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Sea Ice and Year-Round Shipping Analysis for a Potential Mackenzie Delta Ship Terminal

Matthew G. Asplin[1,2], David B. Fissel[1], Keath Borg[3], and Alex Graham[1]

[1] ASL Environmental Sciences, Saanichton, Canada
[2] University of Victoria, Victoria, Canada

ABSTRACT

A proposed year-round shipping route in the Western Arctic Ocean could facilitate the transport of liquefied natural gas (LNG) from Canada's Beaufort Sea to international markets. Arctic sea ice is a significant navigational challenge, posing risks such as ships becoming immobilized by ice pressure as winds push dense ice toward the shore. This study first examines historical and projected sea ice conditions for 2030 – 2060 to evaluate the feasibility of year-round shipping through 2060. A route between Tuktoyaktuk and the Bering Sea is identified, incorporating input from Transport Canada, Indigenous groups, and international authorities. This study then focuses on sea ice conditions near potential LNG offshore facilities, analyzing ice concentration and seasonal changes from 1991 – 2020, and projected ice conditions for 2030 – 2060. The findings will inform future research and support sustainable energy development in the Arctic, ensuring safe and efficient LNG loading and transport amid evolving ice conditions.

KEY WORDS: Arctic sea ice; Arctic shipping; Ice concentration; Climate change; Thickness

INTRODUCTION

This study presents the results of a sea ice desktop study in support of a pre-feasibility study conducted by the Government of the Northwest Territories to support a potential natural gas export project situated in the Mackenzie Delta in the Inuvialuit Settlement Region of the Canadian Northwest Territories. The project concept is known as Mackenzie Delta Liquified Natural Gas (MDLNG) and involves developing conventional onshore natural gas reserves in the area and exporting them to market using special purpose-built Arc7 (PC3) LNG ice breaking tankers (IMO Polar Code, 2016), like the Novatek LNG operation in Eastern Siberia (Humpert, 2021). In the MDLNG concept, a gravity-based structure (GBS) will be situated offshore in ~15 m water depth and supplied with LNG from shore via a sub-sea pipeline.

The key objectives to be addressed by this work are as follows: 1) Conduct a regional (Western Arctic) sea ice investigation to support shipping activities, including defining a shipping corridor guided by Canadian and United States federal shipping corridors, and respectful of Indigenous traditional subsistence activities, key mammal habitat, and hunting seasons; 2) a focused sea ice investigation for MDLNG facilities in the Mackenzie River Delta, including historical and future climate change projections for seasonal sea ice conditions for the periods 2030 – 2045 and 2045 – 2060 with expected implications for shipping. The respective study areas for both objects are outlined in figure 1.

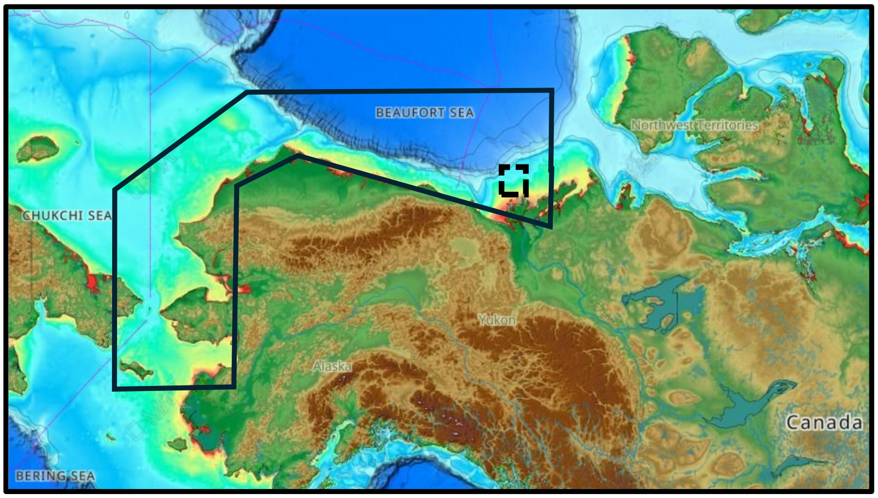

Figure 1. Study Area for Shipping Analysis (black-bounded area) and focused investigation (dashed line bounded area)

PART 1: REGIONAL SHIPPING ROUTE ANALYSIS

Methodology

Historical sea ice conditions are examined for the Arctic Ocean in general and for Canadian and Alaskan Beaufort Sea, and the Chukchi Sea, Bering Strait/Bering Sea regions. The literature review of historical conditions is supported by statistical and trend analysis of sea ice data from Canadian Ice Service charts (CIS, 2024) for 1991 – 2020. The key ice parameter that impacts the viability of year-round shipping transits westward from the Canadian Beaufort Sea continental shelf to the Bering Sea is the presence of old ice, (i.e., second-year ice and multi-year ice). Using a wide range of coupled atmosphere-ice-ocean models, the future ice conditions and impacts on shipping in this region can be estimated.

