POAC'25
St. John's, Newfoundland and Labrador, Canada

Proceedings of the 28th International Conference on Port and Ocean Engineering under Arctic Conditions
Jul 13-17, 2025
St. John's, Newfoundland and Labrador
Canada

Maritime Trends and Ice Risks in Svalbard: Challenges in a Changing Arctic

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ABSTRACT

Climate change is rapidly reshaping the Arctic, with Svalbard experiencing a ~4°C temperature increase over the past 50 years, exceeding regional trends. This warming has led to extensive sea ice retreat, delayed winter freeze-ups, and a 10% rise in maritime traffic between 2013 and 2023. The extended sailing season (+2 months), shifting fish stocks, and increased Arctic tourism, along with regulatory changes like the Polar Code, have reshaped vessel activity. However, maritime expansion in these unpredictable waters heightens navigational risks, emphasising the urgent need for improved ice monitoring, enhanced safety measures, and regulatory oversight. This study analyses the link between sea ice dynamics and vessel activity, assessing how environmental and policy factors shape Arctic shipping patterns.

KEYWORDS: Climate Change, Navigational Challenges, Sea Ice, Svalbard, Ice Charts

INTRODUCTION

Climate change is most pronounced in the Arctic, where the temperature has risen significantly over the last decade, driving ocean acidification, glacier melt, sea level rise, ocean currents, altered precipitation patterns and more frequent extreme weather events (AMAP, 2017; Mudryk et al., 2021). One of the clearest indicators of Arctic change is the substantial decline in sea ice cover, alongside thinning ice (Kwok, 2018) and a reduction in multi-year ice (Meier et al., 2014; Barber et al., 2018; Meier et al., 2022). Spring melt occurs earlier, and freeze-up is delayed, increasing heat absorption in the ice-ocean system and further accelerating warming. Svalbard, in particular, has warmed at a rate exceeding the Arctic average, resulting in a substantial retreat of the seasonal ice edge and a delayed winter freeze-up. These shifts in sea ice dynamics significantly impact maritime activity, influencing both navigational accessibility and operational risks.

Despite the overall decline in Arctic sea ice, interannual variability remains a critical navigational challenge. Temporary ice re-expansion in certain years has disrupted vessel access, requiring constant route adaptations (PAME, 2020). Additionally, current sea ice forecasting models remain limited in their short-term accuracy, creating operational risks for vessels navigating near the ice edge (Wu et al., 2023). This study aims to bridge this gap by examining how vessel activity has adapted to shifting sea ice conditions and evaluating the effectiveness of current maritime policies in mitigating associated risks. Svalbard's location between the Arctic Ocean and the North Atlantic further contributes to its complex ice conditions (Figure 1). The West Spitsbergen Current (WSC) transports warm Atlantic Water northward, limiting ice formation, whereas the East Greenland Current (EGC) carries cold Polar Surface Water southward, affecting local ice conditions (Johannessen et al., 2020). The process of Atlantification, the increasing inflow of warm Atlantic Water, has been accelerating ice loss while simultaneously increasing seasonal fluctuations in ice coverage (Jakobsen et al., 2012). These environmental changes have profound implications for Arctic shipping, necessitating enhanced monitoring, forecasting, and regulatory adaptation.

Figure 1: Arctic region with Svalbard highlighted. Source: The Arctic Portal (2024) modified to highlight Svalbard.

DATA AND METHODS

This study uses Automated Identification System (AIS) data from the Global Maritime Traffic Density Service (GMTDS) and sea ice concentration data from the National Snow and Ice Data Centre (NSIDC) to analyse vessel presence in general and in sea ice. AIS data is converted into monthly raster grids at a 1-kilometre spatial scale, measuring vessel densities per km² per month. This dataset categorises marine vessels into fishing, cargo, and passenger types. Cargo ships include research vessels, as some research vessels serve a dual purpose, carrying cargo alongside their primary research function. However, they exclude service ships, non-commercial ships, and tankers. Passenger ships, in this case, are vessels designed to carry more than 12 passengers, without distinguishing between general passenger vessels and cruise ships. They exclude icebreakers and research vessels (except those classified as passenger vessels) (GMTDS, 2024). Sea ice concentration data is converted into monthly raster grids at a 25-kilometre spatial scale, representing the percentage of sea ice cover in each area, ranging from 15% to 100% (NSIDC, 2024). The spatial analysis of vessel traffic shows that while most operations occur in ice-free waters, some vessels extend into ice-covered regions during specific months.

