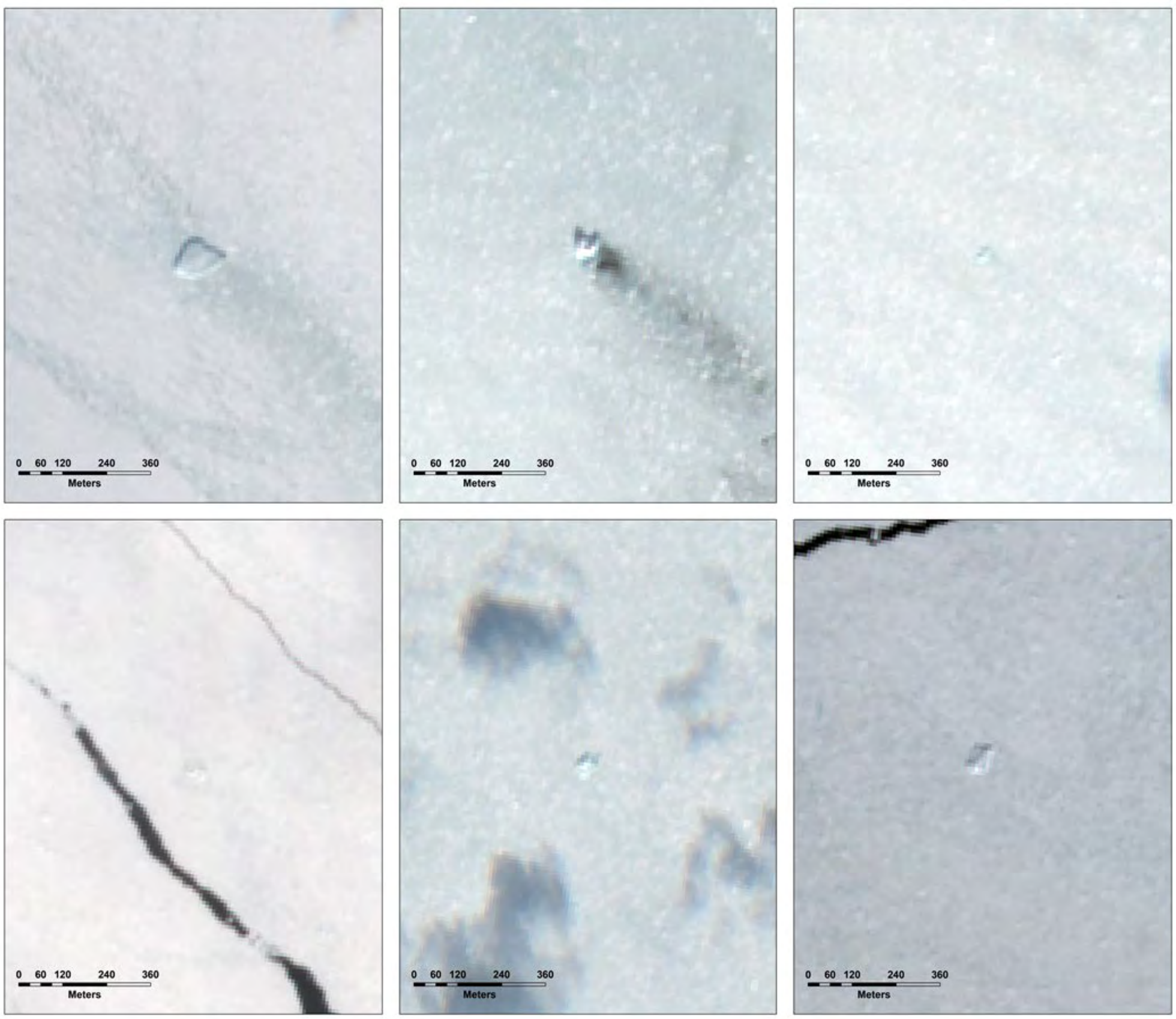

Figure E-4. Examples of icebergs in sea ice that were not detected by the Sentinel-2 Iceberg Detection Script. All target chips are precisely the same scale. Copernicus Sentinel data 2019 and 2020.

that polygon was established (Step 6), it was taken as the center as the polygon and was misaligned with the actual iceberg, resulting in a false negative target. To correct, the spectral thresholding must be further refined or the way in which the process is executed in ArcGIS must be changed. Future work will seek to improve this ability as well as reduce the number of false positive targets presented to the analyst.