Historical Ice Conditions

The Arctic Ocean has seen a major decline in sea ice extent, thickness, and age since satellite records began in 1979, with sharp volume reductions between 2005 and 2010 (IPCC, 2019). Arctic warming, occurring over twice as fast as the global average, has accelerated ice loss. From 1979–2020, ice thickness declined across the Arctic, with the largest reductions (0.5–1.1 m/decade) in the Western Arctic, particularly along the Beaufort and Chukchi Sea margins (Schweiger et al., 2019). Polar pack ice changes include delayed fall freeze-up, earlier spring breakup, and a shift from multi-year to first-year ice (Galley et al., 2016). Ice incursions still threaten shipping, especially during prolonged west or north winds. Landfast ice duration is decreasing by ~2.5–3 days per year (Galley et al., 2012, 2016), with a 53-day seasonal loss between 1973–1977 and 1996–2008 (Barry et al., 1979). The Beaufort Gyre circulates older ice, creating navigation hazards. Ice older than three years is now mostly confined to northern Greenland and the Canadian Arctic Archipelago, known as the "Last Ice" area, though some drifts into the Canadian and eastern Alaskan Beaufort Sea (Moore et al., 2019).

Ice in the Beaufort Sea can be categorized into distinct regimes, including offshore mobile ice, seasonal landfast ice, and a transition zone where ice interactions create variability (Fissel et al., 2013). The transition zone, which overlaps with a proposed shipping corridor (Dawson et al., 2020), experiences dynamic ice conditions influenced by wind and seasonal melt. The Beaufort Sea's ice cover has shifted to a younger and thinner state since ~2007, making it more susceptible to melting (Maslanik et al., 2011; Krishfield et al., 2014; Howell et al., 2016). Canadian Ice Service (CIS, 2024) data (1991 – 2020) show a statistically significant 9.5% per decade decline in total sea ice in August. Old ice has declined modestly but with high interannual variability. From 1991 – 2000 to 2011 – 2020, old ice coverage dropped from 58% to 26% in winter, with summer ice 15 – 25% lower.

The Alaskan Beaufort and Chukchi seas exhibit declining sea ice trends like the Canadian Beaufort Sea. Landfast ice extends from the coastline and stabilizes by winter, but ship navigation is difficult due to thick ridges and keels forming at its boundary. Seasonal landfast ice duration has decreased by ~53 days since the 1970s (~2 days/year) due to later formation and earlier breakup (Mahoney et al., 2014; Mahoney, 2018). Serreze et al., (2016) examined ice season lengths in the Chukchi sea. Ice typically retreated in May, cleared by early August, and reappeared in October. However, the retreat date advanced by 0.70 days per year, and ice onset was delayed by 1.52 days per year, extending the open water season by 2.22 days annually—an 80-day increase over this period (Serreze et al., 2016). From 1979 to 2014, the Chukchi Sea was fully covered by sea ice from December to April, with maximum coverage reaching the Bering Strait by March.

Analysis of CIS Data (CIS, 2024) reveals that from 1991 – 2020, total summer ice coverage declined by 16.4% per decade, with winter ice largely intact but experiencing a sharp drop in old ice, from over 50% in 1991 to ~5% in 2020. Old ice coverage fell from 40% to 10 – 15% in winter and from 20 – 30% to 0 – 10% in summer. Maximum old ice extent dropped from 60 – 70% to 30 – 40% in winter and from 60 – 70% to 10 – 30% in summer.

In the Bering Sea, sea ice formation typically begins in late October to early November and lasts until June, with considerable variability, especially in the southeastern region. Since 2000, the region has experienced alternating periods of extensive and minimal ice, with particularly low ice extents from 2013 to 2019 (Perovich et al., 2019; Thoman et al., 2020). Both the Chukchi and Bering seas are predominantly covered by first-year ice, with multi-year ice confined to the northern Chukchi Sea, and exhibiting significant reductions in ice age over the past decades (Ward et al., 2015; Serreze et al., 2016). In 2011 – 2012, an extraordinary event occurred when multi-year ice was transported southward through Bering Strait due to sustained winds (Babb et al., 2013).

