University of Alaska’s Arctic Domain Awareness Center

Current Edition

Academic Analysis on the Feasibility of Shipping Liquefied Natural Gas From Alaska’s North Slope
Academic Analysis on the Feasibility of Shipping Liquefied Natural Gas from Alaska’s North Slope

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*Current Edition

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*Note: Current Edition is to indicate the Arctic Domain Awareness Center will continue to republish this report as needed if/when significant changes occur that affect the content and conclusions of this report
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OVERVIEW AND MOTIVATION

The Arctic Domain Awareness Center (ADAC) is a U.S. Department of Homeland Security (DHS) Science and Technology (S&T) Office of University Programs (OUP) Center of Excellence in Maritime Research, hosted by the University of Alaska. ADAC supports the U.S. Coast Guard (USCG) and other DHS maritime missions in order to improve capability for Arctic search and rescue, humanitarian assistance, disaster response, and security. This includes efforts to “enable the decision maker” across those mission sets.

A principal motivation for ADAC’s development of this paper, is support to the U.S. Coast Guard with knowledge products that help anticipate future aspects oriented to emerging dynamics of the Arctic. In accordance with current authorizations found in U.S. Code...of the USCG’s 11 mission areas, several include mandates for regulation and safety of Arctic petroleum exploration and maritime transport operations, chief among them are the Ports, Waterways and Coastal Security, Marine Safety, and Marine Environmental Protection missions.

Ports, Waterways and Coastal Security ensures the protection of valuable resources and infrastructure from terrorist attacks through the enforcement of security zones, conducting law enforcement boarding, and the development of security at waterfront facilities. Marine Safety includes licensing mariners, inspecting and documenting U.S. flagged vessels, and investigating marine accidents.

Marine Environmental Protection involves the development and enforcement of regulations to avert the introduction of invasive species into the maritime environment, prohibit unauthorized ocean dumping, and prevent oil and chemical spills.

In 2018, U.S. Coast Guard released a Maritime Commerce Strategic Outlook (MCSO) and in 2019, U.S. Coast Guard released an Arctic Strategic Assessment (ArcSo). These two documents guide U.S. Coast Guard’s strategic planning, policy and programming activities in the U.S. Arctic Extended Economic Zone (EEZ) of the Bering, Chukchi and Beaufort Sea regions. As discussed in both these strategic documents, advancing commerce in America’s ocean regions is in the national interest. As commerce (including marine transportation) is
an important aspect of America’s maritime spaces, thinking through the aspects associated in developing Arctic LNG shipping may become important for the U.S. Coast Guard to consider, study and plan.

Since the completion of the Trans-Alaska Pipeline System (TAPS) in the 1970s, Alaska’s North Slope petroleum has generated considerable energy to fuel American commerce, which has benefitted the North Slope Borough, the State of Alaska and the United States. While Prudhoe Bay and an array of subsequent oil fields on Alaska’s North Slope has delivered more than 18 billion barrels of oil, since there is no means yet to get the product to market, a vast amount of natural gas has yet to be accessed. ¹

While considerable discussions and developmental efforts have transpired to develop an natural gas pipeline to accompany the existing petroleum pipeline to access these untapped resources, the costs estimates are staggering and have yet to prove economically viable to proceed for governments and industry in developing an approximately 800 mile long LNG pipeline to parallel the existing TAPS.

Russia has provided a successful example that natural gas in the Arctic can be developed and brought to market. After considerable investment on the Yamal Peninsula on Russia’s Arctic shorelines, energy consortiums are now producing and delivering Liquified Natural Gas (LNG) to market and correspondingly, expanding commercial activities in the Arctic. Accordingly, LNG production and transport in the Arctic has proven feasible.

The purpose of this study is to analyze aspects of the Russian development efforts and assess corresponding application to Alaska’s North Slope, in order to help U.S. Coast Guard understand many of the facets that developers may face in addressing challenges and risks that face the safe transport of LNG through Alaskan Arctic waters. While it is true Russia proved LNG Arctic Shipping is feasible, it is important to understand the unique dynamics of operating LNG shipping across the U.S. Arctic EEZ and to discern suitable planning factors that face marine operators, potential hazards to flora and fauna and more as discussed in this paper.

¹ https://www.akrdc.org/oil-and-gas
EXECUTIVE SUMMARY

This study focuses on suitability and feasibility of near and mid-term Arctic shipping to transport Alaska’s reserves of natural gas (LNG), from northern Alaska to southern Alaska shipping lanes, within the United States Arctic Exclusive Economic Zone (EEZ) of the Beaufort, Chukchi and Bering Seas. The implications of diminishing ice in the Arctic reveal the potential feasibility to conduct partial or year-round Arctic shipping of LNG natural gas within the United States’ Arctic EEZs with the use of ice forecasting technology, port infrastructure development, and accompanying icebreakers.

The scientific community, maritime operators, and residents within the high north have consistently observed the reduction of Arctic sea ice at an accelerated rate (Mioduszewski et. al, 2019.) Several meters thick multi-year sea ice which less than 30 years ago greatly influenced the overall characteristics of the Arctic Ocean, is now greatly reduced and the summer retreat of sea ice is now routinely opening nearly ice-free waters for longer periods of time across the Bering, Chukchi and Beaufort Seas.

Accordingly, while once the practical usefulness of U.S. Arctic EEZ shipping routes in the Beaufort, Chukchi and Bering Sea regions, were constrained through a limited late summer season spanning from weeks to approximately two to three months, the impacts of recent and projected Arctic warming is resulting in improved confidence in forecasting summer seasons of significantly reduced sea ice. A shipping season of five months might be possible for icebreaking LNG tankers without need of icebreaker escort, similar to vessel traffic already transiting from Yamal across Russia’s Northern Sea Route.

This study provides a brief overview of the Yamal LNG project and the corresponding changes in shipping traffic and infrastructure development along the Northern Sea Route. Additionally, this study reviews the current infrastructure and physical conditions within the U.S. Arctic EEZ. Since Arctic sea ice can yet be unpredictable and the Arctic remains a remote, austere, and potentially hazardous region for shipping, this report includes the benefits and negatives of investing in Arctic shipping, economic opportunities beyond shipping LNG, and the ecological and sociological considerations involved.

Overall, Russia’s LNG activities on Yamal and shipment of product to market via Russia’s Northern Sea Route has demonstrated that LNG can be safely moved to market. Compared to the considerable distances of moving LNG from Yamal to East Asian markets, LNG shipping from the North Slope comprises significantly less time for mariners to negotiate transit in ice-laden waters, which reduces risk factors of operation and risk factors associated with providing any assistance by response forces. There are new and emerging aspect in understanding and characterizing the Arctic marine environment and corresponding decision support which will reduce challenges in safe transit in U.S. Arctic EEZ waters, and overall advances in domain awareness are improving. Communications and connectivity remain poor, and fine scale domain awareness remains a goal to be achieved, and not yet a reality to be enjoyed. Accordingly, gaining progress in these important mission
areas remains for research development, particularly in science and technology in order to continue to reduce risk faced by marine operators in the ice laden waters of the U.S. Arctic EEZ.

In addition to the details on LNG shipping in ice laden waters as is the principal focus of this study, important examination of the suitability of safe on-load stations off-shore in the Beaufort Sea need to be assessed with fine scale engineering detail. The shallow nature of the Beaufort Sea along the Alaska shoreline and the dynamics of sea ice that can quite dramatically be driven on shore, at times, several meters thick, are consequential engineering risks in designing and constructing a safe upload for LNG tankers to address and mitigate.

As such, while in sum, while many would concur using ice hardened vessels, supported by ice breaking escorts when needed, is technically feasible to transport LNG from the North Slope to market via marine conveyance across the Beaufort, Chukchi and Bering Seas (as discussed in this study) key questions remain about the economic feasibility based on the current supply & demand and the corresponding price per metric ton of LNG...which need to be examined by commercial parties.

Figure 2 An illustration of the variances of localized sea ice along the Alaskan Chukchi Sea Coast: Southwest of Point Barrow Alaska. Top: 13 June 2018, Bottom 15 June 2019.
INTRODUCTION

Prudhoe Bay was the first of what would become a considerable series of petroleum extraction developments across the North Slope of Alaska. As it became apparent that a remarkably large petroleum resource was available for extraction, developers needed to conceive a method to bring this product to market. Initially, developers considered delivery of North Slope crude oil to refineries via shipment aboard tankers (Rozell, 2013). A “proof of principal” delivery of the “golden barrel” of Prudhoe crude oil to market via the Northwest Passage of Canada, proved exceptionally slow and difficult, forcing developers to consider an alternative means of product conveyance (Rozell, 2013). Subsequently, the push to construct the Trans-Alaska Pipeline System (TAPS) was born out of the necessity of moving high volumes of crude oil to market, as the existing Arctic sea ice of the time was simply considered insurmountable to routinely negotiate.

While Prudhoe Bay and subsequent North Slope developmental efforts have delivered remarkable quantities of oil to refineries via TAPS, the amount of natural gas which accompanies the oil in the extraction process is largely returned to underground reservoirs. As such, while oil continues to flow from North Slope Alaska, natural gas remains an untapped resource of considerable scale. With the rising demand for natural gas from the growth of East Asian economies, the incentives to deliver North Slope gas to market are growing sharply. Responding to these energy demands, the Russian Federation, with the financial support of the People’s Republic of China (PRC), developed a Liquefied Natural Gas (LNG) facility at Yamal Russia. LNG is now being delivered via purpose-built ice breaking LNG Carriers to both European and East Asian markets along Russia’s Northern Sea Route. Using ice breaking escort when needed, the delivery of Russian LNG to the East Asian market has been made feasible in part due to diminishing sea ice along the Russian Coast. With the growth and successful development of Russian LNG shipping within the Arctic, commercial interest has developed in possibility of a similar delivery system for North Slope LNG (Brehemer, 2019).