E-5. Lessons Learned

The accuracy values quantified here are encouraging. Accuracy of detection is the first step to eliminating false negative (missed) icebergs on the warning products. Our analysts cannot classify what they do not detect. The tradeoff for high accuracy of detection, however, comes with the high number of false positive targets presented to the analyst as well. Rudnickas (2019) addressed the issue of finding balance between 100% detectability and false positives in SAR imagery. Due to the challenge of classifying SAR targets as an iceberg, a ship, or something else, false positive detections in SAR are more likely to end up as false positive icebergs on IIP's product as analysts typically err on the side of caution. While false positives are less threatening than false negatives, they pollute the model, degrade the accuracy of the Iceberg Limit, and reduce mariner confidence. Compared to SAR, analysts have exceedingly high confidence in their classifications in optical imagery, so that, if a target is presented to an analyst, they will likely classify it correctly. In this situation, it is more important to detect all icebergs and less important to reduce the number of false positives which can generally be deleted quickly. In other words, for SN2 analysis, we accept the necessary time required to sort through thousands of false positive targets in order to be more confident of the final product.

E-1. Conclusion

Automation of processes has been a key factor in IIP's ability to increase the amount and accuracy of satellite reconnaissance over recent years. After automating much of the Sentinel-1 SAR workflow, IIP analysts were able to cover much more of the reconnaissance area per day, quickly and efficiently, but confidence in our ability to accurately classify icebergs in SAR imagery had remained questionable. The inclusion of SN2 imagery as a reconnaissance source in 2020 has been invaluable to building analyst confidence in classification in all sensors. Not only has it become a trusted reconnaissance source in itself, but finding opportunities when optical imagery collection is nearly coincident with SAR collection has helped analysts learn and become much more accurate with SAR classification. The IDS presented here has helped to automate the SN2 process. Though there remain many aspects that can be improved, quantifying the detection accuracy as 99% outside of sea ice and 86% within sea ice is an excellent beginning.

E-2. References

2019, 2020, and 2021 Sentinel-2 imagery downloaded from Copernicus Sentinel data.

Rudnickas, D. (2019). Aerial and Multispectral Ground-Truth Verification of Iceberg Detection and Classification Capability in Synthetic Aperture Radar Imagery. *Report of the International Ice Patrol in the North Atlantic (2019 Season)*, Bulletin No. 105, CG-188-74, Appendix B.

International Ice Patrol Satellite Northern Survey Results - December 2020

D. Rudnickas

Introduction

Between December 7 and December 24, 2020, International Ice Patrol (IIP) personnel utilized Sentinel-1, Sentinel-2, and Landsat-8 sensors to conduct a pre-reconnaissance season Northern Survey from 55ºN to 70ºN along the Labrador Coast north of Goose Bay, eastern coast of Baffin Island, and southwestern Baffin Bay. The goal was to estimate the "upstream" iceberg population that could drive aerial reconnaissance decision-making in the early part of IIP's iceberg reconnaissance season. As of December 24, the majority of icebergs in the reconnaissance area are well constrained within first-year sea ice, with the leading ice edge approximately 240 NM south of Cape Dyer. This report provides more amplifying information on the methods utilized and presents the results of the Satellite Northern Survey.

Data and Methods

The majority of reconnaissance was conducted utilizing Sentinel-1 Synthetic Aperture Radar (SAR). Both Interferometric Wide Swath (IW, 20m resolution) and Extra Wide Swath (EW, 50m resolution imagery) were analyzed as available. While Sentinel-2 and Landsat-8 Multispectral sensors were also utilized, the region in which imagery is collected by these missions during this time of year is south of 60ºN due to limited daylight in winter months farther north. No icebergs were detected in Sentinel-2 or Landsat-8 imagery. All Sentinel data were downloaded from the Copernicus Data Hub and Landsat data were downloaded from the US Geological Service's Earth Explorer data repository. In all, 21 Sentinel-1 IW, 30 Sentinel-1 EW, six Sentinel-2, and four Landsat-8 images were analyzed (**Figure 1**). Daily sea ice polygons were provided by the Canadian Ice Service as part of the North American Ice Service.

SAR imagery was processed using the most recent updates to the IIP satellite filtering process that relies upon different Constant False Alarm Rates for target detections based on incidence angle but incorporates a maximum target decibel "catch" to preserve the most prominent targets for analysis. This technique was devised after the 2020 validation effort in which verified icebergs located in Sentinel-2 imagery were tested in coincident Sentinel-1 imagery. The decibel "catch" was shown to allow all verified icebergs to be brought through the filtering process to the analyst for classification, and this Northern Survey additionally served as a test for the newly scripted processes. This was a resounding success.