DATA PROCESSING

To analyse the spatial relationship between maritime activity and sea ice conditions around Svalbard, ArcGIS Pro created detailed maps combining monthly vessel density data (passenger, cargo, and fishing vessels) from 2013 to 2023 with sea ice concentration data. The maps cover a 200,000 km² area around Svalbard, highlighting key navigational patterns and maritime activities between 72°N–86°N and 3°W–45°E. These maps illustrate areas with high vessel density within sea ice, newly navigated regions, and patterns and anomalies in vessel behaviour. Data from the NSIDC provided detailed sea ice type and concentration maps, helping to identify challenging navigational areas and track changes over time.

R Studio (version 4.2.2) analysis identified the spatial and temporal distribution of vessel activities navigating close to ice edges or within partially ice-covered waters (15-30% sea ice concentration). The study revealed risk exposure and adaptation patterns among different vessel types in challenging Arctic environments by correlating vessel density with sea ice conditions.

RESULTS

Maritime Traffic Trends in Svalbard (2013–2023)

Over the past decade, maritime traffic density near Svalbard has increased by approximately 10%, influenced by climate-driven changes in sea ice extent, shifting fisheries, tourism expansion, and evolving shipping patterns (Figure 2) (PAME, 2024).

Fishing vessels operate closest to the ice edge, frequently adjusting their routes in response to seasonal fish migrations and ice retreat (Østreng et al., 2013; Babb et al., 2023). As sea ice declines, fish stocks have shifted northward, forcing fishing fleets to follow these ecological changes (PAME, 2020).

Passenger vessels have also expanded their range further northward, as the retreating ice edge has enabled access to previously inaccessible areas. Expedition cruises increasingly look for close encounters with Arctic wildlife and sea ice, making the ice edge a primary attraction (Marchenko, 2014).

Cargo vessels have largely maintained stable routes, following established shipping lanes. However, they occasionally reroute due to shifting ice conditions, leading to longer transit times and increased logistical uncertainties (Johannessen et al., 2020). Despite the overall decline in long-term sea ice extent, interannual ice variability still influences vessel distribution, with some years showing temporary ice expansion, limiting access to Arctic waters (AMAP, 2017; Wu et al., 2023).