Accordingly, ADAC student fellows with the University of Alaska Anchorage, supported by the Center’s staff, have developed and contributed to the following analysis on the feasibility of shipping Alaska’s North Slope Natural Gas through the U.S. Exclusive Economic Zone (EEZ) of the Beaufort, Chukchi and Bering Seas. The crux of this study is focused on the challenges of marine transportation across these ice-laden waters. This paper is not an engineering analysis of the sea-ice dynamics that need to be considered by shipping firms in assessing the kinds of hulls, hull strength, and vessel power plants needed to safely negotiate Arctic waterways. As an academic report, this analysis is likely insufficient in regards to determination on investment decisions towards the economic or commercial feasibility of an Alaskan North Slope LNG shipment system.

Based on received feedback on this academic paper, ADAC will consider if chartering a similar analysis in needed shipping terminals and associated port facilities along the North Slope would be a useful endeavor.
ADAC’s inspiration for providing this paper is tied to the development of tools that can aide mariner decisions in reducing risk in conducting shipping through ice laden waters of the U.S. EEZ, and that is the development and transition of a modeling system that characterizes sea ice parameters across the Arctic region and the onward development of an Arctic Ice Conditions Index that will be useable by vessel masters in deciding when and where to steam in ice-laden conditions of the Beaufort and Chukchi Seas. The development of these models and decision support tools, and through analysis of the region in which these tools are characterizing conditions at finer scale, indicate to ADAC, in an overall practical sense, the physical characteristics of the U.S. Arctic EEZ is continuing a trajectory of diminishing ice conditions for increasingly important periods of time, that may prove beneficial to shipping of commodities from the North Slope of Alaska to markets in lower latitudes.

Accordingly, and as a matter of note to this introduction and in support of USCG Arctic Domain Awareness, the public good and in order to support mariner decision making in assessing routes and determining risk in steaming in the ice-laden waters, the Arctic Domain Awareness Center has developed and transitioned a High-resolution Ice-Ocean Modeling and Assimilation System (HIOMAS) to provide routine hind cast and forecast of Arctic sea ice. HIOMAS precision modeling of ocean currents, sea ice presence, movement, and ridging of the Circumpolar Arctic has achieved 2 Kilometer (KM) accuracy. A 1 KM resolution edition is in late development by the HIOMAS Principal Investigator. HIOMAS is operating at Axiom Data Sciences, the accredited data computational center, and published on a bi-weekly basis with 7 day hindcast and 30 day forecast through the Alaska Ocean Observation System (AOOS), a National Oceanic and Atmospheric Administration (NOAA) Affiliate, accessible to Alaska Regional National Weather Service, NOAA’s Arctic Environmental Response Management Application (Arctic ERMA) and the U.S. National Ice Center (USNIC).

An additional mariner decision support tool in making specific route of steam across ice laden regions of the U.S. Arctic EEZ, based on the size/class of the vessel, is now in development at ADAC. This is the Center’s Arctic Ice Conditions Index (ARCTICE). This new product is being developed in coordination with HQ U.S. Coast Guard (USCG) Waterways Management, USCG District 17, USCG Research and Development Center, and USNIC. With a planned delivery by June 2021, ARCTICE will provide a series of numeri’s and a corresponding visualization of sea ice conditions (leveraging either HIOMAS or U.S. Navy Research Lab’s sea ice modeling system) as environmental data, cross referenced against 10 distinct vessel classifications. Similar to HIOMAS, ARCTICE is planned to be operated by Axiom Data Sciences and published through AOOS, to be available to a number of customers, including the U.S. National Ice Center. ARCTICE will include an interactive capability for individual mariner calculation via a web-portal.
**PROBLEM STATEMENT**

Is the Alaska Arctic maritime EEZ feasible for Liquefied Natural Gas from Arctic North Slope to market? Based on a warming Arctic, which is reducing the extant and thickness of sea ice in the Beaufort, Chukchi and Bering Seas, a longer shipping season is already being realized, and is projected to continue these factors. Further, through advancing higher fidelity Arctic domain awareness and associated decision support, shipping companies, and vessel masters are realizing increased knowledge in understanding safety of steaming and routes that are likely favorable over others within the US Artic EEZ. Based on warming patterns it is likely that extended seasons of such shipping will be available near term, and considerably greater extended seasons are likely achievable in the mid to longer term. The safety, feasibility, and suitability of Arctic shipping is enabled via icebreaking support or potentially via transport vessels themselves suitable to negotiate ice thicknesses associated known and forecast mean thickness levels of the US Arctic EEZ.

Fully answering the problem requires assessing the current and forecast Arctic Domain, understanding polar region icebreaking factors, vessel design, power plant capability, and the availability of icebreaking to assist when forecasts are in error, resulting in a vessel incapable of negotiating thicker than planned sea ice.

Additionally, but not associated with this study, is a needed cost analysis associated with establishing LNG shipping within the US EEZ to the cost of constructing a Trans Alaska LNG pipeline parallel to the existing TAPS. While it is widely reported in the media that a LNG pipeline would cost more than $50B to construct, there is yet to be publicly available cost estimates of creating the LNG handling facilities on the Alaskan North Slope and Beaufort Sea coasts along with the costs for the number of ice hardened LNG vessels, and associated support commercial ice breakers needed to move product to market.

**ARCTIC LNG: CHALLENGES AND OPPORTUNITIES**

While estimates vary, roughly 30% of the world’s remaining natural gas reserves are expected to lie within the Arctic region (Arctic Council, 2009). While commercial operations face significant challenges from the inhospitable Arctic environment, the coldness of the Arctic presents unique advantages for the natural gas liquefaction process. In order for natural gas to be condensed into its shippable and storable form, Liquefied Natural Gas (LNG), natural gas must be cooled to at -161.6 C (Schmidt, 2013). As the Arctic has colder ambient temperatures, less energy is required to cool and liquify natural gas (Schmidt, 2013) (Jackson et al., 2017) (Bukowski et al, 2016). As the liquefaction process is more energy efficient, Arctic-based LNG facilities can increase their LNG production as average temperatures drop through the long Arctic winter (Schmidt, 2013) (Jackson et al., 2017) (Bukowski et al, 2016). This gives Arctic LNG facilities a distinct advantage over facilities that operate in higher ambient temperatures such as facilities in the Middle-East or Australia (Jackson et al., 2017). Despite this advantage, the cold of the Arctic presents additional challenges to LNG infrastructure, raising the overall cost of development and possibly
limiting the economic benefits of increased production (Mokhatab, 2017) (Bukowski et al. 2017). While the winter season may present Arctic based LNG facilities with an opportunity to increase production, LNG producers must then overcome the logistical challenge of shipping their product to market when sea ice is at its maximum winter extent (Mokhatab, 2017).

**YAMAL LNG PROJECT**

With the Yamal LNG project, operators within the Russian Federation have strategically crafted processes and methods to capitalize upon the substantial economic opportunities inherent in Arctic LNG development. That project, based in the Yamal Peninsula in Western Siberia along the Arctic Ocean Coast, extracts natural gas from the reserves of South Tambey Field. The field’s capable and proven reserves are estimated to be around 926 Billion Cubic Meters (BCM) and production from Yamal is expected to become half of Russia’s total LNG output by 2030 (International Gas Union [IGU], 2019). The total cost of the extraction project is estimated to be 27 Billion USD with the Russian gas company Novatek serving as the primary investor and operator (50.1%) (Yamal LNG). The project is also receiving significant financial support from French oil and gas multinational Total S.A. (20%) (Yamal LNG). The People’s Republic of China (PRC) also has a significant stake in the project as 20% of the project’s total funding comes from the China National Petroleum Corporation and the Silk Road Fund (9.9%) (Yamal LNG). As the Silk Road Fund is a Chinese state owned investment fund created to implement the One Belt, One Road Initiative of the PRC, this investment signals that Chinese policymakers perceive the Yamal energy project and Russia’s development of Arctic energy resources as important to China’s wider trade and economic ambitions (Office of the Under Secretary of Defense for Policy [DoD], 2019).

The Yamal LNG project is the result of the coalescence of multiple factors. Not only does the project help to meet the growing demand of LNG within both the European and East Asian markets, it is poised to significantly increase the Russia’s share of the global LNG market. In 2018 Russia was the sixth largest producer of LNG in the global market (IGU, 2019). With the production of LNG from Yamal LNG, Russia is expected by the International Gas Union to surpass Nigeria and Malaysia to become the fourth largest producer of LNG in the world (IGU, 2019).

In order to develop the infrastructure for natural gas extraction and shipment, the Yamal LNG project had to overcome numerous logistical and environmental challenges. As the site was far from existing transportation infrastructure, a new airport and seaport were constructed (Hannon, 2018). To develop this infrastructure, including power plants and the LNG processing facility itself, developers opted for a modularized approach to the project’s construction as much of the building components were built simultaneously at different construction yards in East Asia and later shipped to Yamal Peninsula (Hannon, 2018). Overall, this allowed for construction to proceed more quickly to compensate for shorter construction seasons imposed by the Arctic winters, while reducing the overall cost of Arctic infrastructure development (Hannon, 2018).
In order to maximize the commercial potential of the project, the new Port of Sabetta, built to support the Yamal LNG project, would need to remain accessible to LNG carriers year-round (Hannon, 2018). Therefore, several sea-ice mitigation measures were adopted. Two ice protection barriers, each between 1,800 and 2,000 meters long, were constructed to protect the main jetties from currents and drift ice (Hannon, 2018). An additional challenge is the formation of “brash ice.” As ice grows back quickly after in the wake of each passing icebreaker, port channels can become clogged with ‘brash ice’ which reforms thicker than the surrounding naturally formed level ice (Riska et al. 2014). Therefore, multiple lanes were established to distribute vessel traffic in the port approach channel and reduce brash ice formation (Hannon, 2018). An additional Brash Ice Management System (BIMS) was considered as well, which uses excess heat energy from the facilities power plant to heat the water near the port (Hannon, 2018). While this system was not employed at the scale of Yamal, it has been employed successfully at Finnish ports in the Baltic Sea and could be scaled for use at future LNG terminal projects in the Arctic (Hannon, 2018). Finally, the port also retains a dedicated support fleet with a port icebreaker and several icebreaking and escort tugs (Hannon, 2018).