The uncertainty in iceberg counts is derived based on the range of observations from different analysts using different sensors with different resolutions. The key distinction comes from comparing IW observations with EW observations within sea ice. The higher resolution from an IW frame allows the analyst to look for smaller icebergs, but also presents an increased number of sea ice features (such as ridges and rafts) to the analyst. This is predicted to increase the number of false positive targets within sea ice using IW imagery. EW imagery, on the other hand,

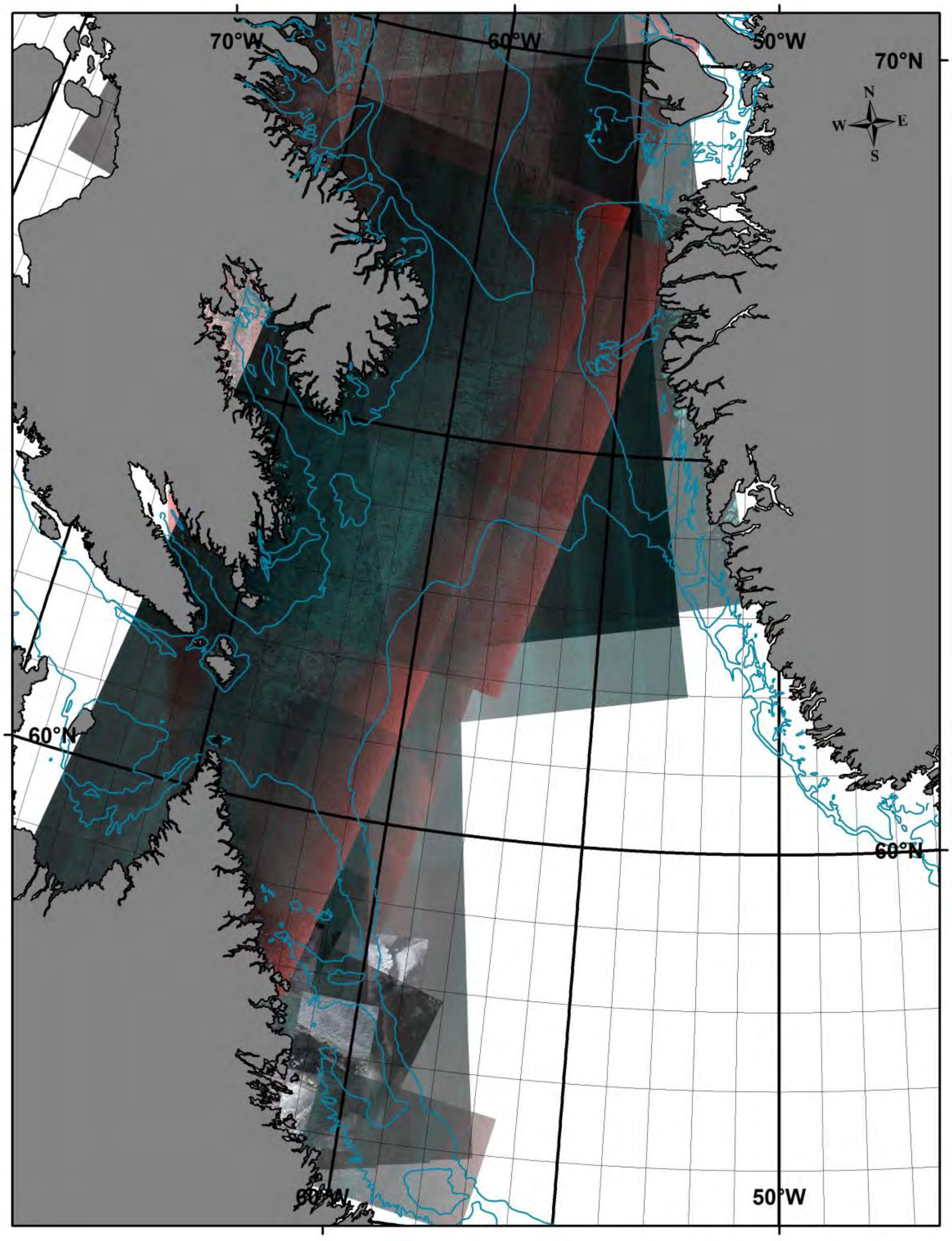

Figure 1. Overview of all frames analyzed during the December 2020 Satellite Northern Survey effort.

has courser resolution and a strong target return is more likely to be an iceberg as the sea ice features are more likely to be undetected. EW frames, therefore, are more likely to result in false negative targets, but the targets that are detected are more likely to be icebergs. Since small icebergs in the northern regions of IIP's operating area are less likely to survive long enough to reach the transatlantic shipping lanes, it is less critical to track them as part of this survey compared to the larger icebergs that are likely to survive. This report provides a range of icebergs within certain regions to account for the likelihood of false negative and false positive targets across the two resolutions.