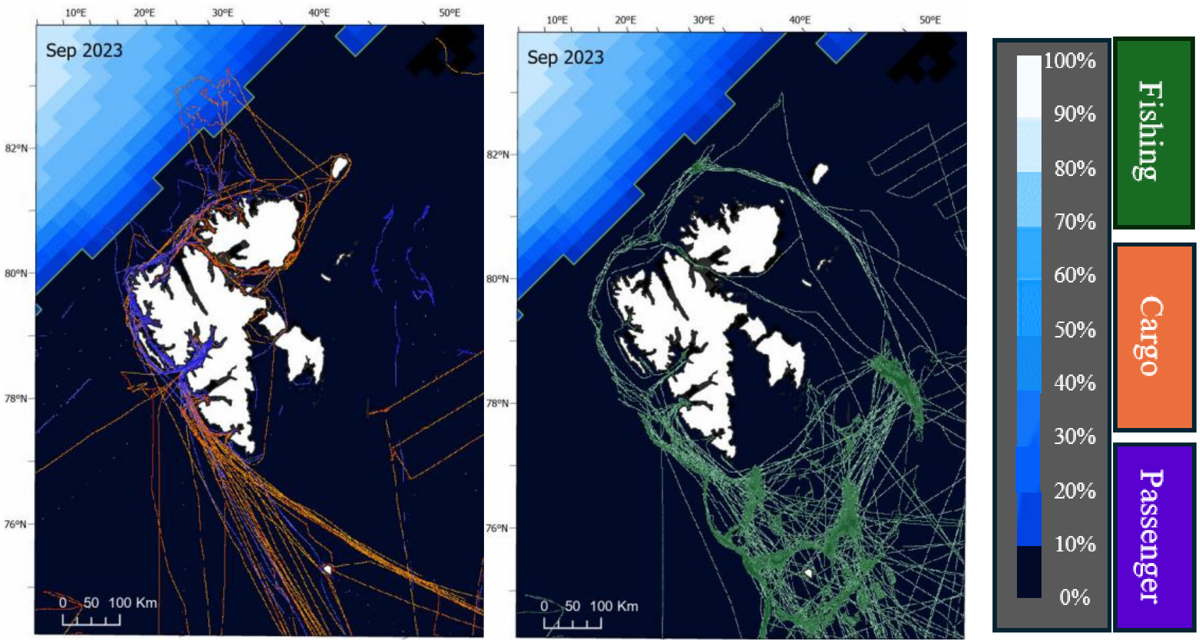

Figure 2: Maps with fixed routes for cargo and passenger vessels (left) and more dispersed routes for fishing vessels (right), September 2023.

The following graph (Figure 3) provides an overview of vessel density (in hours) across different years (2013-2023) for cargo (orange), fishing (green), and passenger (purple) vessels.
Cargo vessels show relatively stable trends (~40,000 hours per year) except for a sharp drop in 2019 (~30,000 hours) and an extreme peak in 2021 (~220,000 hours), likely due to post-pandemic recovery and increased Arctic trade activity.
Passenger vessels steadily increased from 30,000 hours in 2013 to nearly 100,000 hours in 2023. The only anomaly was a sharp drop to 18,000 hours in 2020 and 2021, corresponding to COVID-19 travel restrictions affecting the cruise industry.
Fishing vessels displayed the highest activity, peaking at 350,000 hours in 2022, a 58% increase from 2019. This was driven by shifting fish stocks and extended ice-free periods. A drop in 2020 (230,000 hours) due to the pandemic was followed by a recovery, stabilising around 220,000 hours in 2023.

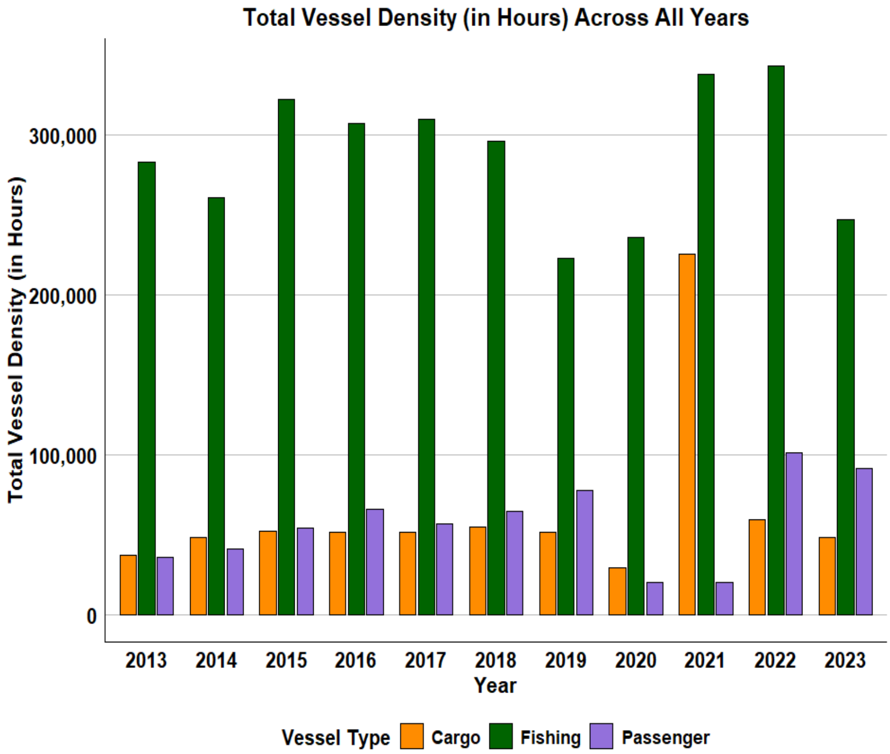

Figure 3: Total vessel density in hours for passenger, cargo, and fishing vessels around Svalbard (2013-2023).

