Mapping vessel traffic patterns in the ice-covered waters of the Pacific Arctic

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Abstract

Recent climate change has caused declines in ice coverage which have lengthened the open water season in the Arctic and increased access to resources and shipping routes. These changes have resulted in more vessel activity in seasonally ice-covered regions. While traffic is increasing in the ice-free season, the amount of vessel activity in the marginal ice zone (ice concentration 15–80%) or in pack ice (>80% concentration) remains unclear. Understanding patterns of vessel activities in ice is important given increased safety challenges and environmental impacts. Here, we couple high-resolution ship tracking information with sea ice thickness and concentration data to quantify vessel activity in ice-covered areas of the Pacific Arctic (northern Bering, Chukchi, and western Beaufort Seas). This region is a geo-strategically critical area that contains globally important commercial fisheries and serves as a corridor for Arctic access for wildlife and vessels. We find that vessel traffic in the marginal ice zone is widely distributed across the study area while vessel traffic in pack ice is concentrated along known shipping routes and in areas of natural resource development. Of the statistically significant relationships between vessel traffic and both sea ice concentration and thickness, over 99% are negative, indicating that increasing sea ice is associated with decreasing vessel traffic on a monthly time scale. Furthermore, there is substantial vessel traffic in areas of high concentration for bowhead whales (*Balaena mysticetus*), and traffic in these areas increased four-fold during the study period. Fishing vessels dominate vessel traffic at low ice concentrations, but vessels categorized as Other, likely icebreakers, are the most common vessel type in pack ice. These findings indicate that vessel traffic in areas of ice coverage is influenced by distant policy and resource development decisions which should be taken into consideration when trying to predict future vessel-ice interactions in a changing climate.

Keywords Arctic · Vessel traffic · AIS · Sea ice · Climate change

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1 Introduction

Warming at four times the global average rate, Arctic marine systems are sentinels for climate change impacts on the world's oceans (Rantanen et al. 2022). Across the Arctic Ocean, the average length of the sea ice season declined at a rate of nearly 12 days per decade from 1997 to 2017 (Peng et al. 2018). These changes have altered the migratory patterns of marine wildlife (Tsujii et al. 2021) and threatened the food security of Indigenous communities in the Arctic (ICC Alaska 2015). Declining sea ice has also increased the accessibility of marine shipping routes (Smith and Stephenson 2013). Strengthened integration between Arctic and global economies has also facilitated increased vessel traffic for resource development (Larsen and Huskey 2015; Brigham 2021). Together, these changes have created a metacoupled Arctic that is highly interconnected with global systems through various flows of natural resources, money, and greenhouse gases (Kapsar et al. 2022a).

Though the length of the ice-free season is increasing, sea ice coverage is still a rate-limiting step for vessels traveling into, out of, or through the Arctic. Even climate models parameterized using the highest emission scenario (RCP-8.5) project that the Northern Sea Route will only be accessible to non-ice strengthened vessels for approximately 4 months of the year through 2050 (Khon et al. 2017). To better understand the impacts of vessel traffic in Arctic systems, it is therefore important to understand the degree to which vessels travel through areas of partial or complete ice coverage.

Vessel traffic in ice-covered areas can amplify impacts on sensitive Arctic marine systems. The threats of vessel traffic in open water include noise, pollution, threat of invasive species introduction, risk of ship strike to marine wildlife, and interference with subsistence practices (Huntington et al. 2015; Erbe et al. 2019). Moderate to heavy ice coverage can amplify noise impacts (Roth et al. 2013), thus elevating the potential risk of negative consequences such as disturbance, loss of communication space, or hearing damage in marine mammals. Additionally, the presence of sea ice complicates the cleanup of oil spills by inhibiting access to spill sites and limiting the effectiveness of traditional containment techniques. Finally, the presence of vessels in pack ice has the potential to disrupt habitats of ice-dependent species, particularly during the spring months when, for example, ice seals use this habitat for denning (Lindsay et al. 2021).

The Pacific Arctic, which encompasses the Chukchi, northern Bering, and western Beaufort Seas, is an important area for studying the impacts of vessel traffic on marine systems (Fig. 1). This region is host to globally important commercial fisheries (Fissel et al. 2021) and also encompasses the Bering Strait, a narrow waterway that serves as the only connection between the Pacific and Arctic Oceans. Only 50 km wide at its narrowest, the Bering Strait is an important migratory corridor for wildlife, including gray whales (*Eschrichtius robustus*) and bowhead whales (*Balaena mysticetus*) (Citta et al. 2012; Heide-Jørgensen et al. 2012). Previous pan-Arctic research has demonstrated that marine mammals in the Pacific Arctic, including gray and bowhead whales, are especially vulnerable to the impacts of vessel traffic (Hauser et al. 2018) and, for ice-dependent species like the bowhead whale, vessel traffic in times of partial or complete ice coverage has the potential to exacerbate impacts compared to open water areas.

In addition to its impacts on wildlife, vessel traffic in sea ice is a major concern for Indigenous communities in the Pacific Arctic. Many communities in this region practice the subsistence harvest of marine wildlife for a majority of their diet (Fall 2016) and their food security depends upon the continued ability to harvest healthy wildlife that is free of contaminants (ICC Alaska 2015). Communities in the Pacific Arctic also frequently use sea
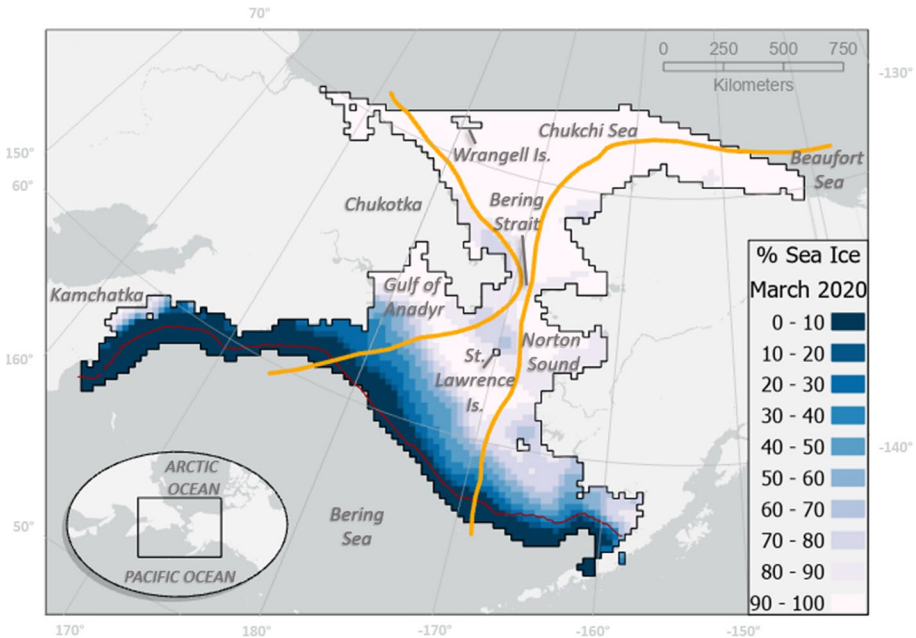
Fig. 1 Map of the Pacific Arctic with percent sea ice concentration in March of 2020. Red line indicates the median March sea ice extent for 1980–2010. Ice extent data were acquired from the National Snow and Ice Data Center. Orange lines represent approximate routes for shipping entering and exiting the Northern Sea Route (west) and Northwest Passage (east), although routes through the Bering Sea vary by destination. Pixels are each approximately 625 km^2 in area

ice as a platform for subsistence hunting and have expressed concerns related to increases in ice-breaking vessel activities in the region (Kawerak Inc. Marine Program 2016).