Perhaps the most critical component of the project is the use of ice-breaking LNG carriers. Novatek has ordered and received 15 specialized Arctic LNG carriers for the Yamal Project and has plans to order up to 42 more to support Yamal and other projects within the Russian Federation (Humpert, 2020). Classified by the Russian Maritime Register of Shipping as Arc7 ice-class, these vessels are roughly equivalent to the International Association of Classification Societies’ (IACS) Polar Class 3 rating and are capable of breaking through ice as thick as 2.1 meters (Gosnell 2018) (Yamal LNG, 2020). Therefore, they are suited for unescorted navigation in the Arctic during the summer and autumn months and are capable of transiting through first year ice during the winter and spring months (Russian Maritime Register of Shipping, 2019). Featuring anti-icing and de-icing capabilities as well as specialized ballast and piping systems to prevent freezing, these vessels are specifically designed to address the unique operational challenges in the Arctic (Gosenell 2018).

While Arc7 class LNG carriers servicing Yamal are capable of completing year-round deliveries to the European market without an icebreaking escort, they are only able to complete deliveries for the East Asian market during the summer shipping season (U.S. Committee on the Marine Transportation System [USCMTS] 2019). This limits their total operational window eastbound along the Northern Sea Route to 92 days total (USCMTS, 2019). To enable more deliveries to the Asian market, Novatek has announced plans to build a new transshipment LNG hub on the Kamchatka Peninsula (Maritime Executive, 2018). When the facility is complete in 2022, LNG carriers from Yamal will have a shorter eastbound travel time along the Northern Sea Route, enabling more unescorted trips during the summer navigation season. LNG would then be stored at the transshipment facility and transferred to conventional carriers that could complete year-round shipments from the Kamchatka Peninsula to the East Asian Market (Maritime Executive, 2018).
THE NORTHERN SEA ROUTE

Since the first shipments of LNG in 2017, The Yamal project is already increasing traffic along the Northern Sea Route (USCMTS, 2019). With additional shipments to the East Asian Market, Russian LNG projects in the Arctic are expected to increase traffic within the Bering and Chukchi, along the border with the US Arctic EEZ (USCMTS, 2019). The U.S. Committee on the Marine Transportation System projects that the Yamal project could add one additional vessel to traffic within the Bering Sea every 1-2 years with vessels crossing the Bering Strait sixty to sixty-four times during the summer operational window (USCMTS, 2019). With a transshipment facility at Kamchatka, Russian LNG carriers could transit the Bering Strait between seventy-six and ninety times within the summer operating season (USCMTS, 2019). This sharp upward trend of increased large vessel traffic in the Bering Sea from the Northern Sea Route continues as number of unique vessels transiting the Bering Strait has increased by 128% since 2008 (USCMTS, 2019).

Despite much shorter transit times, international maritime shipping companies have not regularly utilized the NSR as an alternative to the Suez Canal route for shipping cargo between Asia and Europe (Gosnell 2018) (Shibasaki et. al., 2018). In 2018, the international shipping company Maersk, conducted a trail passage through the NSR and concluded the route was not a commercially viable alternative to traditional routes (USGAO, 2020) This is in part due to vessel operator’s unfamiliarity with the challenges of the Arctic domain, more stringent environmental regulations for operators, and limited infrastructure along the NSR (Shibasaki et. al., 2018). Additionally, the relative volatility of the Russian Ruble in currency markets in recent years has made operational expenses within the NSR less predictable and cost effective (Shibasaki et. al., 2018). In order to meet these challenges, the Russian government is apparently committed to investing in the region’s transportation infrastructure. These investments include four new regional airports, new Arctic railways and ports, and additional icebreakers to support winter commercial operators (Staalesen, 2019). Russian President Vladimir Putin has made declarations of increasing Arctic shipping a national priority, setting annual shipment goals along the NSR of 80 million tons by 2024 and 90 million by 2030 (U.S. Government Accountability Office [USGAO], 2020) (Staalesen, 2019). The Russian Ministry of Natural Resources has determined a total of €143 billion in private investment in resource extraction and infrastructure projects will be needed to meet this goal (Staalesen 2019). While traffic through the NSR is expected to grow significantly in the coming decade, it is projected to fall short of the Russian President’s goals (USCMTS, 2019) (USGAO, 2020).

US ARCTIC EEZ DOMAIN ASSESSMENT

The core issue in assessing the viability of Alaskan North Slope LNG Arctic Shipping is based on the ability of safe transit of vessels throughout the Ice laden waters of the Beaufort, Chukchi and (and to a somewhat lesser extent) Bering Seas. Therefore, knowing the changes of sea ice throughout the year and having acceptable precision in an operational
forecast of sea ice are critical to understand and to decide both physical viability of transit and the commercial feasibility of the project.

**Ice Changes throughout the Year:**

During the past 40 years, the overall area of Arctic sea ice has declined by approximately 2 million square kilometers (772,204 miles) (Bintanja, 2018). On average, the summer sea ice extent has declined more than 40 percent since 1979, and to a lesser extent during the rest of the year (Mioduszewski, 2019). As a result, some regions are experiencing an annual ice coverage reduction of up to three months (Mioduszewski, 2019). While winter sea ice is also declining significantly, ice within the Arctic basin, through which a future Transpolar Sea Route could pass, has been relatively steady and has not yet exhibited significant loss (Humpert, 2012) [Authors note, this is less true today in 2020, based on simply observing pan-Arctic ice conditions in the 8 years since Humpert’s publication]. In contrast, the largest summer Arctic sea ice loss has primarily been along the coasts of Russia and North America (Humpert, 2012) (Bintanja, 2018). However, predictions point to completely ice-free Arctic summers later this century (Mioduszewski, 2019).

![Image](image.png)

*Figure 3* Summer sea ice coverage vs. the winter sea ice coverage to date.

**Note:** The images in Figure 3 show the minimum ice on September 19, 2018 (left) and the maximum amount of sea ice on March 24, 2019 (right). The higher concentrations appear white, and the lower concentrations of ice range from light to dark blue. The yellow line indicates the 1981-2010 median extent for these dates, demonstrating sea ice loss over the last four decades. Image/photo courtesy of the National Snow and Ice Data Center.
Furthermore, the rate of decline of Arctic sea ice volume is approximately double that of ice area resulting in reductions to overall ice thickness (Mioduszewski, 2019). As ice thickness diminishes, it is expected to become more vulnerable to fluctuations in climate variables, and thus, easier to melt and reform (Mioduszewski, 2019). Sea ice older than four-years-old made up 33% of the March ice pack in 1985 but only 1.2% in March 2019 (National Oceanic and Atmospheric Administration [NOAA], 2019)². Retreating from the Alaskan and Eastern Russian coasts, the bulk of the older pack rests along the coast of Greenland Canadian Arctic Archipelago (NOAA, 2019).

As multi-year ice packs begin to disappear within the Arctic, the younger ice that covers much of the Arctic Ocean is thinner and more vulnerable to disruption from environmental conditions. Increasingly severe winter storms across the U.S. Arctic region are producing winds and turbulent conditions that breakup the icepack, leading to previously unseen open water in both the Bering and Chukchi Seas (National Oceanic and Atmospheric Administration [NOAA], 2019). Dramatic examples of the extent of diminishing sea ice in the U.S. Arctic EEZ have been observed in the winters of 2017-2018 and 2018-2019, which provided remarkably significant areas of open water in the Eastern Bering and Chukchi Seas (NOAA, 2019). Variations in seasonal melting and increased open water have made ice floes less predictable as melting one-year ice can release large blocks of multi-year ice which can present an obstacle for maritime traffic (Gosnell 2018).

Within the U.S. Arctic EEZ, sea ice coverage and extent ranges considerably between the Arctic Ocean and Bering Sea. Average seasonal sea ice extent in the Beaufort Sea ranges from 9% water surface area coverage in September to 98% of total surface area coverage at maximum extent (Adams & Silber, 2017). On average, ice maintains 75% or greater surface area coverage for nine months out of the year in the Beaufort Sea (Adams & Silber, 2017). Seasonal sea ice extent maximums and minimums are similar in the Chukchi Sea although the period of 75% coverage is shorter with six months (Adams & Silber, 2017). The Bering Sea experiences less ice coverage with 26% surface area coverage at the seasonal height in March and only two months experience 25% coverage or more (Adams & Silber, 2017).

Overall, sea ice has declined substantially throughout the Arctic basin. ADAC research and sea ice modeling within the U.S. EEZ highlights that the Bering Sea's frequency of ice-free conditions continue to increase. Recent winters have provided what would likely be described as a marginal ice zone (particularly the southern Bering Sea). As a result of substantial research into ice growth and movement ADAC’s HIOMAS and other Arctic sea ice models now describe the existing Arctic sea ice environment with increasing fidelity, leading to decreased risk.