Changing Sea Ice Conditions in Svalbard

Both climate change and oceanographic factors influence the seasonal and interannual variability of sea ice around Svalbard. While long-term trends indicate a steady decline in Arctic sea ice extent, interannual fluctuations still cause temporary ice expansion in certain years, affecting vessel accessibility (Stroeve & Notz, 2018). The variability in ice extent complicates navigation for vessels operating near the ice edge, with fishing vessels in

particular needing to adjust their routes according to seasonal changes in sea ice cover (Eguíluz et al., 2016).
Observational data indicate that while the navigable season has extended by 1 to 3 months over the past few decades, some years still experience unexpected ice re-expansion, temporarily restricting maritime access (Babb et al., 2023). This highlights the importance of short-term sea ice forecasting, which remains challenging due to the high degree of unpredictability in local ice dynamics (PAME, 2020).

Key Navigational Risks Associated with Sea Ice

Despite the observed retreat in Arctic sea ice, navigating through ice-covered waters remains hazardous due to the dynamic and unpredictable nature of ice movement. Several key risks persist:
Ice Drift and Compression: Ships in marginal ice zones frequently encounter drifting ice floes, which can put lateral pressure on vessel hulls, increasing the risk of structural damage (Marchenko, 2014). The rapid movement of ice also increases the likelihood of vessels becoming trapped in compressing ice fields, as seen in past maritime incidents around Svalbard (Babb et al., 2023).
Ice Spray Accumulation: In Arctic conditions, sea spray can freeze on vessel surfaces, accumulating ice layers that increase weight and reduce vessel stability. This phenomenon can lead to mechanical failures, loss of manoeuverability, and even capsising in extreme cases (PAME, 2020).
Unpredictable Ice Barriers: As Arctic ice dynamics change, unexpected ice formations and shifting floes can suddenly block established shipping routes, forcing vessels to reroute or risk becoming ice-bound (Eicken et al., 2011). This issue is particularly relevant for cargo vessels, which rely on stable transit corridors and scheduled shipping lanes.
Forecasting Limitations: Despite improvements in satellite observations, short-term ice forecasting remains highly uncertain due to rapid changes in local ice conditions. Current models typically provide reliable forecasts only up to one or two days ahead, which is insufficient for effective route planning in high-risk ice areas (Wu et al., 2023).

The Role of Ocean Currents in Ice Variability

Svalbard’s sea ice conditions are heavily influenced by regional oceanic circulation patterns, which affect both the extent and stability of ice coverage. The West Spitsbergen Current (WSC), a warm Atlantic current, flows northward along Svalbard’s western coast, reducing ice formation and creating open-water corridors even in winter (Johannessen et al., 2020). Conversely, the East Greenland Current (EGC) transports cold Arctic waters southward, increasing ice concentration in Svalbard’s northeastern and eastern waters (Jakobsen et al., 2012).
The process of Atlantification, characterised by increased warm water inflow into the Arctic Ocean, has been delaying winter freeze-up, accelerating summer melt, and increasing seasonal variability in ice cover (Polyakov et al., 2017). This shift in oceanographic conditions is leading to higher levels of interannual ice variability, making Arctic navigation more uncertain (Wu et al., 2023). This trend has profound implications for maritime operations, as ships must navigate through increasingly unstable ice conditions, requiring greater reliance on real-time ice monitoring and adaptive routing strategies (Stroeve et al., 2018).

Additionally, expanding maritime traffic into Arctic waters raises significant environmental concerns. Increased vessel activity contributes to rising black carbon emissions, accelerating ice melt by reducing ice albedo (PAME, 2024). Furthermore, underwater noise pollution from large commercial vessels disrupts marine ecosystems, affecting species such as narwhals, walruses, and polar bears (AMAP, 2017). There is also a heightened risk of oil spills, particularly as shipping operations expand into ice-covered regions, where oil cleanup is extremely challenging (Johannessen et al., 2020).