Within the Pacific Arctic, the Bering Strait is also a geopolitically important corridor for trade and the right of free passage. In recent years, news agencies have reported increased winter traffic in the Pacific Arctic, including the first winter transit in 2021 by a commercial icebreaking carrier along the Northern Sea Route and through Being Strait (Figure 1; Staalesen 2021). With increased Russian investment in liquified natural gas (LNG), transits of this nature are expected to increase in future years (Brigham 2021). Given expected further increases in vessel traffic and the importance of sea ice for coupled human and natural systems in the Pacific Arctic, there is a need to understand patterns of vessel traffic in ice-covered waters.

The lack of readily available data on vessel movements has hindered fine-scale research on vessel traffic patterns in the past. However, recent efforts to obtain historical ship tracking data and make it more readily available to the public have enabled an increased understanding of vessel traffic in the Arctic Ocean (Berkman et al. 2020; Kapsar et al. 2022b). We now know that Arctic vessel traffic has been increasing in recent years, with the number of ships operating in Arctic waters and the total distance travelled growing by approximately 25% and 75%, respectively, between 2013 and 2019 (PAME 2020). Yet, despite this new access to information, it remains unclear whether growth in vessel traffic has been constrained to the ice-free season or if vessel traffic has also been pushed into ice-covered waters.

Previous approaches to projecting future vessel traffic in Arctic waters have used ice thickness and concentration information to project season length for theoretical vessels of particular ice classes (Stephenson et al. 2011; Smith and Stephenson 2013; Melia et al. 2016; Aksenov et al. 2017; Mudryk et al. 2021). For instance, using climate models Smith and Stephenson project that trans-Arctic ship routes will be seasonally accessible to non-ice strengthened vessels by 2050 (Smith and Stephenson 2013). However, accessibility does not necessarily equate to usage, and there have been few studies examining actual vessel traffic patterns and sea ice distribution concurrently. In two such studies of vessel activities in sea ice in the Canadian Arctic, researchers used least cost path interpretation of once-daily positions to track vessel movements in combination with Canadian Ice Service "Ice Charts" and determined that sea ice coverage is negatively associated with vessel traffic in the Canadian Arctic at both an annual scale and during the shipping season (Pizzolato et al. 2014, 2016). It is unknown whether these associations hold true for other regions.

This study expands upon previous research examining vessel-ice interactions by using high-resolution automatic identification system (AIS) ship tracking data (transmitted approximately every 2 min) and value-added sea ice products derived from microwave remote sensing to evaluate vessel activities and sea ice in the fall and winter in the Pacific Arctic region. By aggregating spatiotemporally concurrent data sets, we examined the amount of vessel traffic in open water (ice concentration <15%), the marginal ice zone (MIZ; ice concentration between 15 and 80%), and in pack ice (>80% ice concentration) in 25-km pixels across the study area. We further identified locations with the greatest total traffic in sea ice and the total amount of vessel traffic across different ice concentrations and vessel types. We also examined the correlation between monthly sea ice concentration/thickness and vessel traffic at a pixel scale. Finally, we assessed patterns of vessel traffic in areas of high bowhead whale concentration. Overall, this study provides new insight into vessel-ice interactions in a changing Pacific Arctic and serves as a foundation for future analysis of vessel traffic impacts on Arctic social-ecological systems and the feasibility of different policies to mitigate these impacts.

2 Materials and methods

2.1 Study area boundaries

The region of interest for this study is the Pacific Arctic, which includes the northern Bering Sea, Chukchi Sea, and western Beaufort Sea (Fig. 1). We defined the boundaries of our study area based on both climatological and logistical constraints. For regions not constrained by vessel data availability, we defined the study area by identifying sea ice pixels with greater than 15% sea ice concentration in at least 1 month during our study period (2015–2020). We chose this definition to include all areas covered by sea ice in the study area. In the northern portion of our study area, our boundary was delimited by the availability of vessel traffic data, which cut off at approximately 74° N. The total study area encompasses 1,650,458 km^2 and is mostly ice-covered from approximately December to April each year (Fig. 1). To account for the sea ice season, which spans multiple calendar years, we present results in terms of the "winters" (i.e., winter 2015–2016 extends from October 2015 through April 2016). To maximize the amount of data available to interpret patterns, we also present partial winters of data for 2015 (January to April) and 2020

(October to December); however, we removed partial years from the analysis when calculating percent change over the study period.

2.2 Sea ice concentration and thickness

Both sea ice concentration and thickness have been demonstrated to play a role in influencing the navigability of Arctic waters (Stephenson et al. 2013; Melia et al. 2016; Stocker et al. 2020). Given the importance of ice thickness as a standard for determining the safety of navigation through methods such as the Polar Operational Limitations Assessment Risk Indexing System (POLARIS) Risk Index Outcome (RIO) method (Wang et al. 2022), we chose a product that contained both thickness and concentration estimates. To this end, we used the CryoSat-2/SMOS Merged Product from the European Space Agency to calculate sea ice thickness and concentration in our region of interest (Ricker et al. 2017). This data set is a value-added product made by combining observations from the CryoSat-2 and the Soil Moisture and Ocean Salinity (SMOS) satellites (Ricker et al. 2017). It uses the mean thickness estimates from both SMOS and Cryo-Sat2, weighted by their relative uncertainties at a given thickness to minimize overall uncertainty in thickness estimates, particularly over thin ice (1 m or less). This is particularly salient for the Pacific Arctic study area, which is dominated by thinner first-year ice, with minimal presence of multi-year ice (Serreze et al. 2016).

The combined CryoSat-2/SMOS Merged Product contains daily sea ice concentration and thickness estimates for October through April of each year based on a 7-day rolling average at a 25 km × 25 km spatial resolution. Sea ice concentration data contained within this product are from the OSI SAF Global Sea Ice Concentration Climate Data Record (OSI-430-b). After acquiring these data, we aggregated them to monthly average values and cropped them to the extent of available vessel tracking data. To account for inaccuracies in sea ice concentration estimates at very low concentrations, we used a cutoff whereby all pixels with sea ice concentration values less than 15% were considered to be ice-free (Strong and Rigor 2013; Stocker et al. 2020). To align with previous studies of sea ice seasonality, we further differentiated sea ice concentration data into two categories: MIZ and pack ice. Each pixel was designated as being in the MIZ in a given month if the sea ice concentration value was greater than 15% and less than 80%. Pixels with a sea ice concentration value of greater than 80% in a given month were designated as pack ice (Strong and Rigor 2013). We calculated ice extent in a given month by taking the sum of the area of all pixels with at least 15% sea ice concentration.