Results and Discussion

A total of 2,304 icebergs were detected in the analyzed frames (**Figure 2**) though more than 1,000 of these were located on the eastern side of Baffin Bay near Disko Island. In the Northern Survey area along the east coast of Baffin Island and Labrador coast from 55ºN to 70ºN, analysis distilled these total detections down to 423 individual icebergs. **Figures 3** and **4** show the results of the daily Northern Survey reconnaissance and **Figure 5** compiles the results into an analysis of the iceberg population in the study region as of December 24, 2020. This survey found no

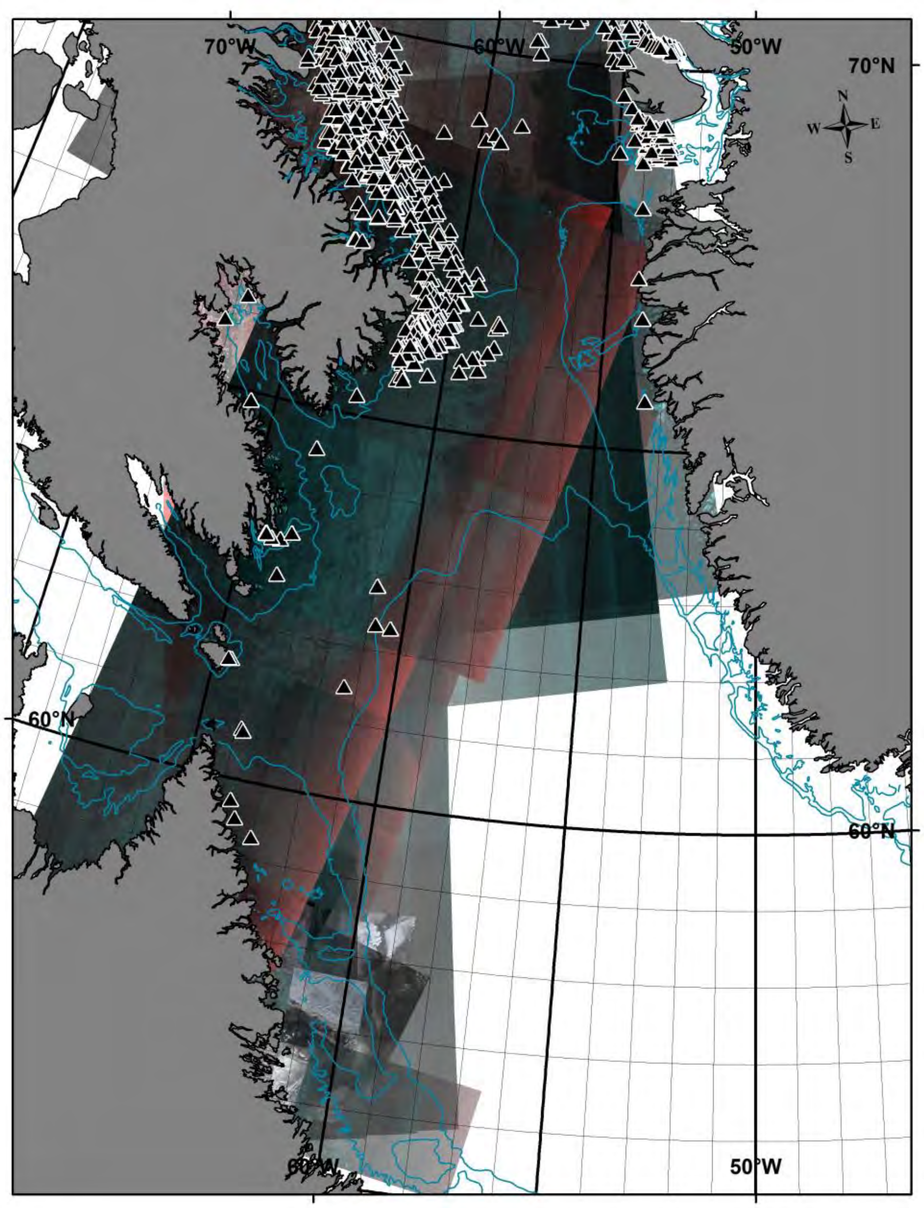

Figure 2. Overview of all iceberg detections during the December 7 – 24, 2020 Satellite Northern Survey effort. Note this does NOT remove subsequent sighting of the same icebergs.