Future Regional Sea Ice Conditions: 2030 – 2060

The presence of old sea ice, i.e. second-year and multi-year ice, plays a crucial role in the feasibility of year-round shipping from the Canadian Beaufort Sea to the Bering Sea. Although the percentage of old ice has drastically decreased over the past 30 years, some old ice remains in the Canadian and Alaskan Beaufort Sea year-round, typically representing 5 – 15% of the area. Future sea ice conditions in this region can be projected using coupled atmosphere-ice-ocean models, although the predictions involve considerable uncertainty (Jahn et al., 2016). It is widely agreed that sea ice extent will continue to decrease (IPCC, 2014; 2019), with varying estimates on when the Arctic Ocean will be ice-free in late summer. Projections range from as early as 2035 (Guarino et al., 2020) to as late as 2070 (Notz and SIMIP Community, 2020). Models such as the Community Earth System Model (CESM) predict that by around 2050, the Arctic Ocean will likely be ice-free in late summer, with first-year ice persisting throughout fall, winter, and spring for the rest of the century. However, small amounts of old ice could remain until about 2050, impacting shipping operations (DeRepentigny et al., 2020).

In the northern Bering Sea, the region expected to be most favorable for shipping, models suggest that future winter ice conditions will resemble those observed between 2014 and 2019, with low ice extents. By the 2040s, winter ice extents are projected to be minimal, with reduced ice coverage continuing through the 2080s (Thoman et al., 2020).

Sea ice motion and dynamic processes are largely driven by winds, particularly from the Aleutian Low, a semi-permanent low-pressure system near the Aleutian Islands, and the Beaufort High over the Beaufort Sea (Asplin et al., 2015). Reductions in sea ice extent and age have increased ice movement and deformation (Rampal et al., 2009). Polar lows—intense storms with winds over 20 m/s—can sometimes reverse the Beaufort Sea Ice Gyre and cause ice divergence (Asplin et al., 2009; NSDIC, 2019). The Beaufort Gyre's influence on ice drift has strengthened due to thinning ice (Kwok et al., 2013). Future projections indicate surface wind speeds may rise by 5% by 2060, intensifying wind forcing sea ice, which could accelerate drift, increase variability, and alter ice lead formation (KAVIK-STANTEC, 2020).

Proposed Shipping Route

Declining ice conditions have led to increased shipping activity in the Canadian Arctic since 1990 (Pizzolato et al., 2014), particularly in the Beaufort Sea, where statistically significant increases in summer and early fall ship travel (40–450 km yr^{-1}) from 1990 to 2015 correlate with reduced sea ice. However, multi-year ice remains a major navigational hazard due to its high mechanical strength (Timco and Weeks, 2010; Pizzolato et al., 2016). A shipping route thus must avoid areas that may still contain multi-year ice in the future.

A proposed optimal shipping corridor (Figure 2) is defined using guidance from proposed preferred Arctic shipping corridors that Transport Canada recently defined using Indigenous input (Dawson et al., 2020), the US and Russian Coast Guards (IMO, 2017), and the Alaska Whaling Commission (AF&G, 2021). This corridor is designed to account for the most challenging sea ice conditions and types (e.g., thick, multi-year ice) (e.g. ICCP 2016, TCCP 2016, ACCP 2016, KAVIK-STANTEC, 2020). The route remains at least 25 nm offshore, where possible, to minimize conflicts with subsistence activities, especially the fall bowhead whale hunt, where shipping noise could be disruptive. However, the corridor allows flexibility for ship captains to adjust routes as needed to avoid hazards like old ice floes, large ridges, and extensive rubble ice.