While uncertainty in sea ice concentration was not provided in the CryoSat-2/SMOS Merged Product, mean winter uncertainty in this product has been shown to be approximately 2.5% in the Northern Hemisphere (Lavergne et al. 2019). Uncertainty in thickness estimates was available within the CryoSat-2/SMOS Merged Product. For ice-covered pixels (>15% concentration) within our data set, the mean uncertainty in sea ice thickness was 0.07 m.

2.3 Vessel activity tracks

AIS transponders are required on all passenger vessels, all cargo vessels over 500 gross tons, and all vessels over 300 gross tons on an international voyage (IMO 2002). When operational, AIS transponders project signals at a maximum interval of every 2 min (and more frequently when the vessel is underway). These signals are received by other vessels, terrestrial receivers, and/or satellite-based receivers. The higher resolution of the AIS data used in this analysis represents an improvement upon previous studies that have analyzed

ship locations within sea ice which used imputed track lines between once-daily locations (Pizzolato et al. 2016).

To quantify vessel traffic patterns, we acquired all AIS data for the study area from January 2015 through December 2020 from exactEarth, a private company that maintains a constellation of satellite-based AIS receivers. We cleaned these data to remove inaccurate positions and/or vessel attributes and joined successive locations into daily segments for each vessel (Kapsar et al. 2022b). After cleaning the AIS data, we rasterized daily segments by spatially intersecting them with the same raster grid used for the sea ice data. We then calculated the total distance travelled (in km) by vessels within each pixel in each month of the study period for which sea ice data were available (i.e., October through April). To mitigate potential edge effects associated with the partial overlap of pixels with the AIS collection boundaries, we included only pixels that fell entirely within the AIS data collection bounding box. To remove frequent erroneous AIS signals (and subsequent errors in traffic values) from ships loitering near ports, we removed pixels containing or adjacent to known ports from the analysis. We repeated this process for all vessel types combined and also for four vessel type subsets (cargo, tanker, fishing, and other vessels). Following the methods of Kapsar et al. (2022b), we designated vessel types using the two-digit code transmitted in static AIS transmission. In this method, "Other" vessels include all vessels not explicitly falling into one of the three types (cargo, fishing, tanker). The "Other" designation thus includes research vessels, tugs, passenger ships, search and rescue vessels, and ice breakers.

2.4 Vessel traffic and sea ice analysis

To determine the relationship between vessel traffic and sea ice in the Pacific Arctic, we first mapped and aggregated the changes in vessel traffic and sea ice across space and through time. For each time period, we defined occupied pixels as those that had at least one vessel pass through them. We then examined the relationship between sea ice concentration and the proportion of occupied pixels for the entire study period as well as the average amount of vessel traffic per occupied pixel across all values of sea ice concentration. To determine whether this relationship differed by vessel type, we also examined the total distance travelled by vessels in different concentrations of sea ice.

To assess the significance and direction of the relationship between sea ice and vessel traffic in the study area, we applied a non-parametric correlation analysis, following the methods laid out in Pizzolato et al. (2016). On a per-pixel basis, we identified the maximum ice concentration value in months for which the total vessel traffic was greater than zero. We then identified all months with no vessel traffic and sea ice concentration greater than the aforementioned maximum. Of these months, we kept the month with the lowest sea ice concentration value and removed the rest of the months from further analysis. The purpose of this method is to remove ties from the data set, which are not accounted for by the Kendall's tau-a rank correlation. For this reason, we also removed all months with no vessel traffic and no sea ice. Unlike Pizzolatto et al. (2016), we did not de-trend the data prior to correlation analysis because our time series was short enough in duration (6 years) that we would not expect to see long-term climate-related trends in sea ice concentration. After this procedure, we calculated the Kendall's tau-a rank correlation to determine the relationship between vessel traffic and sea ice at a pixel scale. We calculated the correlation using both measures of sea ice (thickness and concentration) and vessel traffic (total km travelled).

2.5 Bowhead distribution and vessel activity

We acquired information on the winter distribution (range, concentration, and high concentration areas) of bowhead whales from the Ecological Atlas of the Bering, Chukchi, and Beaufort Sea (Smith et al. 2017). This product synthesizes multiple data sources, including telemetry data, expert opinion, and traditional knowledge. To calculate annual total vessel traffic in areas of high concentration for bowhead whales, we first transformed the data to Alaska Albers and spatially intersected it with vessel activity rasters (see previous section for details on raster creation). We limited vessel activity rasters to November to March to temporally match with winter bowhead distribution data. We then calculated total vessel traffic for each winter in all cells that intersected with bowhead distribution.

3 Results

Over the 6-year study period, AIS-transmitting vessels travelled a total of 771,117 km in partially or fully ice-covered areas. This amount represents approximately 6% of all vessel traffic in the study area from October to April. Fishing vessels made up the greatest percentage of vessel traffic in ice (40%), followed by other vessels (31%), cargo vessels (22%), and tankers (7%). Patterns of vessel traffic varied widely from month to month but were relatively consistent across seasons, with maximums in October for all winters and traffic minimums in January or February, depending on the year (Fig. 2).

Patterns of sea ice and vessel traffic were inversely related, with sea ice extent reaching its maximum in January (2019), February (2020), or March (2016, 2017, and 2018). The maximum annual sea ice extent was lowest in the winter of 2017–2018, covering 61% of the study area. This represents a reduction of 16–26% over other years in the study period. In all years, sea ice extent was relatively consistent during the freeze-up
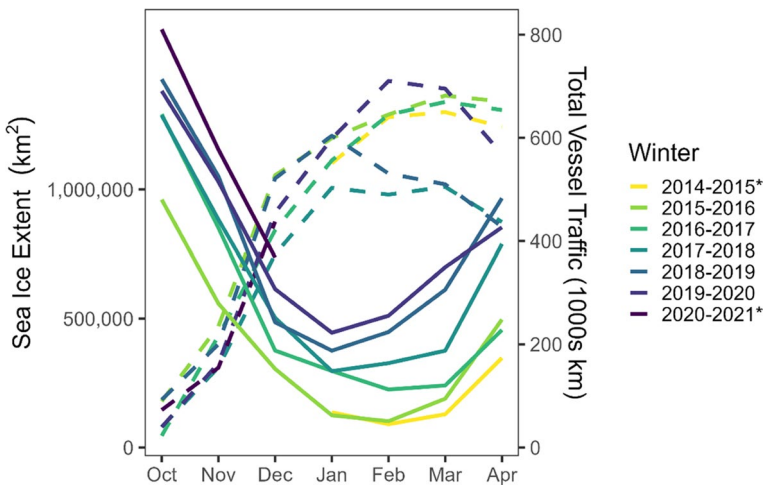

Fig. 2 Monthly total vessel traffic (solid lines) and sea ice extent (dashed lines) for the study period. Data extend from January 1, 2015, through December 31, 2020. Asterisks denote that due to the timeframe of the data, the winters of 2014–2015 and 2020–2021 contain only partial seasons

period from October through December but was more variable in the winter months. Sea ice extent was particularly low in February through April of 2018 and 2019.