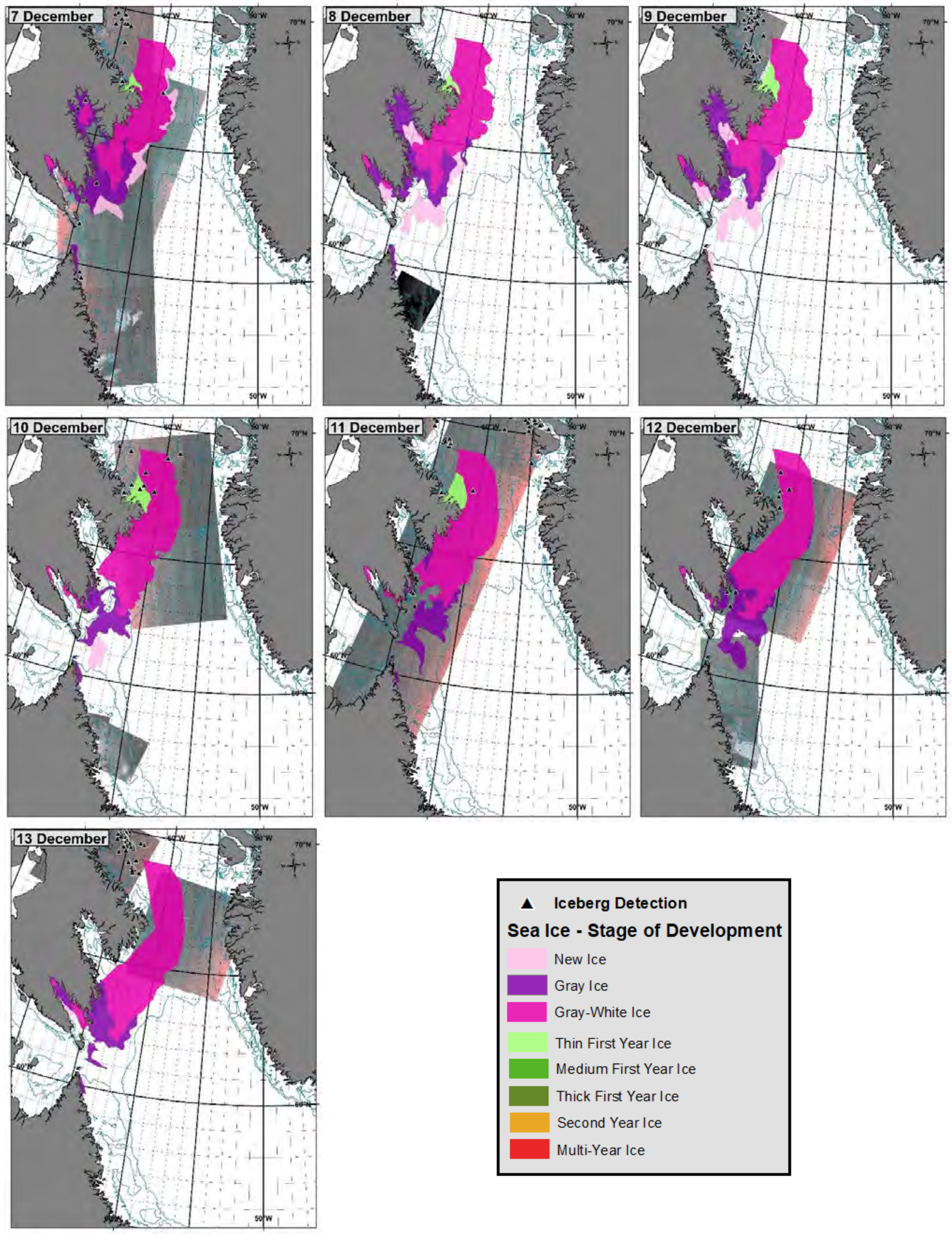

Figure 3. Daily satellite reconnaissance from December 7 to 13, 2020. Canadian Ice Service Sea Ice Stage of Development polygons are overlaid. Sentinel-1 data from Copernicus Data Hub, 2020.