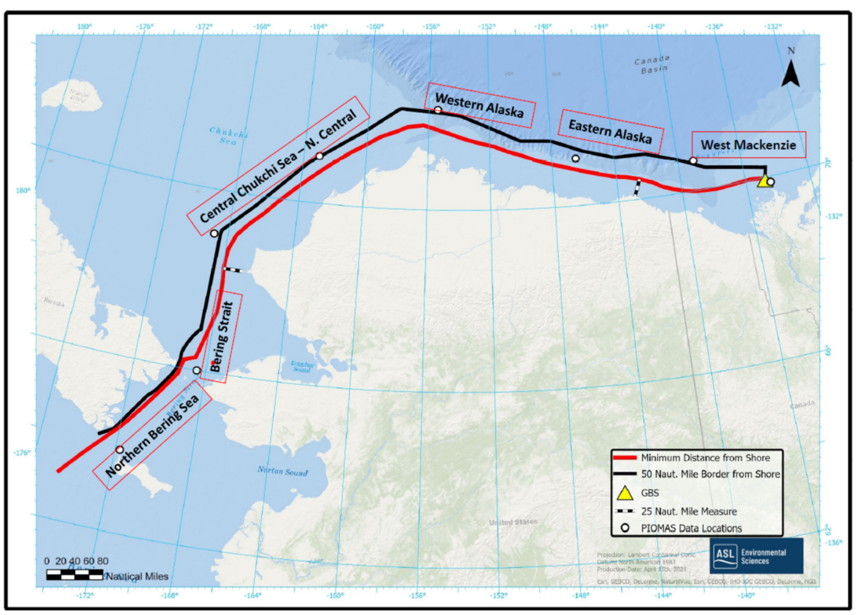

Figure 2. Proposed Shipping Route

Impacts of Present and Future Sea Ice Conditions on Shipping

A review of present and future sea ice conditions over the full length of the shipping route from the western Mackenzie portion of the Canadian Beaufort Sea to Northern Bering Strait shows infrequent obstacles to proposed shipping by Arc 7/PC3 class LNG carriers, even in the winter to spring period. It is well known that first year sea ice is highly deformed in the Beaufort and Chukchi Sea transition zone through many previous studies involving remote sensing: e.g. Barber et al., 2014; Haas, 2012; and upward-looking sonar observations: Melling et al., 1993; Fissel et al., 2014; Fissel et al, 2015a; Fissel et al, 2015b. The time scales of the heavily deformed first year ice (aka "massive marine ice features") are described in Fissel et al, 2014 and Fissel et al., 2015a; b for interannual and seasonal variability.

Under present conditions, the number of interruptions in ship passages in the Beaufort Sea and northeastern Chukchi Sea is estimated to be two or fewer occurrences on the time scale of ship passages (e.g. a few days) in a 10-year period (due to heavily deformed first year ice and intrusions of old ice from the offshore and upstream portions of the western Arctic Ocean) in winter to spring. In summer and fall, the number of interruptions would be even fewer, perhaps one in a 10-years period, due to very infrequent potential incursions of old ice. From the central Chukchi Sea to Northern Bering Strait, the number of interruptions in ship passages will be even fewer due to the lower likelihood of old ice incursions and the reduced thickness of first year ice.

For the future periods of 2030 – 2045 and 2046 – 2060, the number of interruptions is expected to be further reduced. The presence of old ice is expected to continue to decline due to the ongoing dramatic reductions in the age of sea ice and under ongoing Arctic atmospheric warming. By approximately 2050, climate models generally agree that old ice will cease to occur within the Arctic in most years. In the Beaufort Sea and northeastern portion of the Chukchi Sea, obstacles to shipping due to sea ice conditions are expected to become very rare occurrences even in the winter to spring, with approximately one event in a 10-year period for 2030 – 2045 and approximately one in a 15-year period from 2046 – 2060. For the southern portion of the shipping route from the central Chukchi Sea to the northern Bering Sea, no obstacles to shipping are expected during 2030 – 2060 even in the winter to spring months when only seasonal first year ice is expected to be present.

PART 2: MACKENZIE DELTA ICE CLIMATOLOGY & 2030–2060 PROJECTIONS

Methodology

Sea ice concentration and stage of development were analyzed monthly using weekly digital ice chart data from the Canadian Ice Service (CIS) archives (1991–2020) for a focused area in the Mackenzie Delta Region of the Western Arctic. The CIS digital data are based on manual interpretation of RADARSAT-1 (primary since 1996) and RADARSAT-2, NOAA-AVHRR, Envisat ASAR, and in situ observations, aerial, and marine surveys (Fequet, 2002). The CIS Archive Documentation Series details the accuracy and quality indices of these data for each region over time (Canadian Ice Service, 2006). Ice concentration, extent, and stage of development were analyzed at a 4-km resolution, with additional analysis at a 12-km resolution in the focused area. Results are presented for the annual ice season, defined by CIS as beginning October 1st, when surviving first-year ice is reclassified as second-year ice.

Sea ice concentration and age data were extracted from CIS egg code classifications in the digital charts. To streamline analysis and account for overlapping development stages, we grouped ice into four broad categories (Table 1): young ice (Class I), thin first-year ice (Class II), medium to thick first-year ice (Class III), and old ice (Class IV). Potential impacts refer to ice obstacles that may slow ship transit or require course changes to avoid large ice features. Large impacts indicate widespread thick ice, ridges, or features requiring ice management or icebreaker escort. We provide semi-quantitative results for major segments along the proposed route (Figure 2), focusing on the most recent decade (2011–2020) and two future periods: 2030–2045 and 2046–2060. Despite large interannual variability, sea ice severity has shown a clear decline along the entire route over the past 30–40 years.