In general, vessel traffic decreased with increasing sea ice concentration. In pixels with no sea ice in a given month, 57% contained at least some vessel traffic. At 15% ice concentration, the percentage of pixels with vessel traffic decreased to 37%, and at 80% ice concentration, 4% of pixels were occupied by vessels (Fig. 3). In addition to a higher percentage of pixels with vessel traffic at lower ice concentrations, there was also more traffic overall in each pixel at lower ice concentrations (Fig. 3).

Spatial patterns of the distribution of vessel traffic were distinct between the MIZ and pack ice (Fig. 4). Vessel traffic in the MIZ was widespread throughout the study area, with the exception of the central Bering and Chukchi Seas and Norton Sound (Fig. 4). Vessel traffic in pack ice appears to be a subset of vessel traffic in the MIZ and was concentrated in the western Beaufort Sea along the northern coast of Alaska, and in the western Chukchi sea along the Northern Sea Route and up to Wrangell
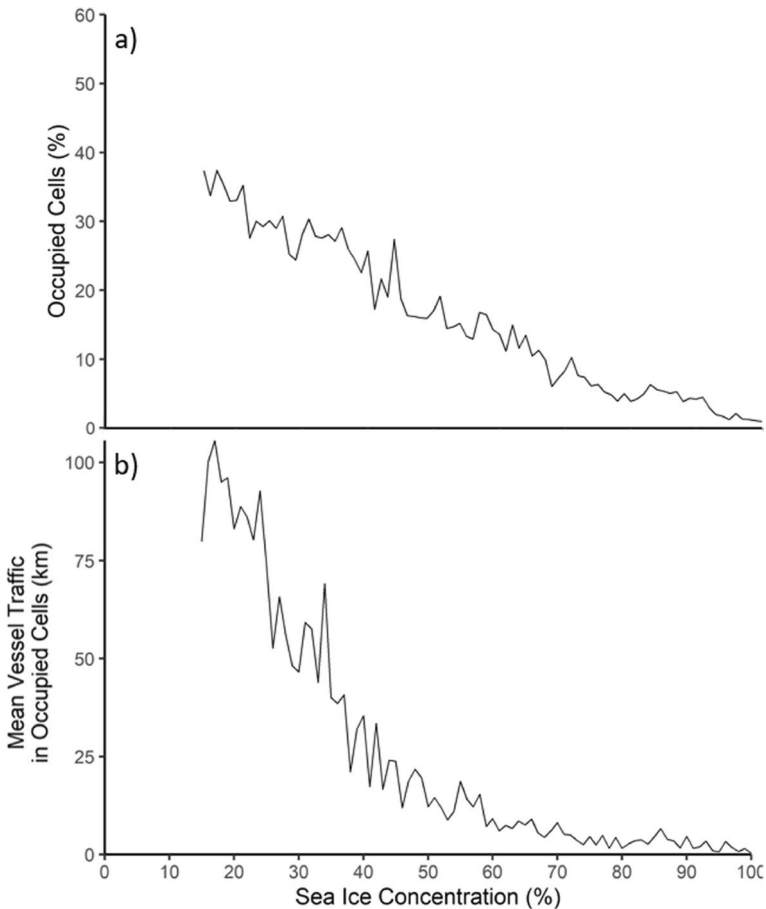

Fig. 3 Changes in vessel traffic by sea ice concentration for the entire study period. **a** Occupied pixels are defined as those with at least 15% sea ice concentration and total distance travelled by vessels greater than zero for a given month; **b** mean vessel traffic (km travelled) in pixels with at least 15% monthly average sea ice coverage. Values were combined across all months of the study period
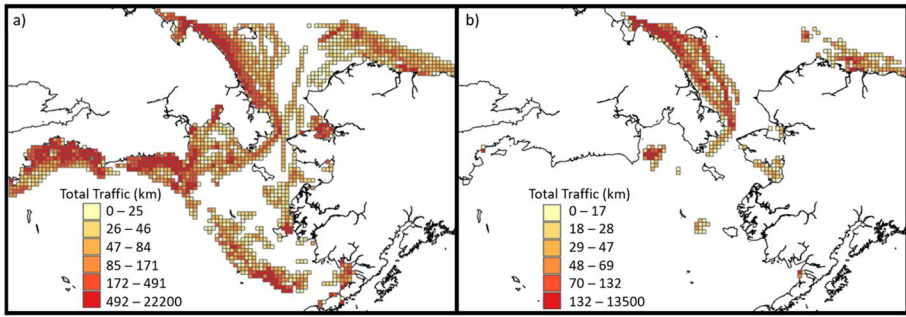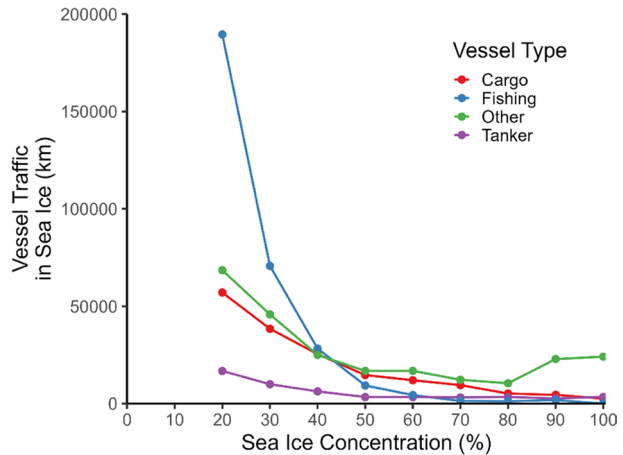
Fig. 4 Vessel traffic (total km travelled) from 2015 to 2020 in **a** marginal ice zone (MIZ; i.e., sea ice concentration between 15% and 80%), **b** pack ice (i.e., sea ice concentration > 80%). Map data are presented on a quantile scale

Fig. 5 Changes in total vessel traffic (km) by sea ice concentration and vessel type

Island. The amount of vessel traffic per pixel in the MIZ and pack ice was both heavily skewed with a few areas containing significant traffic and many areas with very little or no traffic.

The relationship between vessel traffic and sea ice concentration varied among vessel types (Fig. 5). Fishing vessels travelled the greatest total distance in ice-covered areas, but stayed primarily along the ice edge (<30% concentration), and were rarely found in areas with more than 50% concentration of sea ice. Other vessel traffic was the dominant vessel type in pack ice, likely indicating icebreaker activity. (icebreakers fall under the Other vessel type in this typology.) Cargo and tanker traffic both decreased consistently with increasing ice concentrations.