Vessel Activity in Ice-covered Waters

While the long-term decline in sea ice has facilitated increased maritime activity, the persistence of interannual variability continues to impose operational constraints. Despite these risks, vessel traffic in ice-covered waters has steadily risen, with ships spending more time navigating within these marginal ice zones. The following maps (Figure 4) show vessel interaction with sea ice.

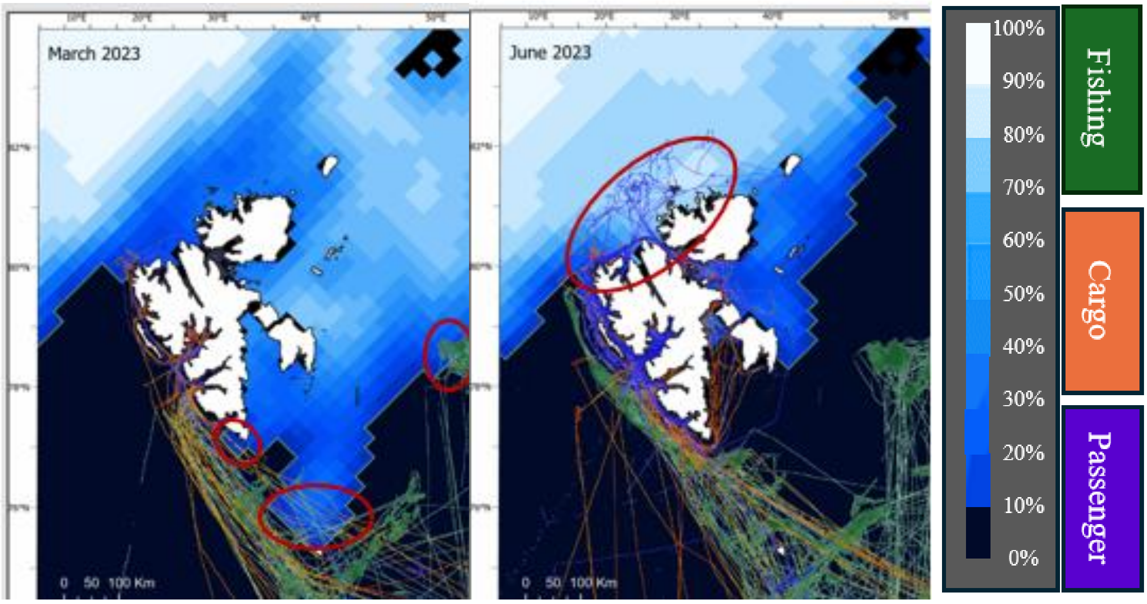

Figure 4: Fishing vessels (green), passenger vessels (purple), and cargo vessels (orange) navigating into sea ice (circled in red) in the east, south and north of Svalbard.

Maritime activity in 15–30% sea ice concentration zones has increased, particularly for fishing vessels, which continuously adapt to shifting ice conditions (Babb et al., 2023). The greatest navigational risks near Svalbard occur in these regions, where vessels encounter drifting ice floes, ice compression, and unpredictable ice movements, heightening the risk of collisions and operational disruptions (Johannessen et al., 2020). Although vessels operate across various ice concentration levels, only icebreakers and research vessels typically navigate areas with >30% ice concentration. Due to the limited vessel traffic in these high-ice regions, this analysis focuses primarily on 15–30% sea ice concentration zones.

The following dual-axis graph (Figure 5) illustrates vessel activity in sea ice, with grid cell activity (bars) indicating where vessels operated, and vessel hours (lines) reflecting how long vessels spent in ice-covered waters. Comparing these metrics helps assess whether maritime traffic is becoming more concentrated or dispersed, influencing navigational safety, environmental impacts, and Search and Rescue (SAR) preparedness.

Fishing vessels exhibited a 58% increase in total vessel hours in 2022, correlating with prolonged sea ice retreat and increased access to historically ice-covered regions (Babb et al., 2023). This expansion reflects both favourable ice conditions and economic incentives to exploit more northern waters. Fishing activity in ice-covered waters is largely dictated by ecosystem shifts and seasonal sea ice retreat, as commercial fish species move closer to or beyond the ice edge (PAME, 2020).