Classification	Stages of Development included	Impacts to Ship Transits
Class I (new to young ice)	1,2,3,4,5	no impacts on ship transits
Class II (thin first-year ice)	6,7,8,9	no impacts on ship transits
Class III (medium to thick first-year ice	1. and 4.	potential impact if ice is highly deformed
Class IV (old ice)	7., 8., and 9.	largest impact to ship transits

Monthly Sea Ice Concentration 1991 – 2000 and 2011 – 2020

Monthly mean maps are produced for total ice concentrations (Figure 3) for 1991 – 2000 and 2011 – 2020 (not shown). Winter months (January – April) with maximum sea ice extent show no change and are combined as a composite map.

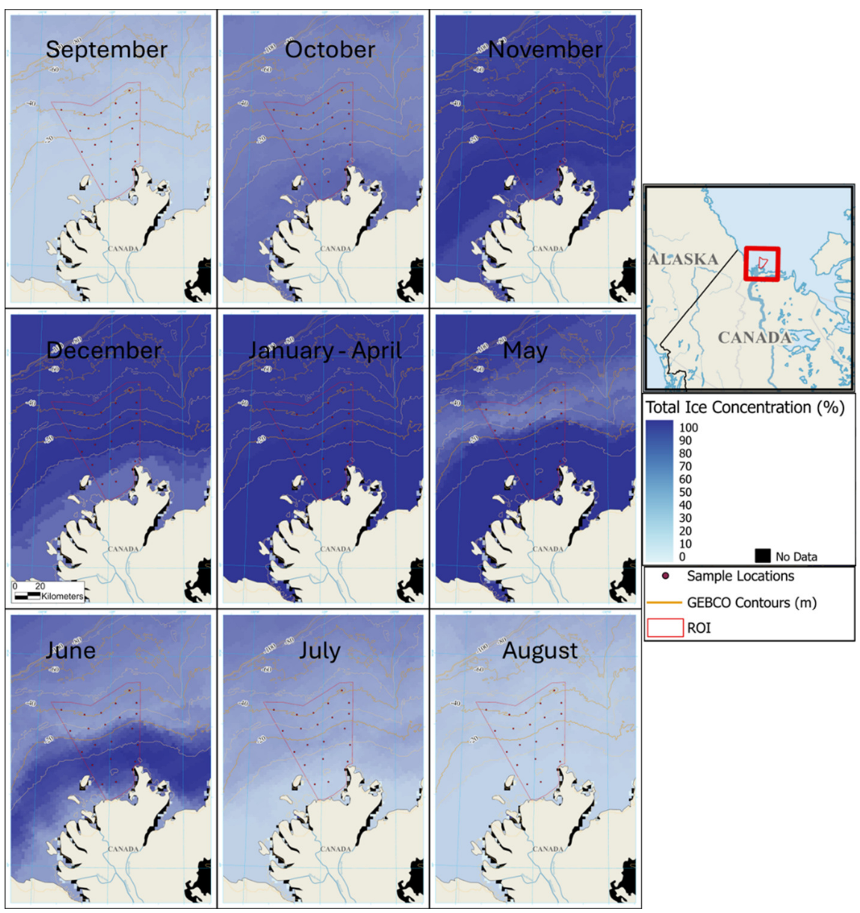

Figure 3. Mean sea ice concentration for September, October and November (top row), December, January-April, May (middle row), June, July and August (bottom row) for 1991 – 2000. January-April is a composite of all four months. Detailed sea ice information was extracted at gridpoints for statistical assessment

To highlight the change in ice phenology and concentrations across the two decades examined above, we subtracted the values of (1991 – 2000) from (2011 – 2020) (Figure 4). The resulting monthly change in mean ice concentrations are shown. Winter months (January – April) with maximum sea ice extent show no change and are shown as a composite map. Changes in sea ice concentration are evident for October, and June – September. May exhibits a modest reduction in sea ice extent, reflecting variability in the presence of sea ice leads, and the timing of the spring opening of the Cape Bathurst Flaw Lead.