Correlations between vessel traffic and sea ice were largely consistent across both concentration and thickness metrics. Of the pixels with significant correlations between vessel traffic and sea ice concentration, 99.8% were negative (Fig. 6a), indicating increasing sea ice concentration is associated with decreased vessel traffic. Similarly, 99.5% of all cells with significant correlations between ice thickness and vessel traffic were negative (Fig. 6b). Significant relationships between vessel traffic and sea ice were concentrated along the area of maximum ice extent and
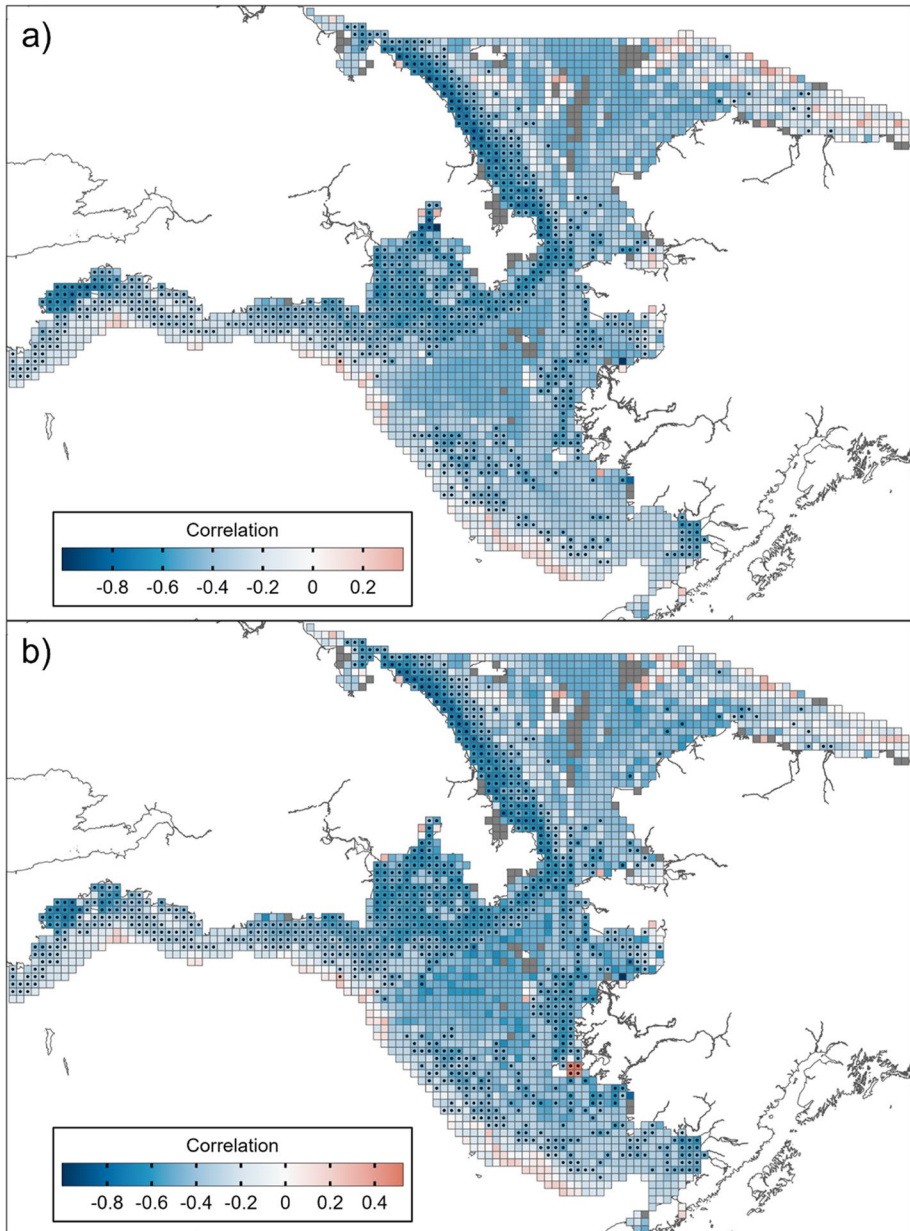
Fig. 6 Kendall's tau-a correlation values for monthly average **a** sea ice concentration and **b** sea ice thickness and total vessel traffic (km) from October to April in 2015 through 2020. Significant correlations ($p < 0.05$) are marked with an asterisk. Grey pixels had no vessel traffic during the study period

known routes northward through the Bering Strait. There was little to no association between vessel traffic and sea ice in the central Chukchi and Bering Seas, likely due to the minimal amounts of vessel traffic in those areas.

While the study period is relatively short in duration (five complete winters), there were notable increases in the overall amounts of vessel traffic in both ice-free and ice-covered waters. Total vessel traffic in the region during this period increased by 50%. At the same time, the total distance travelled by vessels in the MIZ increased by 14%, while the growth of vessel traffic in pack ice was 17%.

Patterns of vessel-ice associations overlapped substantially with areas of concentration for bowhead whales (Figs. 4 and 7). Likewise, increases in vessel traffic in ice were concentrated in the bowhead habitat. Vessel traffic in areas of high concentration for bowhead whales increased four-fold during the 5-year study period, from 9032 km in the winter of 2015–2016 to 40,178 km in 2019–2020 (Fig. 7). The majority of this traffic was due to fishing vessel activity in the concentration area located in the Gulf of Anadyr. Notably, vessel traffic in areas of high bowhead concentration in November and December of 2020 (46,253 km) already exceeded totals from 2019 to 2020, indicating a continuation of the previous pattern. Vessel traffic in areas of high concentration and concentration increased at faster rates (345% and 377%, respectively) than traffic across the range of bowhead whales in winter (162%).

4 Discussion

By examining spatiotemporal patterns of vessel traffic in ice-covered areas, this analysis contributes real-world insights that can be used to better predict the impacts of changing sea ice on vessel traffic and its cascading consequences for Arctic coupled human and natural systems. Below, we discuss some of the important findings of this study.

4.1 Vessel-ice interactions vary by vessel type

Similar to previous research, we found that vessel traffic and sea ice concentration and thickness exhibit a negative relationship at monthly time scales in the Pacific Arctic
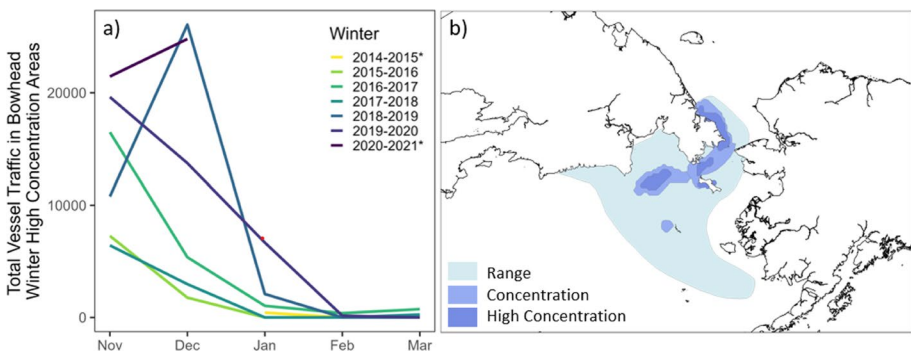

Fig. 7 **a** Winter (November to March) vessel traffic (km) in areas of high concentration for bowhead whales (Balaena mysticetus). **b** Bowhead whale winter (November to March) range (light blue), concentration areas (medium blue), and high concentration areas (dark blue). Distribution data were acquired from the Ecological Atlas of the Bering, Chukchi, and Beaufort Seas. Asterisks denote incomplete seasons of data (i.e., January to March for 2015 and November to December of 2020)

(Fig. 6). This result is congruent with research from the Canadian Arctic which found a similar pattern of decreasing vessel traffic with increasing sea ice (Pizzolato et al. 2014). However, sea ice does not entirely exclude vessels, and the presence of vessels in partially or fully ice-covered areas is, in part, related to vessel type.