Regional Accessibility for Maritime Traffic: Current and Future

The reduced ice extent navigation seasons within the U.S. Arctic EEZ differ greatly between Alaska’s Arctic seas. The Beaufort Sea is only accessible for vessel activity from July through September (Adams & Silber, 2015). The Chukchi Sea has a wider window of operations with vessel activity from May through November (Adams & Silber, 2017). Currently, barges and bulk carriers restrict transits within a window from June to October (Adams & Silber, 2017). This means a limited operational window for resource extraction operations within the U.S. Arctic EEZ. Red Dog Mine operates a port along the Chukchi Sea 20 miles south of Kivalina and can only receive supplies or ship product to market for approximately 100 days out of the year (Teck Resources Limited, 2017).

With reductions in summer season ice extent, regional operators have steadily grown their summer operating season within the US Arctic EEZ. In September 2019, The U.S. Committee on the Marine Transportation System submitted its updated “Ten-Year Projections of Maritime Activity in the US Arctic, 2020-2030.” The report details current levels of vessel activity as well as projections of future vessel traffic within the Arctic based on economic, political, and physical factors. The Committee’s “Most Plausible” scenario estimates that 377 unique vessels could be operating within the U.S. Arctic EEZ by the end of the decade (USCMTS, 2019). This would be an increase of 50% over current levels and 200% over 2008 (USCMTS, 2019). These trends would be in line with the growth of the summer navigation season over the past decade. Based on vessel activity data from the last ten years, the summer reduced ice extent vessel transit season in the U.S. Arctic EEZ has grown on average 10 days per year, from 144 days in 2010 to 200 days in 2018 (Adams & Silber, 2017) (USCMTS, 2019). While reductions in sea ice extent during the summer months enables more vessels to access the Arctic, expectations for continued growth are also based on increased economic activity within the Arctic in general (USCMTS, 2019) (Adams & Silber, 2017).

Current US Arctic EEZ Infrastructure

Current physical infrastructure within the U.S. Arctic EEZ is deficient for handling regular large vessel traffic (USGAO, 2020). (USCMTS, 2019). Overall the region lacks the infrastructure typical of a modern maritime transportation system (USGAO, 2020). Not only is physical infrastructure within the region limited, but there are significant gaps of information and monitoring capability of physical and environmental conditions within the U.S. Arctic EEZ (USGAO, 2020) (USCMTS, 2019). These limitations, coupled with the region’s remoteness, make operations within the region challenging and expensive (USGAO, 2020).

Currently, there is no U.S. deep-water port within the Beaufort and Chukchi Sea capable of supporting large vessel traffic. The closet U.S. deep-draft port in the region is Dutch Harbor in the Aleutian Islands which is roughly estimated (depending on routing) at approximately 1,535 nautical miles from Barrow Harbor in Utqiagvik, Alaska (USGAO, 2020) (USCMTS 2019.) In addition, there are no ports along the Bering Strait that are capable of servicing or
refueling large cargo or tankers (USCMTS, 2019). The closest large commercial vessel refueling station is also located in Dutch Harbor. There are also no facilities capable of handling waste disposal from increased commercial traffic within the region (USCMTS, 2019). While ports and facilities could be built, communities along the Bering Sea and Arctic Coast already face significant challenges with safe and environmentally responsible disposal of locally produced waste (Zender Environmental, 2015). Finally, as of this date, the United States has not designated any locations along the Alaskan EEZ coast as a ‘Harbor of Safe Refuge,’ meaning that vessel operators within the region currently assume the increased risk of not having any predefined areas to take shelter in the event of severe weather or other incidents (USGAO, 2020) (USCMTS, 2019). Although the U.S. Coast Guard has identified Port Clarence as a potential future port of refuge in the Arctic, the USCG has yet to make any official declaration for the site (USGAO, 2020) (USCMTS, 2018).

There are also significant challenges to Search and Rescue (SAR) operational ability within the U.S. Arctic EEZ. The nearest U.S. Coast Guard Air Facility is located on Kodiak Island, meaning incident response times to the Arctic are much slower compared to other coastal regions with the United States (USCMTS, 2019). In order to enhance the U.S. Coast Guard’s operational ability, the USCG forward deploys helicopters from Kodiak to Cold Bay and St. Paul Island to correspond with commercial fishing operations within the Bering Sea (USCMTS, 2019). The USCG has periodically maintained seasonal forward operating locations at Utqiagvik, Kotzebue, and Deadhorse during the Arctic summer (USCMTS, 2018). As a part of Operation Arctic Shield, the USCG forward deploys two MH-60T Jayhawks to Kotzebue and deploys USCG cutters to support SAR efforts throughout the Arctic (Smith, 2017) (USGAO, 2020). Although far from the Arctic domain, additional SAR support can be provided to the region through the Alaska Air National Guard, United States Air Force, and United States Army (Smith, 2017). Three search and rescue squadrons with the Alaska Air National Guard are stationed at Eielson Air Force Base in Fairbanks, Alaska and Joint-Base Elmendorf Richardson in Anchorage, Alaska and are often deployed to SAR efforts across Alaska (Smith, 2017). As SAR assets are stationed far from the Arctic, fuel consumption limits the duration and distance SAR resources can operate (Smith, 2017). The great distance and severely limited fueling facilities make sustained operations and Mass Response Operations (MRO) dependent on local sources of fuel or the deployment of forward arming fuel points (FARP) (Smith, 2017). Despite this, local SAR assets are available to assist with SAR operations. As an example, the North Slope Borough maintains a Sikorsky S-92 helicopter and SAR crew capable of effecting long-range offshore response operations (Smith, 2017).

Coupled with the lack of physical infrastructure, U.S. federal agencies and commercial operators face a significant lack of information about conditions within the region. Only 4.1% of the U.S. Arctic bathymetry is in keeping with modern international standards (USGAO, 2020) (Committee on Transportation and Infrastructure, 2018). Additionally, only 12,882 miles of the 33,900 miles of Arctic Alaskan shoreline has been mapped using modern methods (USCMTS, 2019). The Arctic and Western Alaskan coast have significant gaps in
water level monitoring infrastructure that significantly impedes the ability for coastal communities and mariners to monitor coastal flooding (USCMTS, 2019). There are also significant limitations in weather forecasting; NOAA weather forecasts for the Arctic are only predictive for two to three days in advance compared to five to seven days within the rest of the United States (USCMTS, 2019).

Operations planning complications stemming from the poor fidelity of environmental monitoring and coastal bathymetry are compounded by severe communications limitations within the region. Options for satellite communications providers become severely limited above 70° and the region has inadequate telecommunications infrastructure (USGAO, 2020) (Smith, 2017) (USCMTS, 2018). While stations at Utqiagvik and Nome are capable of transmitting real-time weather observations, stations in Western Alaska often lack internet and power stability (Kettle et. al, 2019). Although USCG ship-based radar and land-based NOAA stations are capable of collecting some information about weather and ice conditions, they are restricted in their ability to communicate information between users as low bandwidth forces users to keep data packages small (Kettle et. al, 2019).

Lack of infrastructure and information make operations within the U.S. Arctic EEZ expensive and cost prohibitive for many operators (USGAO, 2020). Without improved SAR capabilities, insurance rates are expensive and often vary between insurers and shippers (USCMTS, 2019). In order to improve insurance rates, residents and commercial interests within the region have called for a unified regime of insurance rates for operators within the Arctic (USCMTS, 2019). With standardized insurance rates for the region, the cost of doing business within the Arctic would be more predictable and more commercial activity could be incentivized within the region (USCMTS, 2019). Although the Federal government has made progress in addressing gaps in infrastructure within the U.S. Arctic EEZ, a report from the U.S. Government Accountability Office found that these efforts lacked coordination and possibly missed opportunities to affect a broader outcome (USGAO, 2020). Managing structures meant to unify federal policy in the region like the 2013 National Strategy for the Arctic Region document are now outdated and the governing bodies like the Arctic Executive Steering Committee are currently inactive (USGAO, 2020). Without defined roles or active management, federal agencies developed projects to address infrastructure concerns often competed with one another for funding (USGAO, 2020). Ultimately the report recommends that the Federal Government should perform a new assessment of the risk imposed by infrastructure gaps to the environmental, societal, and economic system of the U.S. maritime Arctic (USGAO, 2020). This assessment would then inform a new interagency strategy, developed by the Executive Office of the President, which will identify priorities and goals for future infrastructure investment in the U.S. Arctic EEZ (USGAO, 2020). As the report notes, a high degree of interagency coordination with concrete performance measures are necessary to ensure government-wide objects are met and continuity of policy is preserved as Executive Administrations change (USGAO, 2020).
Precision advance in assessing domain awareness: HIOMAS

In order to assess viability of Arctic shipping from the North Slope of the Arctic coastline, it is crucial that decision makers be provided environmental factor awareness with reasonably high fidelity in order to accurately account for risk. The Arctic Domain Awareness Center has recently completed and transitioned a model with the overall highest known precision to date, and is but one such tool, useful for such decision making. ADAC’s High-resolution Ice-Ocean Modeling and Assimilation System (HIOMAS) simulates and predicts sea ice and ocean currents in the Arctic Ocean (figure 4). This system is calibrated and validated using a range of available sea ice and ocean observations. HIOMAS is used for near real-time

Figure 4 ADAC’s HIOMAS at 2 KM resolution Circumpolar Arctic
hindcasting and daily to seasonal forecasting of Arctic Ocean currents, sea ice, and other environmental changes. The research accounts for: (1) the prediction of spatial distribution of ice motion and thickness, (2) the fraction of thick-ridged or multi-year ice, and (3) the retreat and advance of ice edges. These are the sea ice factors that are most relevant to Arctic operators.