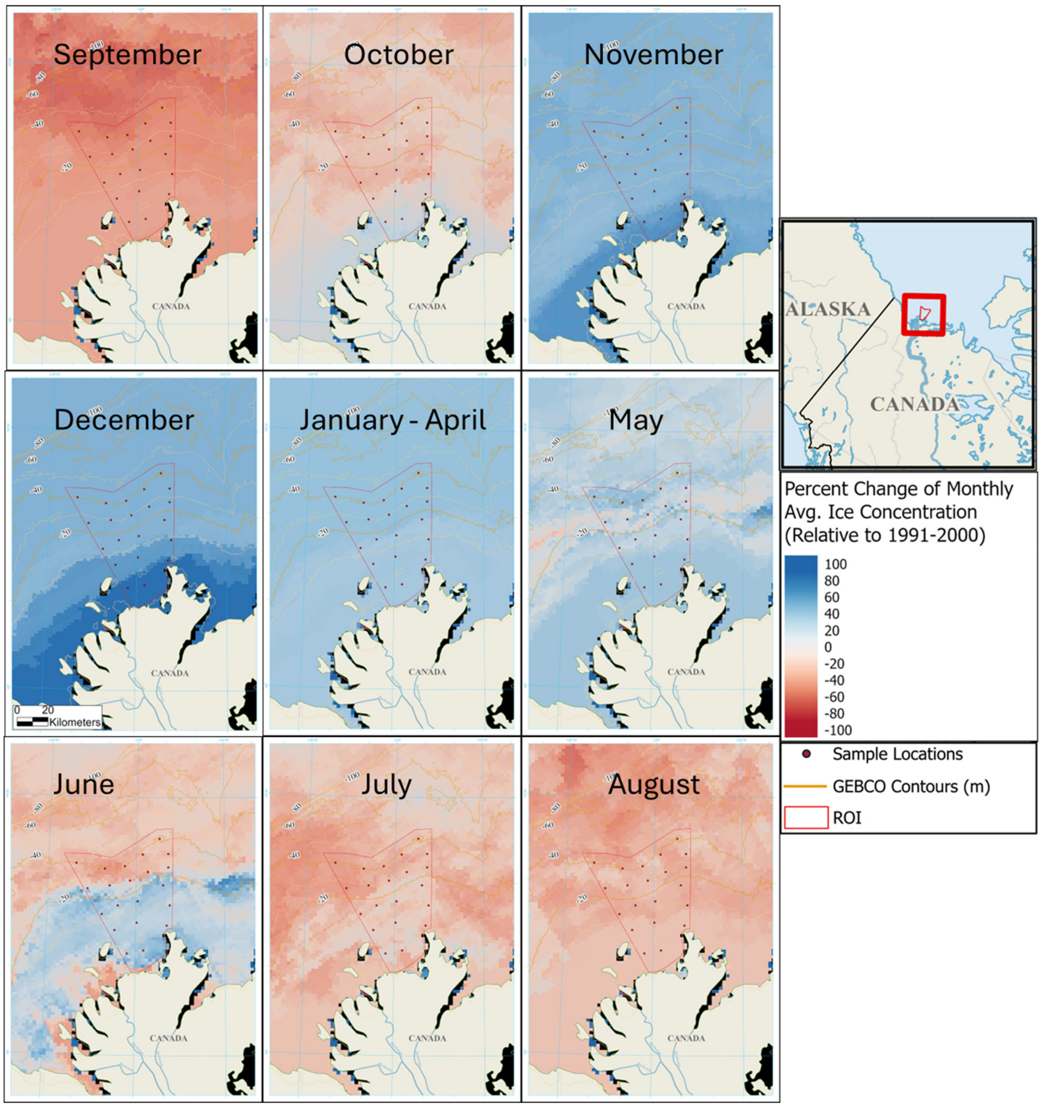

Figure 4. Change in sea ice concentration for September, October and November (top row), December, January-April, May (middle row), June, July and August (bottom row) between 1991 – 2000 and 2011 – 2020. January-April is a composite of all four months. Detailed sea ice information was extracted at gridpoints for statistical assessment

Decadal Changes in Mean Monthly Sea Ice State Development

Changes in mean monthly concentrations of Class III and Class IV ice types between 1991 – 2000 and 2011 – 2020 in the focused area of interest are calculated and interpolated using bsplines. Changes in mean monthly sea ice concentration values for Class IV ice types are presented in tenths of total coverage (values range from 0 – 10) for all months (Figure 5).