Fishing vessels were the most common type of vessel operating within icy waters, but only at low ice concentrations (<50%). These vessels appeared to more closely follow the ice edge, mostly likely following the distribution of targeted species. While commercial fishing is limited to non-trawling activities above approximately 60° North on the US side (North Pacific Fishery Management Council 2020), fishing activities on the Russian side extend northward into the Gulf of Anadyr. Furthermore, in part as a result of the northward shift in the distribution of pollock (Maznikova et al. 2023; Levine et al. 2023), Russia opened its first commercial pollock fishery north of the Bering Strait in 2020. As sea ice recedes, the northward movement of fishing activities into and above the Bering Strait could result in a bottleneck, concentrating fishing activity and marine mammal movements in a smaller area. Fishing vessel interactions with ice-covered areas could also pose an increased safety hazard given that these vessels are not typically ice-strengthened.

Unlike the MIZ, vessel traffic in pack ice was dominated by Other vessels. Icebreakers, which are classified as Other vessels in this typology, are the most likely contributor to vessel activity in pack ice. However, due to privacy-related restrictions in the AIS data set, we were unable to distinguish icebreakers from other vessel types. Future research integrating auxiliary data sets of vessel information could be used in a more detailed analysis of the relationship between different vessel types and sea ice.

4.2 Vessel-ice interactions occur along established transportation routes and in areas of natural resource development

Vessel traffic in the study region does not appear to be closely tied to sub-annual changes in sea ice extent (Fig. 4). This finding is evident during the winters of 2017–2018 and 2018–2019 when ice extent was substantially lower than in previous years, but the overall amount of vessel traffic did not increase proportionately. This result is supported by previous research in the Canadian Arctic which also found that decreases in sea ice are not directly driving vessel activity (Dawson et al. 2018). Rather, economic factors associated with the cost of transportation and natural resource development are the largest drivers of vessel traffic in the region (Wagner et al. 2020; Constable et al. 2022).

Given its remoteness, challenging weather conditions, and high operational costs associated with operating in and around sea ice, it is logical that economic and policy factors play a key role in driving vessel-ice interactions in the Pacific Arctic. Political and economic connections between distant systems and the Arctic create telecoupled systems whereby vessel-ice interactions in the Pacific Arctic are impacted by distant decision-making and global economic factors (Pizzolato et al. 2014; Aksenov et al. 2017; Waloven et al. 2023). Thus, national and international policies (e.g., bans on fishing activities), investments in natural resource development (e.g., mines, oil, and gas), and infrastructure development (e.g., ports, pipelines) can have substantial impacts on both the overall amount of vessel traffic as well as the degree of vessel-ice interactions in the study area. These impacts can be seen in the spatial patterns of vessel-ice interactions revealed in this study where the majority of vessel traffic in pack ice was located along known shipping routes and in areas

of active natural resource development. Below, we discuss a couple of specific examples of this pattern from this analysis.

On the North Slope of Alaska in the Beaufort Sea, vessel traffic in pack ice is associated with areas of known oil and gas activity. For example, after an exploratory well drilled in the Nikaitchuq lease area in late 2017 (State of Alaska 2018), vessel traffic activities in the pixel containing the drilling area increased from 130 km and 1743 km in 2015 and 2016, respectively to 5208 km and 5734 km in 2017 and 2018, respectively. These waters are shallow and no deep-draft commercial ships or icebreakers can operate this close to the shore.

On the western side of the Bering Strait, vessel activities in sea ice covered a broader area including the Gulf of Anadyr as well as the northern coast of the Chukotka Peninsula up to Wrangell Island (Fig. 4). These activities are reflective of Russian fishing vessel activities as well as destinational shipping along the Northern Sea Route. Russia uses ice-breaker escorts to extend the length of the shipping season along the Northern Sea Route (Brigham 2021), and it is likely that the concentration of vessel traffic in pack ice along the northern coast of Chukotka is a result of ice-breaker escorted voyages (Fig. 4). Given Russia's stated commitment to increased operationalization of the Northern Sea Route for eastbound transit to Asian destinations as well as China's reliance on Russian oil and gas for its Polar Silk Road initiative, vessel traffic in sea ice in this region is likely to continue increasing into the medium-term future. In fact, Russia has commissioned 15 icebreaking Arc7 LNG carriers designed to transport LNG from Europe to Asia. Despite delays, these icebreakers are expected to be coming online beginning in 2024 (Staalesen 2022).

4.3 Vessel-ice interactions are prevalent in ecologically important areas

Patterns of vessel-ice associations show marked overlap with ecologically important wintering areas for bowhead whales. In particular, our findings indicate that vessel-ice associations along the Northern Sea Route overlap with areas known to be occupied by bowhead whales during their fall migration through the Bering Strait and their wintering grounds in the northern Bering Sea (Quakenbush et al. 2010; Citta et al. 2012).

Increased vessel traffic in ice-covered bowhead whale concentration areas could exacerbate the impacts of vessel noise and also increase the risk of ship strike and entanglement. Between 1990 and 2012, approximately 12% of bowhead whales harvested by Alaska Native subsistence hunters showed signs of entanglement with fishing gear and a further 2% had scars associated with vessel strikes (George et al. 2017). Increased fishing activity in the Gulf of Anadyr in recent years (Kapsar 2022), coupled with our finding that fishing vessels are the most common vessel type in the MIZ, provides evidence that current risks of entanglement are likely higher today than in previous decades. With regard to the risk of ship strike, while the presence of sea ice may slow down vessel traffic and reduce the overall risk, further analysis of vessel speeds along the Northern Sea Route is needed to more fully evaluate the degree of ship strike risk.

In addition to effects on bowhead whales, this area on the western and northwestern sides of the Bering Strait was also identified by Hauser et al. (2018) as a region of high vulnerability in a study of seven Arctic marine mammal species, indicating that potential impacts of vessel-ice associations are not limited to just bowhead whales.

4.4 Limitations and future directions

While this study builds upon the findings of previous research, there are several factors that must be considered when interpreting the results. Although AIS data is one of the most comprehensive sources of position information on vessels at a global scale, it does not cover all vessel traffic. Notably for this analysis, military vessels are exempt from AIS carriage requirements. Given that the Pacific Arctic contains the only shared border between the USA and Russia, there are likely military vessels in the region whose presence is not recognized in these data. Since many vessels with ice-breaking capacity are military in nature, our results likely represent an underestimate of the true amount of vessel traffic in sea ice.

Specific vessel activities should not be directly inferred by the presence of a given vessel type. In other words, just because a fishing vessel moves through a given area does not mean it is actively fishing in that region. Similarly, cargo vessels are not always carrying cargo through a given location. Furthermore, some vessel types are frequently used for multiple purposes. For example, research on fish distribution and population dynamics is often done aboard fishing vessels. In the case of the current study, our finding of the presence of fishing vessel activity near the ice edge does not necessarily mean that vessels are actively fishing in this region. Further research on vessel movement patterns and the elimination of known research vessels from this category would be needed to definitively confirm active fishing in this region.