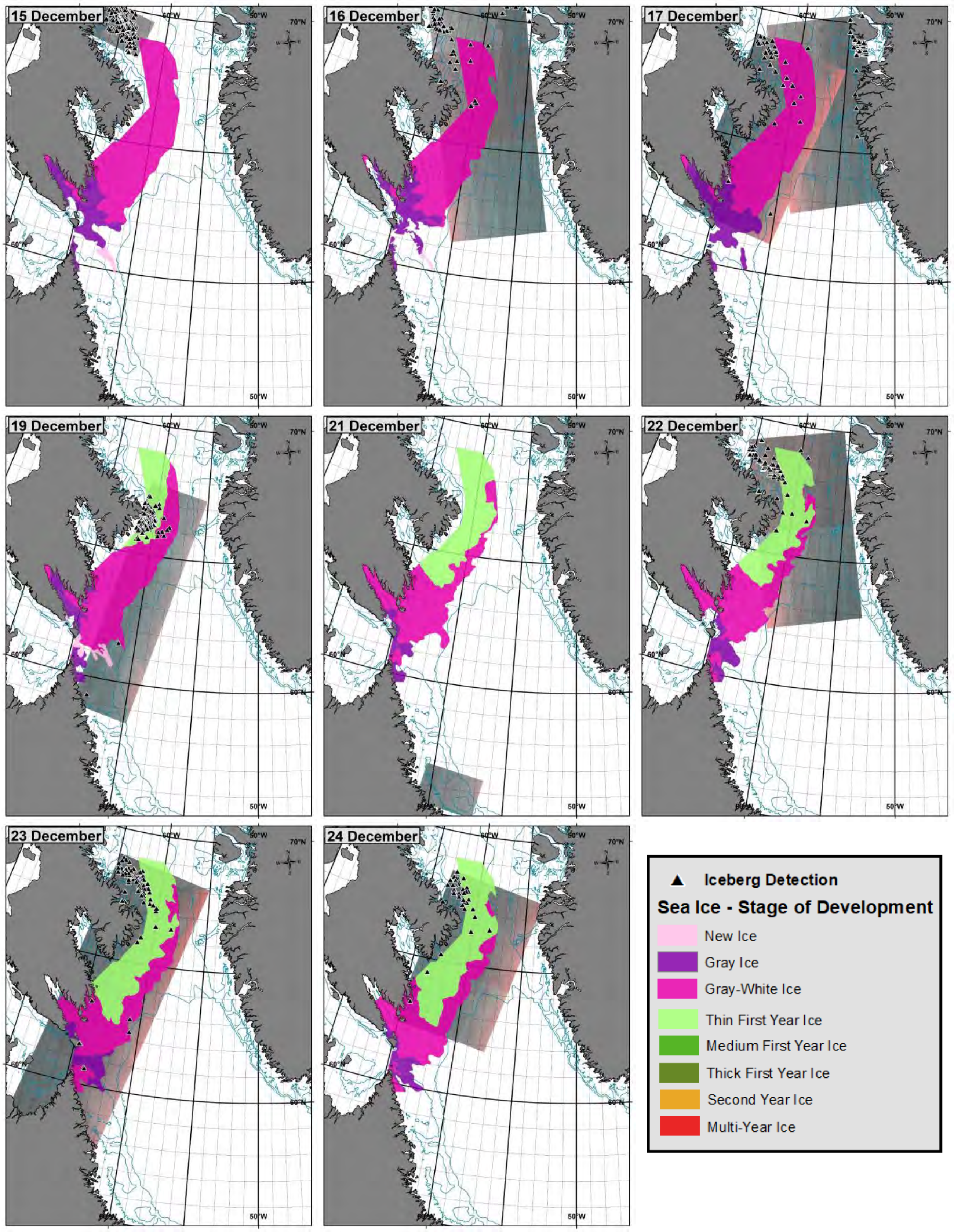

Figure 4. Daily satellite reconnaissance from December 15 to 24, 2020. Canadian Ice Service Sea Ice Stage of Development polygons are overlaid. Sentinel-1 data from Copernicus Data Hub, 2020.