Accurate high-resolution prediction of ocean currents and sea ice conditions enhances accurate decision making by shippers in deciding overall viability of shipping, and then, if/once a decision to proceed with the investment, HIOMAS can support specific voyage determination (timing and route of steam). The prediction data supports other stakeholder’s decision-making in planning and management of economic activities. In addition, the data is useful for other modeling efforts, such as oil spill and wave modeling. An inherent strength of HIOMAS is the ability to generate high precision models of sea ice thickness, the movement of ice, and ocean currents across the Arctic Ocean. Recent ADAC research concentrated on integrating validation of modelling and integrating HIOMAS into a modelling service accessible to USCG operations in order to aid in predicting Arctic sea ice and currents on daily to seasonal time scales.

As described in detail in ADAC’s Annual Program Year 5 report, the Center coordinated model destination for HIOMAS to Axiom Data Sciences which supports the Alaska Ocean Observation System (AOOS), a National Oceanic and Atmospheric Administration (NOAA) Affiliate located in Anchorage Alaska. The 2 km resolution HIOMAS was transitioned to Axiom so that Axiom can continue to provide HIOMAS support to the U.S. Coast Guard, NOAA, National Weather Service, and Arctic commercial and private interests (in support of the public good). In June 2019, ADAC’s 2 km resolution HIOMAS software was installed in an Axiom computer cluster, together with various data preprocessing and post-processing routines and scripts. These routines and scripts were modified so as to allow weekly hindcast and forecast. After that, a number of hindcast and forecast test runs were conducted on Axiom computer cluster, obtaining the expected results. HIOMAS modelling is now generating 2km resolution pan-Arctic hindcast and forecast weekly, producing one week of hindcast results and one month of forecast results.3

HIOMAS provides Arctic shippers a robust numerical tool useful to assess high-resolution hindcast and forecast of Arctic sea ice and ocean currents. This is done by modeling and publishing HIOMAS on a customer driven schedule at 2 KM resolution pan-Arctic and 1 KM resolution for the U.S. Arctic Extended Economic Zone (EEZ) in the Chukchi and Beaufort Seas. In regard to 1 KM HIOMAS, ADAC, planned and experimented to create a higher precision focusing on the U.S. Arctic EEZ,) i.e., the Alaska waters in the Beaufort and Chukchi Seas). Focusing on such a subset region of the Arctic may allow HIOMAS to achieve

3 See Arctic Domain Awareness Center Website for details on Center Annual Reports at https://www.arcticdomainawarenesscenter.org and/or call, Center personnel at 907 786-0708.
even higher horizontal resolution. ADAC has planned to target this refinement on 1 km resolution (figure 5).

The Center developed and tested the 1 km resolution HIOMAS, which runs well. However, research so far has found that the 1 km resolution HIOMAS for the U.S. Arctic EEZ is particularly challenging because of the uncertainty of relatively long model open boundaries around a small model domain (the U.S. Arctic EEZ). As a result, the model created sea ice thickness has not yet met the specified performance metrics.

ADAC respectfully notes that no high resolution (< 4 km) models have previously been used for daily to seasonal forecast of Arctic sea ice and currents.

HIOMAS involves expert mathematical modeling of the Arctic Ocean to obtain sea ice thickness and sea ice and ocean current movement using atmospheric forcing data and satellite provided data. Research project developed HIOMAS from the Pan-arctic Ice–Ocean Modeling and Assimilation System (PIOMAS, Zhang and Rothrock, 2003). PIOMAS is a well-established modeling and assimilation system with advanced sea ice and ocean model components and is capable of assimilating satellite derived sea ice concentration. Its realistic sea ice output is widely disseminated and recognized worldwide by scientists, sea ice enthusiasts, interested bloggers, media organizations, and government officials.

Developed based on PIOMAS, HIOMAS has a much higher horizontal resolution than PIOMAS, now achieving 2 km resolution for the entire Arctic Ocean. Such high resolution is essential to improving the prediction of sea ice concentration, thickness, motion, and ocean
circulation. Due to the increased resolution, many of the model parameters may need adjustment in areas such as ice strength and ocean viscosities. A key adaptation for HIOMAS was integrating forecast atmospheric forcing from the NOAA National Center for Environmental Prediction (NCEP) Climate Forecast System (CFS) into HIOMAS.

NOAA’s CFS consists of coupled atmosphere, sea ice, and ocean model components with data assimilation. The CFS forecast ranges from hours to months: there are a total of 16 CFS forecast runs every day, of which four runs go out to nine months, three runs go out to one season, and nine runs go out to 45 days. These runs all created 6-hourly forecasts of atmospheric data that are widely accessible in real time, and thus ideal for forcing the HIOMAS forecast. Using the CFS forecast forcing, the researcher conducted daily to seasonal forecast experiments on a monthly basis. Forecasts can be initiated more frequently if emergencies occur in the Arctic that need a rapid response. Forecast results will help the researcher investigate and potentially answer previously stated science questions.

The science review for this project is extensive. U.S. National Ice Center (USNIC) provides short-term numerical forecasts of sea ice extent and concentration using the Polar Ice Prediction System (PIPS), combined with satellite observations (Cheng and Preller, 1999). PIPS use forecast forcing from an atmospheric forecast model to drive a coupled ice–ocean model to predict the future state of the ice cover days in advance.

PIPS was later replaced by the Arctic Cap Nowcast/Forecast System (ACNFS). Most recently, ACNFS was replaced by the Navy’s Global Ocean Forecast System (GOFS), developed at the Naval Research Laboratory at the Stennis Space Center (NRL-SSC). Like the PIPS and ACNFS models, GOFS also consists of a coupled ice–ocean model driven by forecast forcing from an atmospheric forecast model. Scientists at the NRL-SSC have been conducting hindcasts and short-term and seasonal forecasts of Arctic sea ice using GOFS3.1. In addition, the Canadian Ice Service is also providing short-term forecasts of sea ice in Canada’s navigable waters.

After the dramatic retreat of Arctic sea ice during the summer of 2007, the U.S. SEARCH and the European DAMOCLES programs recommended a community-wide prediction effort — the September Arctic Sea Ice Outlook. The focus of the Outlook is on the area of the overall Arctic sea ice extent and hence different from the focus of HIOMAS forecast. This effort has been ongoing since 2008 with increasing participation (Stroeve et al., 2014).

For the September 2014 Arctic Sea Ice Outlook, 23 research groups worldwide participated, employing various methods that combined observations, statistical and numerical models, and empirical analyses. Among the 23 contributions are 10 predictions from numerical models, including coupled ice–ocean models.

Community involvement in the Outlook (as discussed in the previous paragraph) has shed considerable light on the predictability of the area of September Arctic sea ice extent. Most

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4 http://www.arcus.org/search/seaiceoutlook/ and now http://www.arcus.org/sipn/sea-ice-outlook
of the numerical models participating in the Outlook have a coarse horizontal resolution (> 10 km). These numerical models focus on the predictions of total September Arctic sea ice extent, and few predict ice thickness and ice edge locations; which is not particularly useful for assisting the planning and management of economic activities and USCG operational missions in the Arctic Ocean. Among these numerical models, only Navy Research Laboratory’s ACNFS (later GOFS HYCOM) models has a high horizontal resolution (4 km) comparable to the 4 km resolution HIOMAS.

However, unlike HIOMAS, GOFS/HYCOM is primarily for hindcasts and short-term forecasts. Its seasonal forecasts are mainly for scientific exercises, focusing on September Arctic ice extent. In addition, the sea ice model in GOFS is different from that in HIOMAS. The HIOMAS sea ice model is adapted from PIOMAS, which has proven to simulate ice thickness with low mean bias and high model-observation correlation (e.g., Schweiger et al., 2011). This is why PIOMAS sea ice output is used extensively. ADAC and the research team believe the high-resolution HIOMAS results will be even more Arctic operator-friendly and more broadly utilized. In addition, it is our hope that the experiment on 1 km resolution HIOMAS on a subset region covering the U.S. Arctic EEZ will be successful, and particularly useful to Arctic operations in the Chukchi and Beaufort Sea regions.

Lastly, while HIOMAS is now working as an operational support capability, HIOMAS and the associated science support team remain capable to conduct specific sea ice analytics to support planners and decision makers. As one example, the below viewgraphs represent HIOMAS model variances oriented to specific months over a sequence of years. This analysis highlights that March can be the toughest month to negotiate any Arctic shipping route within the US Arctic EEZ.
Icebreakers are required to keep shipping lanes free of ice, allowing ships to transit safely and engage in commerce, supply goods to isolated communities, maintain scientific research outposts, and conduct search and rescue operations (Drewniak et. al., 2018).

**U.S. Capabilities**

The United States currently has three operational icebreakers in its polar fleet, USCGC POLAR STAR and USCGC HEALY are operated by the Coast Guard, and R/V NATHANIAL B. PALMER is operated by the National Science Foundation (NSF). Among the three, only USCGC POLAR STAR, which is around 40 years old and already nearly three decades past its expected lifetime, is a heavy icebreaker (USCG Office of Waterways and Ocean Policy [USCG-WWM] 2019). POLAR STAR uses two separate propulsion systems: diesel-electric and gas turbine, which provide up to 75,000 horsepower and can break six-foot thick ice at three
knots, with a displacement of 13,200 tons. It is considered one of the most powerful non nuclear-powered icebreakers in the world. The Polar Star is currently used to support U.S. operations in McMurdo station in Antarctica (O'Rourke, 2010).

USCGC HEALY, a medium icebreaker, mainly supports National Science Foundation (NSF) Arctic research activities and serves as the primary icebreaker used in the U.S. Arctic (USGAO, 2020) (O'Rourke, 2020). It has a diesel-electric propulsion system with 30,000 horsepower of propulsion power, and displaces 16,000 tons, with the ability to break up to three and half feet of ice continuously at three knots (Jones, 2015).