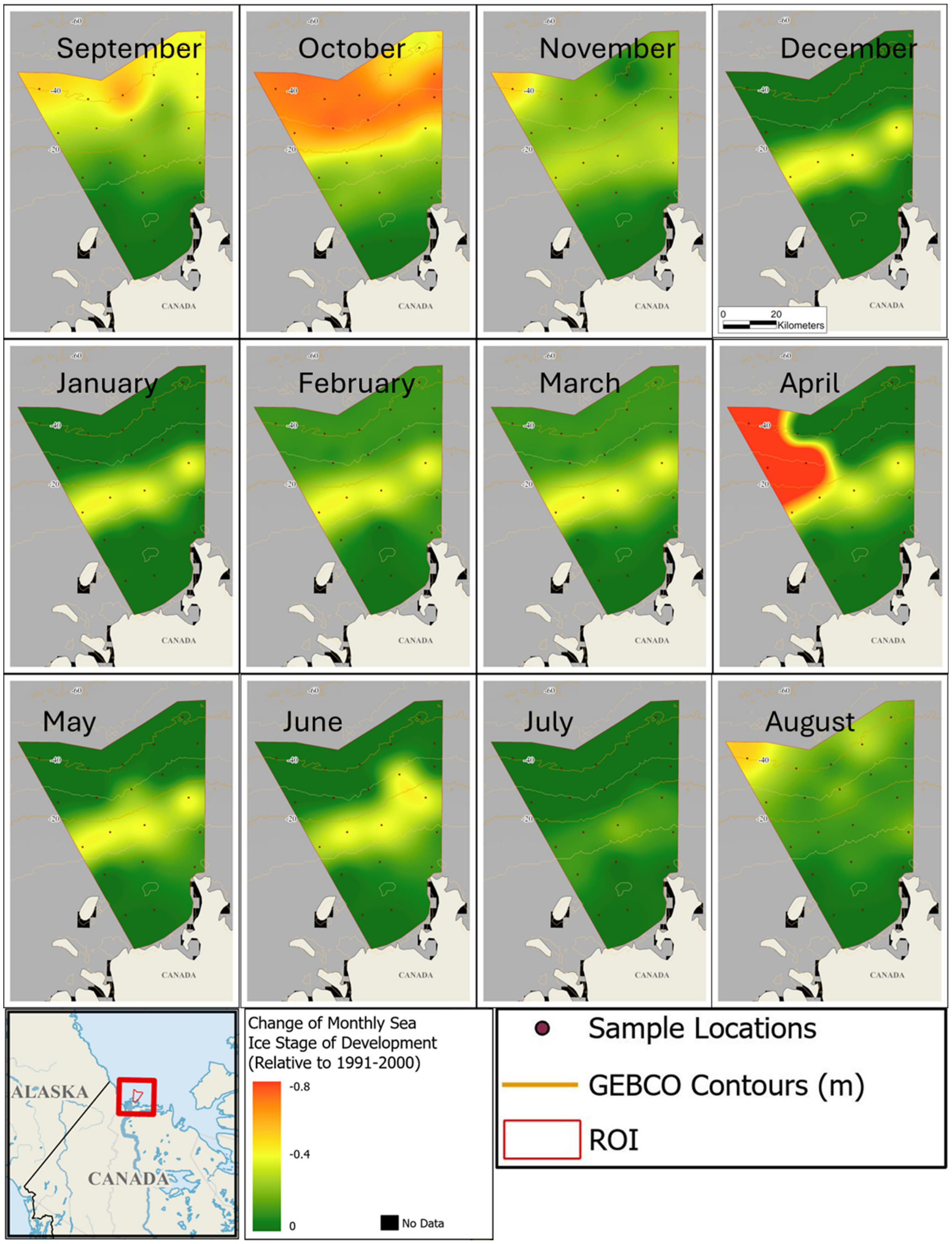

Figure 5. Change in mean monthly sea ice concentrations for Class IV ice (September to August)

Future Projections of Sea Ice Conditions in the Canadian Beaufort Sea

Projections under the RCP 8.5 scenario indicate a high likelihood of ice-free conditions (defined as <30% sea ice coverage) occurring in the southern Canadian Beaufort Sea towards 2060. The probability of such conditions exceeds 60% in August and September, ~50% in

October, and ~20% in November. Up to 75% of the natural variability in sea ice trends is linked to annual atmospheric fluctuations (Olonscheck et al., 2019), and atmosphere-ocean teleconnections influenced by tropical ocean anomalies (Screen and Deser, 2019). The uncertainty in predicting ice-free conditions is estimated at around two decades (Jahn, 2018).

The definition of 'ice-free' significantly impacts probability and timing estimates (Laliberté et al., 2016). Using a threshold of 5% ice area, there is a 50% probability that all Canadian regions will experience ice-free conditions in September by 2050 under the RCP 8.5 scenario, with the Canadian Beaufort Sea being ice-free in August and September. Increasing the open-water threshold to <30% ice area suggests more persistent ice-free conditions. Downscaled projections for the study area indicate that extended periods of <30% sea ice concentration, particularly during summer (June–October), will likely occur between 2045 and 2060, representing favorable conditions for future shipping operations.

Future Ice Mobility and Old Ice Intrusions

Coupled climate model predictions reveal a high degree of uncertainty regarding future wind patterns, making precise sea ice velocity predictions challenging. The projected decline in sea ice extent and concentration corresponds with an increased risk of old ice floes entering the region. These floes, originating from the last ice area (LIA) and circulating southward in the Beaufort Gyre, currently enter the shipping corridor occasionally, particularly from March to June. Between 2030 and 2045, the probability of such intrusions is expected to decline, with occurrences becoming rare by 2045–2060. When total sea ice concentration drops below 30%, remnant old ice floes will be more susceptible to wind forcing. However, transiting icebreakers and ships should be able to avoid them with relative ease.