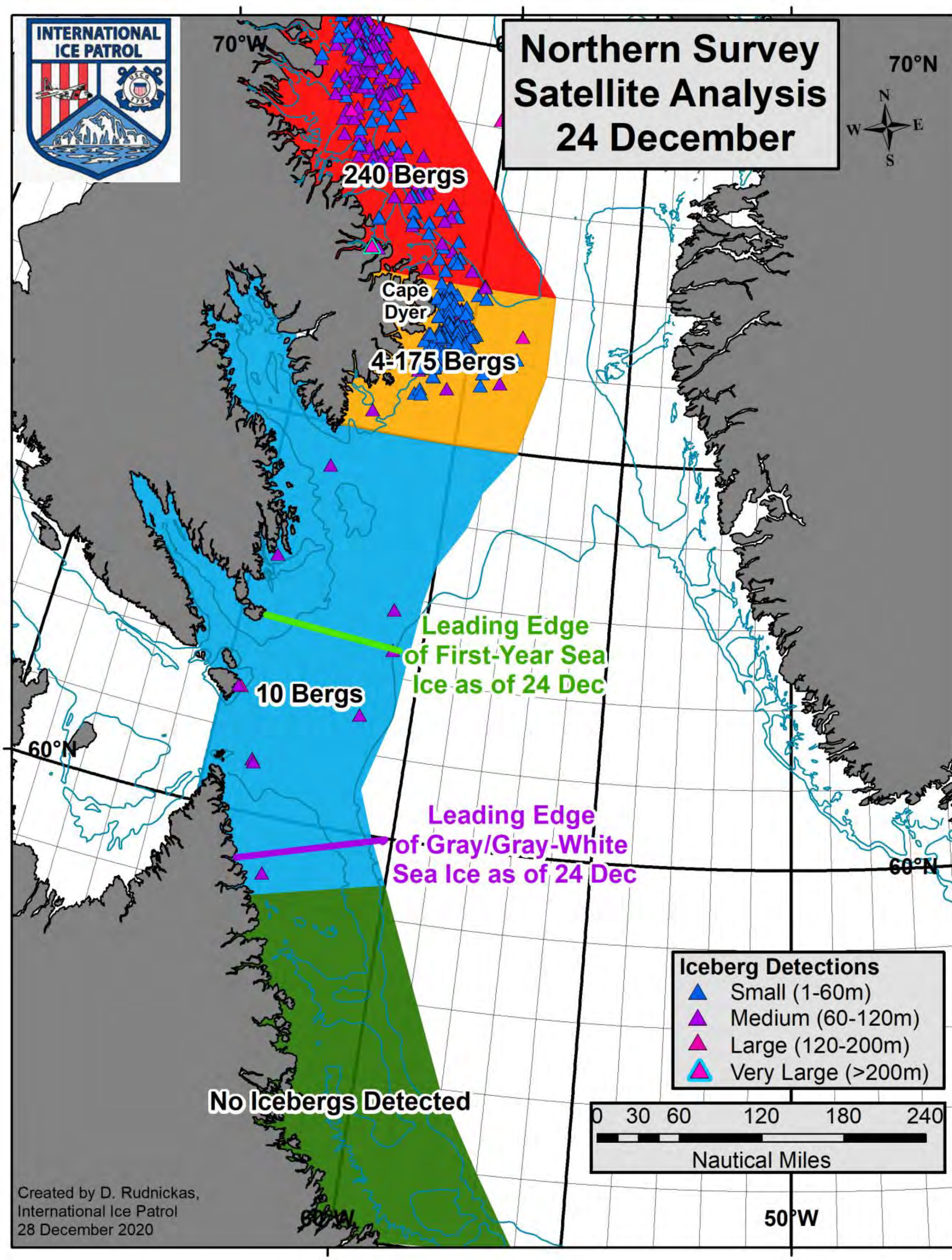

Figure 5. Analysis of the December 2020 Satellite Northern Survey results with the final iceberg population detected as of December 24, 2020 and the reconnaissance area divided into four populations. Icebergs symbolized by size.

icebergs south of 59ºN. Ten isolated icebergs were detected between 59ºN and 65ºN. North of 67ºN, along the northeast coast of Baffin Island, this survey estimates there to be 240 icebergs within first year sea ice. Between 65ºN and 67ºN in the western side of Davis Strait in the vicinity of Cape Dyer is an area of special interest for this study. Icebergs within this region will have already departed Baffin Island and are drifting south toward the Grand Banks. Here, daily EW imagery from December 22 - 24 detected four individual icebergs in this region, and earlier frames up to 10. However, analysis of an IW image on December 19 detected 175 icebergs. As discussed in the Data and Methods section, the range of icebergs between four and 175 in this area was used to document the uncertainty within the survey and is most likely due to higher resolution imagery being able to observe sea ice features that are being conservatively classified as icebergs. This far north, higher resolution IW imagery is collected less frequently than the near-daily lower resolution EW, so that even though three days of more recent low resolution imagery over the area showed four icebergs since the higher resolution 175 detections, both are included here to denote the area and magnitude of uncertainty in this critical area. Further investigation of the area as it drifts south toward more frequent IW collections and multispectral sensors should be conducted to more accurately determine the iceberg population here.