R/V NATHANIAL B. PALMER, a light icebreaker, displaces 6,500 tons and can break three feet of ice continuously at three knots. This icebreaker’s only mission is to support NSF research in Antarctica (O'Rourke, 2020).

The US has approved plans to build six additional heavy icebreakers at an average cost of $700 million each through the U.S. Coast Guard Polar Security Cutter (PSC) Program. The U.S. Coast Guard expects the first of these ships to be ready for commission by 2023 (O'Rourke, 2020).

China’s Interest and Capabilities

While China does not have any borders in the Arctic, it has invested great interest in Arctic shipping. Furthermore, its economy and international trade are largely dependent on shipping. The transportation of goods via the Northern Sea Route or the Northwest Passage (NWP), as opposed to the Panama Canal or the Suez Canal, can save thousands of nautical miles and reduce transportation times by several days. Over the course of a year, such a shortcut could save shippers a remarkable sum of money. In addition, the NWP provides a route devoid of the political instabilities and marine piracy associated with the southern routes. China is currently conducting Arctic research and owns and operates two icebreakers (Hong, 2011).

Canada’s Capabilities

Canada has ten operational icebreakers with three more currently under construction and an additional six planned (USCG-WWM, 2019). As the Canadian icebreaker fleet maintains shipping lanes and supports commerce throughout the vast Canadian Arctic Archipelago, the fleet is vital to the communities of the Canadian Arctic. Despite the need for robust icebreaking support in the region, the Canadian icebreaker fleet faces similar issues to that of the United States with a rapidly aging fleet (Drewniak et. al., 2018).

In order to meet both short-term needs and long-term capabilities, the Canadian government has put additional resources towards maintaining and expanding the Canadian icebreaker fleet (Drewniak et. al., 2018). A new heavy icebreaker, the John G. Diefenbaker, is set to replace the aging Louis S. St-Laurent which was originally expected to be decommissioned in
While additional icebreakers are under construction, the Canadian government has explored plans to lease civilian icebreakers to meet maintain shipping lanes in the short term (Drewniak et. al., 2018).

**Russia’s Capabilities and Comparison to United States**

Russia has the largest icebreaker fleet in the world (Drewniak et. al., 2018). In addition to Russia’s existing ships, eleven new icebreakers are currently under construction: three of which are nuclear-powered with an additional four in the planning phase (Drewniak et. al., 2018) (O’Rourke, 2020). Russia’s NS Arktika, which is expected to enter service May 2020, has 80,000 horsepower and is designed to break 10-foot-thick ice. Arktika is the biggest nuclear-powered icebreaker ever built. Russia’s nuclear-powered icebreakers (the only such in service in the world) have the advantage of not requiring refueling, thus, they are able to operate for much longer (Drewniak et. al., 2018).

In order to bolster ship traffic along the NSR, Russia plans to phase in significant improvements to infrastructure and SAR services along its Arctic coast. Current plans include developing some of its existing ports to handle a greater traffic demand, building coal, oil, and container terminals and fertilizer-handling facilities, as well as a new railroad, and a deep-water seaport capable of handling high container traffic (Milakovic, 2018). Although still deficient, Russian Arctic SAR capabilities are more robust than those of the United States or Canada. There are currently four emergency response centers along the NSR, and three SAR centers, one of which operates year-round.

In order to overcome satellite communications deficiencies, Russia has built signal-enhancing stations, as well as radio centers and coastal radio stations (Milakovic, 2018). Additionally, Russia’s Marine Rescue Service is responsible for responding to oil spills, and two of its ice breakers have oil spill response equipment (Milakovic, 2018).

Russia has also been steadily improving its NSR navigational aids and communication capabilities, including providing navigational charts and floating markers, as well as coastal markers and zone-specific ice pilot books, among others. Russia’s Northern Sea Route Administration (NSRA) website also provides updated meteorological services and sea ice condition forecasts (Milakovic, 2018). The NSRA organizes ice-breaking escorts for vessels operating along the route and collects tariffs from vessel operators based upon their use of ice-breaking escorts (Shibasaki et al. 2018). Although the tariff schedule has been volatile due to fluctuations in the value of the Russian Ruble, these fees help to support the administrative costs associated with managing the Northern Sea Route and help to support enhanced infrastructure with the Russian Arctic EEZ (Shibasaki et. al 2018).

The United States has not yet established an equivalent authority to govern shipping within the U.S. Arctic EEZ (although establishing such an authority could be quickly realized if U.S. National leadership determined such action was urgently needed). While the United States Coast Guard is statutorily authorized to assist commercial shipping, (and does so routinely in
the Great Lakes) the USCG has not traditionally utilized their few polar icebreakers to support commercial operations (USCGS 2019). The only USCG icebreaker stationed in proximity to the U.S. Arctic EEZ, the USCGC Healy, mainly supports the National Science Foundation (USCGS 2019). In order to enhance maritime operations within the Arctic, the Alaska congressional delegation, along with Senator Angus King of Maine, have proposed the Shipping and Environmental Arctic Leadership Act, or SEAL Act (2019), to the United States Senate. The bill would create an Arctic Seaway Development Corporation that collects maritime shipping fees within the Arctic EEZ and direct funds for infrastructure development. Although current vessel traffic within the U.S. Arctic EEZ is far less than in the Russian Arctic, the bill is intended to provide investments that improve the commercial viability of Arctic shipping and the capability of the Federal government to respond to the growth of maritime traffic in the future.

**ECOLOGICAL/BIOLOGICAL CONSIDERATIONS**

As a remote and highly complex ecosystem, the potential of current and future human activity like shipping on the Arctic environment is not fully understood. Any activity within the region will need take into account the unique biodiversity within the region and the impact on species within the Arctic Environment. Historically, maritime transport related pollution incidents and chemical spills pose a serious risk to Arctic wildlife (Gross, 2018). These effects are not limited to a single species as introduction of pollutant chemicals can travel through the food-web and impact the humans that consume or subsist on these various Arctic species.

Effective coordination of Federal, State, and local government, in conjunction with informed commercial response strategies, are critical to mitigate the growing risk of ecological disruption within Arctic maritime region that comes with increased vessel traffic and human activity. This is important for the successful implementation and execution of Arctic shipping of any resource, especially cargo and freight shipping, in order to preserve the delicate Arctic ecosystem.

**Blue Economy**

Alaska boasts a highly-valued fishing industry as a renewable and sustainable resource, not only for the state’s economy, but for the subsistence of Alaska Natives and coastal communities. The Bering Sea is one of the most productive ecosystems in the world and its associated fisheries are critical both for local food security and the Western Alaskan economy (Fletcher et. al., 2016.) In 2014 half of the top ten most valuable commercial fisheries were within the Bering Sea region (Fletcher et. al., 2016). Bristol Bay hosts the largest commercial salmon fishery in the world; in the average year more Sockeye salmon are harvested within the Bering Sea than Russia, Canada, Japan, and the Lower 48 combined (Fletcher et. al., 2016). The region also attracts tourism associated with wildlife viewing and sport fishing. The fisheries in Alaska sustain suitable fish populations, but benthic fish, such as Arctic cod, serve as a resource for apex predators and are sensitive to
changes in the oceans (Logerwell, 2018). When compared to warmer regions, biodiversity is typically less in the Arctic seas due to the presence of ice, and the relative lack of year-round nutrient flow. However, this is expected to change as diminishing ice increases the availability of access to fish populations, as well as increases the need to boost and sustain the importance of fish hatcheries.

**Risk to Marine Mammals**

Marine mammals are especially at risk to shipping traffic from pollution, noise pollution and ship strikes (Hauser et al, 2018). The Arctic provides crucial habitat to Polar Bears, Pacific Walrus, Stellar Sea Lion, seal species like the Ringed Seal, as well as a variety of cetacean species. As Arctic cetacean species like Beluga and Bowhead whales use sound to both communicate and to detect their environment, a quiet marine environment is vital for their social and foraging behaviors (McWhinnie et. al., 2018). Therefore, the noise pollution produced by frequent tank and cargo vessel transits poses a considerable risk to populations of cetacean species that migrate to the Bering Sea and the Arctic, including migrating gray and humpback whales, as well as year-round Arctic species like the Bowhead whale (McWhinnie et. al., 2018). Understanding and managing sea traffic that accounts for cetacean migratory patterns would be an effective measure to help sustain their populations while minimizing loss to protected species (Hauser et al, 2018) (McWhinnie et. al., 2018). In 2018, the International Maritime Organization established designated shipping lanes and island buffer zones within the Bering Sea (IMO 2018). These new transit areas include buffer zones along the coast to divert shipping traffic away from known wildlife populations as well as local vessel traffic. While following shipping lanes is voluntary for operators within the region, IMO shipping lanes have a high rate of compliance as insurers often require compliance (Rosen, 2018). No sea lanes have been established for the Beaufort Sea where cetacean species like the bowhead whale and beluga migrate and maintain critical habitat (Arctic Council, 2009). Measures like areas to be avoided, traffic exclusion zones, and speed reduction zones could reduce risk and limit the impact of noise pollution on cetacean species (McWhinnie et. al., 2018).

**Pollution Risk**

Although it is unknown if vessel collisions occur with a high enough frequency to impact the populations of marine mammals, chemical pollution poses a larger risk to both marine mammals and the hunters that subsist on them (Fletcher et. al., 2016.). Pollutant chemicals in lower trophic level organisms can travel up the food chain from marine fish to humans. Even if the impact of pollution is limited, the perception of seafood contamination can impact both commercial and subsistence harvests of certain species or within an area that is perceived to be contaminated (Fletcher et. al. 2016.).