Future Freeze-up Timing and Landfast Ice Formation

At present, sea ice begins forming in October and November, with young ice types rapidly thickening into first-year ice (Barber et al., 2010; Galley et al., 2016). Fast ice typically develops between December and February as first-year ice continues to thicken and deform. Future projections remain uncertain due to complex interactions between ocean heat fluxes, air temperatures, wind forcing, and freshwater discharge from the Mackenzie River. Sea ice concentrations are expected to remain at 9+/10 to 10/10 from December to July, with a 10% chance of old ice incursions between 2020 and 2030. By 2030–2045, freeze-up is projected to be delayed until November, with thin ice types persisting into December. The formation of fast ice will continue from December to February. By 2045–2060, freeze-up may be significantly delayed, with open water and thin first-year ice present well into late fall. Substantial freeze-up may only occur by late November, potentially delaying the development of extensive offshore landfast ice. Thin first-year ice cover could persist into December, introducing increased variability in ice extent and thickness.

The extent of the landfast ice zone between 2030–2045 and 2045–2060 is highly uncertain. While delayed freeze-up impacts landfast ice onset, the region is still expected to experience fully developed sea ice cover during winter (9+/10 to 10/10 ice concentration). Fast ice formation should continue between the 15–20 m isobath, though interannual variability in its extent and thickness may increase. The development of mobile winter pack ice due to prolonged easterly wind forcing (Asplin et al., 2021) or shifts in atmospheric patterns (Moore et al., 2018) could influence landfast ice formation, though impacts remain difficult to quantify.

Open Water Season Trends

Increasing trends in the duration of the open water season in the Canadian Beaufort Sea have been observed (Galley et al., 2016). However, the immediate area surrounding the study site does not exhibit significant trends in open water duration due to the continued presence of extensive landfast ice, which remains in place 30–40 km offshore in 9 out of 10 years. This increasing trend is expected to persist into 2030–2060, but the exact duration of the open water season will depend on multiple factors, including landfast ice breakup timing, wind-driven clearing of springtime ice and delayed freeze-up in the fall (Fissel et al., 2020).

The timing of landfast ice breakup will be influenced by the opening of the Cape Bathurst Flaw Lead, wind forcing (both magnitude and direction), solar insolation, air temperatures, ocean heat fluxes, and changes in the hydrological regime of the Mackenzie River. Variations in river discharge volumes and freshwater temperatures will impact landfast ice breakup timing. By 2045–2060, landfast ice breakup is expected to be affected, though mean changes will likely fall within historical interannual variability.

CONCLUSIONS

The impact of future sea ice conditions on shipping along the proposed route is based on regional and focused sea ice climatology (1999 – 2020) and projected ice conditions. The analysis considers an Arc7 LNG carrier with IMO PC3 ice navigation capabilities. The hypothetical corridor accounts for traditional subsistence activities and transportation patterns in Indigenous northern communities in Alaska (KAVIK-STANTEC, 2020; AF&G, 2021) and Canada, following federal guidelines from Transport Canada (Dawson et al., 2020), the U.S. Coast Guard, and the Russian Federation Coast Guard (IMO, 2017.

Projections for the Canadian Beaufort Sea indicate significant changes in sea ice conditions between 2030 and 2060, with increasing periods of ice-free conditions in summer and delayed freeze-up in fall. While uncertainty remains regarding future wind patterns and ice mobility, the likelihood of old ice intrusions will diminish over time. The persistence of extensive winter sea ice cover and landfast ice formation remains probable, though with increasing interannual variability. These findings provide critical insights for shipping operations, energy development, and environmental planning in the Arctic.

Projections for the Canadian Beaufort Sea from 2030 to 2060 indicate longer ice-free summers and delayed fall freeze-up, though extensive winter ice cover and landfast ice formation will likely persist with increasing variability. While future wind patterns and ice mobility remain uncertain, the likelihood of old ice intrusions will diminish over time. Seasonal shipping conditions are expected to improve (Wei et al., 2020), but risks remain from large, mobile multiyear ice floes, particularly those from the "Last Ice Area" (Moore et al., 2019), at least until mid-century when late summer ice free conditions will largely preclude the presence of old ice. These hazardous ice features may drift southward, posing ongoing navigational challenges. Interannual variability could still produce severe ice seasons. Additional uncertainty stems from evolving ocean-sea ice-atmosphere interactions, ocean heat fluxes, and shifting Arctic ice dynamics, now dominated by first-year ice. Continued research will be essential for informing Arctic shipping, energy development, and environmental planning.

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