Of the 423 individual icebergs observed in the survey area, 241 (57.0%) were observed as small icebergs (15-59m waterline length), 176 (41.4%) were observed as medium icebergs (60-119m), six (1.4%) were observed as large icebergs (120-199m), and only one (0.2%) was observed to be a very large iceberg (200m or greater). Of special note, 66% of small icebergs (159) were found in the 65ºN-67ºN region of Cape Dyer by Sentinel-1 IW imagery. These were small enough to not be detected in the more recent EW imagery, but also have a higher chance of being related to sea ice features at this point in the season. It will be extremely challenging to determine whether these are indeed small icebergs or sea ice features until Sentinel-2 multispectral imagery can be collected or a reconnaissance flight can be conducted over this region of the floe. Also of note, 85% of medium icebergs (175) and 67% of large icebergs (6) were detected north of 67ºN, having not drifted out of Baffin Bay yet. As discussed earlier, the icebergs of highest interest in the survey area are medium and larger icebergs as these are most likely to survive the drift down the coast to reach the transatlantic shipping lanes. The fact that over half of the iceberg population in the survey area was detected as small icebergs that could be false positive detections of sea ice features and only 1.4% percent of the detected icebergs were of large size, is indicative of a population that is less likely to survive the drift to the Grand Banks. The single very large iceberg that was detected during this time frame is an approximately 490m ice island fragment located within a fjord at approximately 67º15'N 63º30'W. During the course of this survey, it was only tidally oscillating within the fjord and was not part of the main population of icebergs flowing south.

The majority of icebergs (approximately 97%) are well-contained within first year sea ice, with the larger concentrations of icebergs located approximately 240NM from the leading edge. The leading edge of the first year sea ice was observed to first pass south of Cape Dyer on December 18 and is estimated to be drifting south at approximately 22NM per day, based on the average drift rate from December 18 - 24. As of December 24, this leading edge has approximately 1,000NM to travel along the 1,000m bathymetric contour to reach 48ºN. By a simple time, speed, distance calculation using these estimated numbers, the leading edge of first year sea ice could potentially be expected to arrive at 48ºN in approximately 45 days, in the second week of February. Assuming that the larger concentration of icebergs approximately 240NM from the leading edge is moving at the same speed, this group of icebergs could reach 48ºN approximately

10 days later, in the middle of February. This crude estimation discounts the effects of any storm systems and current variability that could impact the sea ice as well as the drift of the icebergs.

Conclusion

This study has shown a relatively small population of icebergs in the upstream pipeline that transports icebergs from Baffin Bay to the transatlantic shipping lanes. More than half of this population is still within Baffin Bay and 97% of it is currently contained within the first year sea ice that is drifting south. 42% of the overall population is located within the 65ºN to 67ºN Cape Dyer region that is subject to a significant amount of uncertainty. The Satellite Reconnaissance Branch at IIP will monitor this region as it drifts south to determine whether this segment of the population is closer to four or 175 icebergs. It is recommended that the IIP Operations Center track the leading edge of the Gray/Gray-White sea ice in the polygon shapefiles available from the Canadian Ice Service and, once IIP commences producing the Iceberg Limit, ensure that this leading edge is included within the Limit.

The need for ground-truth verification of these results cannot be overstated. IIP's satellite reconnaissance program has advanced significantly over recent years, but the limitations of sensor resolution and analyst experience continue to provide both false positive and false negative targets that pose a risk to the maritime community. While this study presents IIP's best effort at satellite reconnaissance in this region, our processes are still a work in progress and, to improve, must be validated by other data sources.

It should be noted, that a Satellite Northern Survey of this kind has never been attempted by IIP. Therefore, it is difficult to compare these results to any other season and attempt to predict season severity as this is only one data point with no trend to compare it to. Hopefully, however, this single data point will be built upon over coming years and this sort of reconnaissance can be correlated to season severity prior to the traditional IIP reconnaissance season. Please direct any questions on these results or discussion to the author (LT Don Rudnickas, Satellite Reconnaissance Branch Chief, IIP, Donald.W.Rudnickas@uscg.mil).

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