Another limitation of our study is with regard to the distribution of sea ice within a pixel. This analysis assumes that ice coverage within a pixel is homogenous, but this is likely not the case. In many instances of low ice concentration, ice coverage is most likely clustered in one portion of a pixel. This means that, in some cases, vessel traffic that has been categorized as "in ice" is not in actuality transiting through ice directly but rather is moving close to the ice edge. Despite this assumption, the parallel increases in total vessel traffic in both the MIZ and pack ice indicate that overall increases are not the result of vessel traffic along the ice edge. Future analyses at finer spatiotemporal scales with higher resolution data on sea ice concentration could help to tease out the ice conditions encountered by individual vessels.

Future research could also benefit from a more integrative metric of sea ice coverage that is relevant to vessel traffic, such as the POLARIS RIO, which provides a risk index for the safety of navigation based on sea ice thickness measurements. For instance, future analyses could use AIS data to build upon work such as that of Fedi et al. (2020) who evaluated RIO conditions at the locations of maritime accidents along the Northern Sea Route. Paired with AIS, this approach could be applied to identify areas or types of ships exhibiting "risky" navigation practices.

5 Conclusions

It is widely accepted that climate change is reducing Arctic sea ice coverage and that Arctic vessel traffic is increasing. However, the degree and distribution of vessel traffic in areas of ice cover remain understudied. In this analysis, we examined the spatiotemporal patterns of vessel-ice interactions in the Pacific Arctic. We found that fishing vessels dominated vessel traffic in areas of marginal ice coverage. Mapping the spatial distribution of vessel

traffic in ice-covered areas further revealed that vessel-ice interactions are most prevalent along existing routes, including areas of concentrated vessel activity in sea ice on the North Slope of Alaska and the Northern Sea Route in Russia. Vessel-ice interactions along the Northern Sea Route are concerning given the high degree of spatiotemporal overlap with areas of high winter concentration for bowhead whales, an important subsistence species. These findings represent an important step towards guiding spatial management measures for vessel traffic in dynamic regions where sea ice cover plays a substantial role in shaping the spatiotemporal dynamics of both ecological and human activities.

Authors' contribution All authors were involved in data interpretation as well as the conceptualization, writing, reviewing, and editing of the manuscript. KK collected data and ran the analysis.

Data availability Sea ice data used in this analysis are openly available from the National Science Foundation (NSF) Arctic Data Center at https://doi.org/10.5194/tc-11-1607-2017. Due to third-party restrictions, an anonymized and generalized form of the vessel traffic data is available from the NSF Arctic Data Center at https://doi.org/10.18739/A2P55DJ23. Exact anonymized raster data sets used in this analysis can be made available by the authors upon request.

Declarations

Competing interest The authors declare no competing interests.

References

Aksenov Y, Popova EE, Yool A et al (2017) On the future navigability of Arctic sea routes: high-resolution projections of the Arctic Ocean and sea ice. Mar Policy 75:300–317. https://doi.org/10.1016/j.marpol.2015.12.027

Berkman PA, Fiske G, Lorenzini D (2020) Baseline of next-generation Arctic marine shipping Assessments - oldest continuous pan-Arctic satellite automatic identification system (AIS) Data Record of Maritime Ship Traffic, 2009-2016. Arctic Data Center. https://doi.org/10.18739/A2TD9N89Z

Brigham LW (2021) The Russian maritime Arctic: region of great change in the 21st century. CIWAG Maritime Irregular Warfare Studies. 2. https://digital-commons.usnwc.edu/ciwag-case-studies/02

Citta JJ, Quakenbush LT, George JC et al (2012) Winter movements of bowhead whales (Balaena mysticetus) in the Bering Sea. Arctic 65:13–34

Constable AJ, Harper S, Dawson J et al (2022) Cross-chapter paper 6: polar regions. In: Pörtner H-O, Roberts DC, Tignor M et al (eds) Climate Change, 2022: Impacts, Adaptation and Vulnerability. Cambridge University Press, pp 2319–2368

Dawson J, Pizzolato L, Howell SEL et al (2018) Temporal and spatial patterns of ship traffic in the Canadian Arctic from 1990 to 2015. Arctic 71:15–26. https://doi.org/10.14430/arctic4698

Erbe C, Marley SA, Schoeman RP et al (2019) The effects of ship noise on marine mammals—a review. Front Mar Sci 6:606. https://doi.org/10.3389/fmars.2019.00606

Fall JA (2016) Regional patterns of fish and wildlife harvests in contemporary Alaska. Arctic 69:47–64. https://doi.org/10.14430/Arctic4547

Fedi L, Faury O, Etienne L (2020) Mapping and analysis of maritime accidents in the Russian Arctic through the lens of the polar code and POLARIS system. Mar Policy 118:103984. https://doi.org/10.1016/j.marpol.2020.103984

Fissel B, Dalton M, Garber-Yonts B et al (2021) Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska and Bering Sea/Aleutian Islands area: economic status of the groundfish fisheries off Alaska, 2019. https://www.fisheries.noaa.gov/alaska/ecosystems/economic-status-reports-gulf-alaska-and-beringsea-aleutian-islands

George JC, Sheffield G, Reed DJ et al (2017) Frequency of injuries from line entanglements, killer whales, and ship strikes on Bering-Chukchi-Beaufort Seas bowhead whaleS. Arctic 70:37–46. https://doi.org/10.14430/arctic4631

Hauser DDW, Laidre KL, Stern HL (2018) Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route. Proc Natl Acad Sci 115:7617–7622. https://doi.org/10.1073/pnas.1803543115

Heide-Jørgensen MP, Laidre KL, Litovka D et al (2012) Identifying gray whale (Eschrichtius robustus) foraging grounds along the Chukotka Peninsula, Russia, using satellite telemetry. Polar Biol 35:1035–1045. https://doi.org/10.1007/s00300-011-1151-6

Huntington HP, Daniel R, Hartsig A et al (2015) Vessels, risks, and rules: planning for safe shipping in Bering Strait. Mar Policy 51:119–127. https://doi.org/10.1016/j.marpol.2014.07.027

ICC Alaska (2015) Alaskan Inuit food security conceptual framework. https://iccalaska.org/wp-icc/wp-content/uploads/2016/03/Food-Security-Summary-and-Recommendations-Report.pdf

IMO (2002) Resolution A.917(22): Guidelines for the onboard operational use of shipborne automatic identification systems (AIS). https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/AssemblyDocuments/A.917(22).pdf

Kapsar K (2022) The metacoupled Arctic and North Pacific: Analyzing the spatiotemporal patterns and impacts of marine vessel traffic in coupled human and natural systems (Publication No. 29166813). [Doctoral thesis, Michigan State University]. ProQuest Dissertations and Theses Global

Kapsar K, Frans VF, Brigham LW, Liu J (2022a) The metacoupled Arctic: human-nature interactions across local to global scales as drivers of sustainability. Ambio 51(10):2061–2078. https://doi.org/10.1007/s13280

Kapsar K, Sullender B, Liu J, Poe A (2022b) North Pacific and Arctic marine traffic dataset (2015-2020). Data Brief 44:108531. https://doi.org/10.1016/j.dib.2022.108531