Larger vessels such as tankers and cargo ships expose the local environment to oil and other chemical contaminants. Currently tankers calling at U.S. ports make up 46% of weighted oil pollution within the Bering Sea (Fletcher, S. et. al. 2016). One of the largest
resource extraction projects within the region, Red Dog Mine, accounted for 65% of weighted oil exposure for the Bering Strait area (Fletcher, S. et. al. 2016). Even without large scale incidents such as spills, the development of a deep-water port and increased Arctic shipping related to a North Slope LNG operation would introduce chemical containments to waters of the U.S. Arctic EEZ.

Although the IMO’s Polar Code prohibits the dumping of sewage and other waste on Arctic ice or in Arctic waters, the lack of deep-water ports or waste reception facilities within the U.S. Arctic EEZ could encourage illegal dumping by vessels transiting the region (Fletcher et. al. 2016). With increases in vessel traffic through the Arctic, waste reception facilities near the Arctic will face increased pressure on their waste handling capacity (Fletcher, S. et. al. 2016).

Combustion of fuel can release a variety of harmful particulates including black carbon, sulfur, ash, and other heavy metals (Arctic Council, 2009). Black carbon emissions, or soot, has negative affects specific to the Arctic environment (Schröder et al, 2017). In addition to the negative impacts on public health, black carbon can reduce the ability for ice to reflect solar radiation and cause snow and sea ice to melt faster (Arctic Council, 2009). This type of air pollution may act differently in extremely cold environments than in other environments. In order to investigate this, the use of scenario monitoring, such as the program GEM-MACH, can simulate scenarios based on ship types and traffic (Gong et al, 2018). Air pollution is a concern for Alaskan health as its effects can lead to various issues, including cardiovascular disease (Lin et al, 2018). Air pollution in the Arctic may behave differently, evident by low air quality in cities such as Fairbanks, due to lack of wind to disperse air pollutant from coal energy production, wood burning stoves, and car exhaust and Norilsk, Russia, due to under regulated environmental development and industry.

Lastly, another factor regarding ecological security in the region would fall under the anticipated addressable to identify and respond to a chemical spill and cleanup of petrochemical or other bulk commodity leak from a ruptured or leaking vessel. Arctic spills and clean-up efforts are understudied. The lack of manpower and accessibility makes it difficult to implement clean-up methods in the Arctic shipping lanes, but technology for clean up under ice is even less understood. There are several proposed methods for tackling chemical clean up in the Arctic environment, but Arctic test data is limited. Additionally, clean-up approaches for spills that have been absorbed by active ice are still largely unknown. These particular spills have the potential to leak and spread as the ice floats and thaws over the course of a year. Authors note, ADAC has conducted and transitioned Arctic Oil Spill Modeling (AOSM) to NOAA’s General NOAA Operational Modeling Environment (GNOME), which serves as a practical starting point in characterizing oil spills in an ice-laden Arctic environment. ADAC is continuing additional efforts to determine improved Arctic oil spill models to add advanced spill characterization of oil in an Arctic marine environment that includes critical oil and ice model interactions.
SOCIOLOGICAL/ECONOMIC CONSIDERATIONS

The increased economic and maritime activity that would accompany a North Slope LNG project would present both financial opportunity and challenges to the people of Alaska’s Arctic and Western Coast. An Alaskan North Slope LNG project would provide additional tax revenue to a state experiencing consistent yearly fiscal deficits as crude oil prices remain low. Tax revenue would also support local governments within the region such as the North Slope Borough as they in turn are facing increasing fiscal strain with reductions in State support for public services. Federal and possibly State investment in infrastructure to support Arctic shipping could also generate more economic activity within the U.S. Arctic EEZ. The development of a deep-water port within the Arctic would make the region more accessible to larger vessels and potentially attract additional maritime traffic to region (USCMTS 2019). As increased traffic would require additional infrastructure investments and the further development of services for maritime activity like tug and salvage operations, a deep-water port could inspire a feedback loop of economic development within the region (USCMTS 2019). If this scenario were to become a reality, economic activity from Arctic shipping could provide vital resources and infrastructure support to communities facing coastal erosion and other environmental challenges from climate change.

However, increased economic and maritime activity within the Arctic would also present challenges to traditionally remote and subsistence-based communities. Other Arctic communities within proximity to increased Arctic shipping traffic have experienced both ecological and social disruption (Olsen et. al., 2019). Not only would an increase in tanker and cargo vessel traffic also increase the likelihood of pollution incidents, but as the Arctic becomes more accessible to tourism, local communities have experienced litter and social disruption from visitors (Olsen et. al 2019). These disruptions have also led to disturbances in the behavior of local animal populations (Olsen et. al., 2019). This in turn disrupts the lives and hunting practices of subsistence hunters within the region. Therefore, any investment in Arctic shipping must take into account the rights of Alaskan Natives to govern deeded land and sustain their protected traditional ways of life. Alaska Native direct leadership participation in policy and governance is critical to ensuring that policies pass without stripping the indigenous people of rights protected in U.S. and State of Alaska statutes.

TECHNOLOGY AND RISK ASSESSMENT

In order to improve the viability of shipping within the U.S. Arctic EEZ, the United States will need to address the same challenges as faced by other Arctic Nations in developing shipping. Simply due to a rapidly changing Arctic physical environment that is increasingly difficult to characterize at fine scale, the U.S. Coast Guard is at a disadvantage in having to deal with increased risks (such as fast-moving or rapidly decaying ice) that are not completely understood, to effectively monitor and patrol the considerably vast U.S. maritime EEZ. Therefore, the Congressional authorizers and appropriators should consider providing
the U.S. Coast Guard additional sensor and communication stations throughout the Arctic in order to monitor the region much more thoroughly (Tingstad, 2018).

Currently, the Arctic Domain Awareness Center’s (ADAC) High-Resolution Modeling of Arctic Sea Ice and Currents (HIOMAS) project is working towards addressing this need and will aid the Coast Guard in responding to Arctic oil spills, as well as in SAR operations (Zhang, 2019). In addition, the technology is now capable of identifying ice leads within two kilometers resolution, which would prove beneficial for navigating ice-heavy waters (Zhang, 2019).

Another area of concern for the Coast Guard is its lack of ability to physically respond to an incident in the Arctic in a timely manner, the main challenges being the vastness of the Arctic, the harsh environmental conditions, and the lack of available infrastructure, resources, and trained personnel required for a response (Tingstad, 2018).

The presence and changing ice in the Arctic Ocean complicate this matter further, as there are currently no effective methods for cleaning oil from ice. This issue is further compounded by the ability of ice to both trap and absorb spilled oil (Zaki, 2018). Another ADAC project, the Long Range Autonomous Underwater Vehicle (LRAUV), is addressing this issue through its development of an underwater vehicle that is equipped with oil sensors and complex remote navigation systems. Using these features, the LRAUV can be launched from shore or by helicopter to remote locations, and then steered remotely in order to detect oil spills beneath the ice (Kukulya, 2016). Given the LRAUV’s remote capabilities, it may be feasible to address oil-spill removal using a similar vehicle and model (Zaki, 2018).

**ARCTICE: Integrating vessel capability with environmental factors**

One of the challenges encountered when navigating Arctic waters, is evaluating the relative risk associated with traversing ice infested water. To address this challenge, ADAC’s research investigators have developed the Arctic Ice Condition Index (ARCTICE), an easy-to-understand numeral communicating ice hazards in relation to the ice capabilities of an individual vessel. ARCTICE includes the entire Arctic Ocean but focuses on the U.S. Exclusive Economic Zone (EEZ), including the Bering, Chukchi and Beaufort Seas. It is intended as the primary tool for USCG ship captains and commercial mariners alike, for their Arctic sailing route planning.
ARCTICE uses the International Maritime Organization Polar Code and the POLARIS amendment specifications as the backbone of the algorithm. This algorithm takes in environmental data, like ice concentration, stages, and thickness, and outputs a navigation chart illustrating relative risk associated with ice/vessel interactions. Charts are produced for Polar Ship Categories A, B, and C, as illustrated in figure 7 (IMO Polar Code, 2016).

In this figure, vessel capabilities are juxtaposed against ice stage and ice thickness. The relative risk to each category of vessel increases from green (low risk), to yellow (moderate risk), to red (high risk).

Recommendations from the IMO are that vessels do not navigate through areas when the risk value (RV) or risk index outcome (RIO) is less than 0, illustrated in figure 8 (“Guidance on methodologies for assessing operational capabilities and limitation in ice,” 2016).

Negative values indicate higher potential risk for catastrophic vessel/ice incidents. However, ship crew and the captain have the final say in all navigation decisions.

ARCTICE uses the High-resolution Ice-Ocean Modeling and Assimilation System (HIOMAS), an Arctic sea ice model developed at ADAC, for the ARCTICE algorithm. HIOMAS, which currently has the highest spatial resolution (2 km) among all Arctic sea ice models, is potentially
The algorithm is currently producing output charts, and three such charts are shown in figures 9, 10, and 11 for Polar Classes 1, 5, and 7.

Figure 8 Risk Index Outcome (RIO) values compared to vessel ice capabilities.

Complemented by data from other models such as NOAA Global Real-Time Ocean Forecast System, the NOAA-ESRL Coupled Arctic Forecast System, and/or the Canadian Pressured Ice Model.

The algorithm is currently producing output charts, and three such charts are shown in figures 9, 10, and 11 for Polar Classes 1, 5, and 7.