Kawerak Inc. Marine Program (2016) Bering Strait voices on Arctic shipping: moving forward to protect Alaska native ways of life and the natural resources we rely on. Nome, Alaska. https://kawerak.org/wp-content/uploads/2018/04/BSVAS-report2016.pdf

Khon VC, Mokhov II, Semenov VA (2017) Transit navigation through northern sea route from satellite data and CMIP5 simulations. Environ Res Lett 12:024010. https://doi.org/10.1088/1748-9326/aa5841

Larsen JN, Huskey L (2015) The Arctic economy in a global context. In: The New Arctic. Springer International Publishing, pp 159–174

Lavergne T, Macdonald Sørensen A, Kern S et al (2019) Version 2 of the EUMETSAT OSI SAF and ESA CCI sea-ice concentration climate data records. Cryosphere 13:49–78. https://doi.org/10.5194/tc-13-49-2019

Levine RM, De Robertis A, Grünbaum D et al (2023) Climate-driven shifts in pelagic fish distributions in a rapidly changing Pacific Arctic. Deep Sea Res 2 Top Stud Oceanogr 208:105244. https://doi.org/10.1016/j.dsr2.2022.105244

Lindsay J, Laidre K, Conn P et al (2021) Modeling ringed seal Pusa hispida habitat and lair emergence timing in the eastern Bering and Chukchi Seas. Endanger Species Res 46:1–17. https://doi.org/10.3354/esr01140

Maznikova OA, Emelin PO, Sheibak AY et al (2023) Can an invader support commercial fishing? A case study of walleye pollock Gadus chalcogrammus in the western Chukchi Sea. Deep Sea Res 2 Top Stud Oceanogr 207:105222. https://doi.org/10.1016/j.dsr2.2022.105222

Melia N, Haines K, Hawkins E (2016) Sea ice decline and 21st century trans-Arctic shipping routes. Geophys Res Lett 43:9720–9728. https://doi.org/10.1002/2016GL069315

Mudryk LR, Dawson J, Howell SEL et al (2021) Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. Nat Clim Chang 11:673–679. https://doi.org/10.1038/s41558-021-01087-6

North Pacific Fishery Management Council (2020) Fishery management plan for groundfish of the Bering sea and Aleutian islands. Anchorage. https://www.fisheries.noaa.gov/management-plan/groundfish-bering-sea-and-aleutian-islands-management-plan

PAME (2020) Arctic shipping status report #1. https://pame.is/projects/arctic-marine-shipping/arctic-shipping-status-reports/723-arctic-shipping-report-1-the-increase-in-arctic-shipping-2013-2019-pdf-version/file

Peng G, Steele M, Bliss AC et al (2018) Temporal means and variability of Arctic Sea ice melt and freeze season climate indicators using a satellite climate data record. Remote Sens (Basel) 10:1328. https://doi.org/10.3390/rs10091328

Pizzolato L, Howell SEL, Dawson J et al (2016) The influence of declining sea ice on shipping activity in the Canadian Arctic. Geophys Res Lett 43:12146–12154. https://doi.org/10.1002/2016GL071489

Pizzolato L, Howell SELL, Derksen C et al (2014) Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. Clim Change 123:161–173. https://doi.org/10.1007/s10584-013-1038-3

Quakenbush LT, Citta JJ, George JC et al (2010) Fall and winter movements of bowhead whales (Balaena mysticetus) in the Chukchi Sea and within a potential petroleum development area. Arctic 63:289–307

Rantanen M, Karpechko AY, Lipponen A et al (2022) The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ 3:168. https://doi.org/10.1038/s43247-022-00498-3

Ricker R, Hendricks S, Kaleschke L et al (2017) A weekly Arctic Sea-ice thickness data record from merged CryoSat-2 and SMOS satellite data. Cryosphere 11:1607–1623. https://doi.org/10.5194/tc-11-1607-2017

Roth EH, Schmidt V, Hildebrand JA, Wiggins SM (2013) Underwater radiated noise levels of a research icebreaker in the central Arctic Ocean. J Acoust Soc Am 133:1971–1980. https://doi.org/10.1121/1.4790356

Serreze MC, Crawford AD, Stroeve JC et al (2016) Variability, trends, and predictability of seasonal sea ice retreat and advance in the Chukchi Sea. J Geophys Res Oceans 121:7308–7325. https://doi.org/10.1002/2016JC011977

Smith LC, Stephenson SR (2013) New Trans-Arctic shipping routes navigable by midcentury. Proc Natl Acad Sci 10:6–10. https://doi.org/10.1073/pnas.1214212110

Smith MA, Goldman MS, Knight EJ, Warrenchuk JJ (2017) Ecological atlas of the Bering, Chukchi, and Beaufort Seas, 2nd edn. Audubon Alaska, Anchorage, AK. https://ak.audubon.org/conservation/ecological-atlas-bering-chukchi-and-beaufort-seas

Staalesen A (2021) Tanker embarks on first ever mid-winter voyage on Northern Sea Route. The Barents Observer. https://thebarentsobserver.com/en/arctic-lng/2021/02/tanker-embarks-first-ever-mid-winter-voyage-northern-sea-route

Staalesen A (2022) Arctic tanker trouble for Novatek's new flagship project. Barents Observer. https://thebarentsobserver.com/en/industry-and-energy/2022/12/arctic-tanker-trouble-novateks-new-flagship-project

State of Alaska (2018) North slope oil and gas activity. https://dog.dnr.alaska.gov/Documents/Maps/ActivityMaps/NorthSlope/NS_ActivityMap_May2018.pdf

Stephenson SR, Smith LC, Agnew JA (2011) Divergent long-term trajectories of human access to the Arctic. Nat Clim Chang 1:1–5. https://doi.org/10.1038/nclimate1130

Stephenson SR, Smith LC, Brigham LW, Agnew JA (2013) Projected 21st-century changes to Arctic marine access. Clim Change 118:885–899. https://doi.org/10.1007/s10584-012-0685-0

Stocker AN, Renner AHH, Knol-Kauffman M (2020) Sea ice variability and maritime activity around Svalbard in the period 2012–2019. Sci Rep 10:17043. https://doi.org/10.1038/s41598-020-74064-2

Strong C, Rigor IG (2013) Arctic marginal ice zone trending wider in summer and narrower in winter. Geophys Res Lett 40:4864–4868. https://doi.org/10.1002/grl.50928

Tsujii K, Otsuki M, Akamatsu T et al (2021) Annual variation of oceanographic conditions changed migration timing of bowhead whales Balaena mysticetus in the southern Chukchi Sea. Polar Biol 44:2289–2298. https://doi.org/10.1007/s00300-021-02960-y

Wagner PM, Hughes N, Bourbonnais P et al (2020) Sea-ice information and forecast needs for industry maritime stakeholders. Polar Geogr 43:160–187. https://doi.org/10.1080/1088937X.2020.1766592

Waloven S, Kapsar K, Schwoerer T et al (2023) Global gateways as telecoupled human and natural systems: the emerging case of the Bering Strait. Ambio 52(6):1040–1055. https://doi.org/10.1007/s13280-023-01835-2

Wang C, Ding M, Yang Y et al (2022) Risk assessment of ship navigation in the northwest passage: historical and projection. sustainability. 14(9):5591. https://doi.org/10.3390/su14095591