Figure 9 ARCTICE output chart for Polar Class 1 vessels. Chart shows relatively low risk (blue) for all but coastal areas (red) where fast ice is still present.
The next phase of the ARCTICE project, in years 2020-2021, will encompass testing the accuracy of the ice hazard forecast. The algorithm currently forecasts ice conditions up to one month in advance and has hindcasting capability of up to one month. Forecast accuracy will be determined by comparing ARCTICE charts to other forecast systems and may integrate observer data. After this final stage for ARCTICE, ADAC intends for the project to be leveraged by U.S. National Ice Center with public access, pending agreement.
CONCLUSION

As the Yamal LNG project demonstrates, LNG shipping within the Arctic is possible. However, despite the theoretical possibility of a North Slope LNG Shipping system, considering the feasibility of such a project reveals the operational limitations within the U.S. Arctic EEZ. Upkeep and development costs will no doubt be expensive and would require collaboration and investment through local communities, commercial interest, and all levels of government to conduct more research, develop infrastructure, and enhance operational capabilities within the U.S. Arctic domain. Given the challenges associated with a North Slope LNG shipment system, The U.S. Committee on the Marine Transportation System only includes such a project in their ‘Accelerated, But Unlikely Scenario’ in their Ten-Year Projections of Maritime Activity in the US Arctic, 2020-2030 report (USCMTS, 2019).

The economic viability of an LNG shipment system would be impacted by the limited operational window imposed by ice conditions within the U.S. Arctic EEZ. To maximize the summer navigation season, an LNG project from the North Slope would require purchasing specialized ice-breaking LNG carriers, such as the Arc7 class carriers operating along the Northern Sea Route. Although these vessels have proven capable of navigating the entirety of the Northern Sea Route through the summer shipping season, any commercial venture within the U.S. Arctic EEZ should consider the availability of USCG icebreakers within the region to assist tankers in case they become trapped in unnegotiable ice conditions. Although the USCGC Healy could be available to assist with an emergency, a commercial LNG project on the North Slope would likely need to consider utilizing a commercial icebreaker like previous resource exploration ventures in the U.S. Arctic similar to previous Royal Dutch Shell operations and the current Yamal LNG project.

Additionally, the project would likely require some form of a deep-water port along the North Slope close to the extraction sites. Developing such a port would be challenging logistically and could impact the economic viability of the project. As the port would need to be accessible to LNG carriers regardless of ice conditions, any Alaskan LNG operation along the North Slope would be required to adopt ice condition mitigation strategies similar to the Yamal LNG project to ensure ship access to LNG terminals. Other mitigation strategies such as the large-scale Brash Ice Management System (BIMS) or the development of an offshore floating LNG terminal should be investigated (Zhao et. al. 2011) (Lewis et. al. 2016). The strategy of an offshore LNG terminal could be explored as a method to avoid the relatively shallow waters along the Arctic Coast (Lewis et. al. 2016). Additionally, Novatek has chosen to invest in an LNG transshipment facility along the Kamchatka Peninsula to maximize LNG delivery during the summer shipping season. A similar facility at Dutch Harbor or south of the Bering Sea could increase the efficiency of LNG delivery from the North Slope. This would allow for more LNG deliveries between Alaska and the East Asian market as carriers could make more deliveries during the summer shipping season, while a transshipment facility outside of the winter ice extent could operate year-round.
As commercial interests would attempt to maximize the summer shipping season, overall traffic in the Bering Sea and the U.S. Arctic Domain would increase. Bringing Alaskan North Slope LNG to market would certainly provide economic benefits to the region and the state as a whole, but also increase the potential for pollution incidents within the region and impact the behavior of marine mammals. As Arctic shipping is a relatively new phenomenon, the effects of increased traffic on the environment are not fully understood. Further research is critical to establishing environmental baselines allowing a full understanding of impacts that increased vessel traffic and infrastructure development will have on the existing socio-economic status of people living along the Western and Arctic Alaskan coast.

The implementation of the International Maritime Organization’s Polar Code and new shipping lanes in the Bering Sea should aid in regulating vessel traffic within the region and reduce risks of incidents in both the Russian and U.S. EEZs. However, these first steps need to be complimented by infrastructure improvements and investments in SAR and spill response capability. In addition, the USCG will need to carefully consider a strategic patrol strategy that deploys icebreakers and maritime domain awareness flights in concert with increases in cargo and tank vessel transits of the U.S. Arctic EEZ. Increased investments in new communications and environmental monitoring technologies that provide significant improvements in the accuracy and fidelity of weather forecasts will greatly reduce risks and allow for effective route planning.

Despite these challenges, it is highly likely that a maritime LNG delivery system would be less expensive than a Trans-Alaska LNG pipeline project. An Alaskan LNG pipeline system has been regularly reported within Alaskan media to cost around 43 billion USD, while the reported cost of commercial investment in the Yamal LNG project was 27 billion USD (Brehemer 2019) (Yamal LNG). This does not include federal subsidies and additional costs borne by the Russian Federal government to support the development of a deep-water port at Yamal and other infrastructure along the Northern Sea Route. While the Yamal LNG project faced similar logistical and environmental challenges as a theoretical North Slope LNG project, additional cost analysis would have to be performed to determine the total cost of creating a similar project within the Alaskan market. This cost analysis would be critical to determine the projected operating costs of LNG handling facilities on the Alaskan North Slope and Beaufort Sea coasts, a transshipment facility along the Aleutian Islands, as well as the costs of specialized Arctic LNG tankers needed to move product to market.

Accordingly, if the total package of procuring and sustaining an LNG tanking operation along the US Arctic EEZ was in fact less than the cost of procuring and sustaining a Trans Alaska LNG pipeline, it is likely environmental factors within the US Arctic EEZ would enable such an operation.

Arctic nations-states such as the Russian Federation have demonstrated a rapid and competitive shift in the economic development of the Arctic. In addition, nation-states from outside of the Arctic such as the People’s Republic of China have demonstrated their interest in developing the natural resources within the Arctic and improving the ability of
cargo vessels to transit the Northern Sea Route. Traffic related to this economic activity is already increasing vessel traffic along the Northern Sea Route, which at a critical juncture runs through the Bering Sea and the narrow Bering Strait. Traffic within the Chukchi and Bering Seas is expected to grow regardless of the U.S. Federal government’s investments within the region or the development of North Slope LNG shipping season.

Therefore, there is an imperative for policymakers within the United States and the State of Alaska to consider how to manage the risk associated with shipping within the Arctic environment, regardless of the realization of an LNG shipping system in the U.S. Arctic EEZ. There is an opportunity to address issues of vital importance to coastal communities in Alaska as well improve the infrastructure that supports domain awareness within the U.S. Arctic EEZ. The Department of Defense and Department of Homeland Security have begun increasing their interest in bolstering awareness and capabilities in the Arctic. A long-term implementation strategy will be recommended to increase safety and security of the Arctic Marine Transportation System (MTS) as Arctic shipping is currently feasible and will become increasingly so every year, assuming current projections of Arctic sea ice retreat continue. Addressing the challenges associated with Arctic MTS development, icebreaker deployment, and ecological and sociological concerns, would increase the economic viability of Alaskan LNG production and better secure the US National Interests in the Arctic.

In closing, this paper is an outcome from an ADAC student workforce development activity. Accordingly, the reflections of the paper are principally oriented to advance critical thinking about a complex topic, but not provide definitive decisions on whether or not industry should proceed with what would likely be a multi-billion-dollar investment. As such, this paper should not be construed as an official position of ADAC, the University of Alaska and/or the Department of Homeland Security Science and Technology Office of University Programs.
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**TERMS OF REFERENCE/LEXICON**

<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tbody>
<tr>
<td>AIRSS</td>
<td>Arctic Ice Regime Shipping System; a Canadian regulatory standard currently in use as a requirement of the Arctic Shipping Pollution Prevention Regulations</td>
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<tr>
<td>AIS</td>
<td>Automatic Identification System</td>
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<td>ADAC</td>
<td>Arctic Domain Awareness Center</td>
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<td>Arctic ERMA</td>
<td>Arctic Environmental Response Management Application; an information platform under NOAA</td>
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<tr>
<td>ARCTICE</td>
<td>Arctic Ice Condition Index; an easy-to-understand numeral to communicate ice conditions that are relevant to the capabilities of a vessel</td>
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<td>CIS</td>
<td>Canadian Ice Service</td>
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<td>CRNC</td>
<td>National Research Council Canada</td>
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<td>CRREL</td>
<td>US Army Corps of Engineers Cold Regions Research and Engineering Laboratory</td>
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<tr>
<td>DHS S&amp;T UP</td>
<td>Department of Homeland Security Science and Technology Office of University Programs</td>
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<tr>
<td>EEZ</td>
<td>Exclusive Economic Zone</td>
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<tr>
<td>HIOMAS</td>
<td>High-resolution Ice-Ocean Modeling and Assimilation System; an Arctic sea ice model developed as an ADAC project, currently of the highest spatial resolution among public Arctic sea ice models</td>
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<tr>
<td>ICECON</td>
<td>Ice Conditions Index for the Great Lakes Region</td>
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<td>IMO</td>
<td>International Maritime Organization</td>
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<td>LNG</td>
<td>Liquefied Natural Gas</td>
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<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>NWS</td>
<td>National Weather Service</td>
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<tr>
<td>POLARIS</td>
<td>Polar Operational Limit Assessment Risk Indexing System; rules of navigation for the Arctic shipping developed by incorporating Canada's Arctic Ice Regime Shipping System and Russian Ice Certificate</td>
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RDC  Research and Development Center
RIO  Risk Index Outcome; a method used by POLARIS to quantify ice condition

Sea Ice
Model  Prediction model for sea ice; with parameters such as ice concentration, ice thickness, ice velocity, etc.

UAA  University of Alaska Anchorage
UAF  University of Alaska Fairbanks
USCG  U.S. Coast Guard
USNIC  U.S. National Ice Center
Validation  Limited to comparison between ARCTICE to field observation; not subject to CG VV&A process
WMO  World Meteorological Organization