Passenger vessels have also expanded operations in ice-covered waters, particularly during peak summer months, when expedition cruises actively seek ice-covered regions to enhance the tourist experience (Marchenko, 2014). Passenger vessel activity peaked in 2022 and 2023, reflecting rising demand for Arctic tourism in regions with dynamic ice conditions (PAME, 2024).

Cargo vessels typically avoid high-ice areas, however, temporary peaks in Arctic trade activity have resulted in occasional operations within sea ice zones, particularly in 2021, when post-pandemic economic recovery contributed to a brief increase in cargo ship activity (Babb et al., 2023).

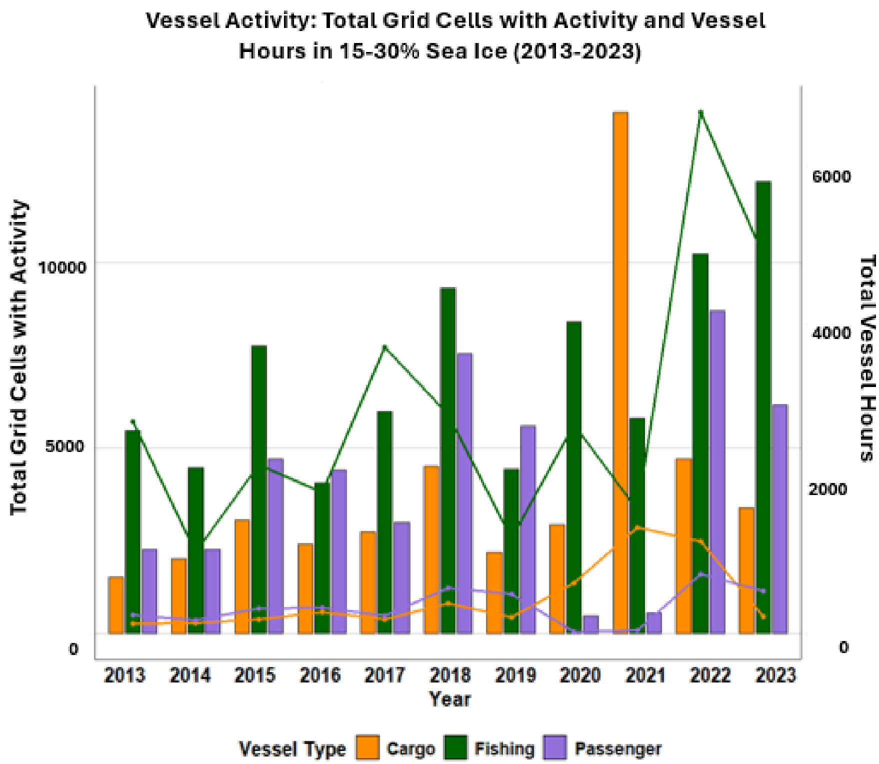

Figure 5: Total vessel density activity (in hours)in 15–30% sea ice concentration (per km^2) (passenger, cargo, and fishing vessels) around Svalbard (2013-2023).

The following maps (Figure 6) illustrate vessel traffic variability in sea ice during two distinct months, April and July, highlighting seasonal differences in maritime operations.

In April, fishing vessel density in ice-covered waters appears more stable, with peaks in 2018, 2022, and 2023, corresponding to years with higher sea ice extent, particularly in the south and east of Svalbard. During these years, passenger vessels also expanded their operations into ice-covered regions, moving northward into the ice. As northern Svalbard becomes enclosed by ice during this period, vessels no longer need to travel as far to encounter ice, leading to higher vessel density in years with extensive ice coverage.

By July, ice retreat allows for greater maritime access, influencing vessel distribution. Fishing vessels were present in sea ice between 2015–2017 and again in 2023, showing a notable increase in activity during these years. Passenger vessel activity in sea ice peaked in 2022 and 2023, particularly in northern waters, where tourism demand for ice-covered experiences intensified. In contrast, earlier peaks in 2015 and 2017 were concentrated in Hinlopen Strait, where high ice extent shaped navigational patterns. Over time, passenger vessel presence in sea ice has generally increased, except for the decline in 2020 and 2021, coinciding with the COVID-19 pandemic's impact on Arctic tourism.

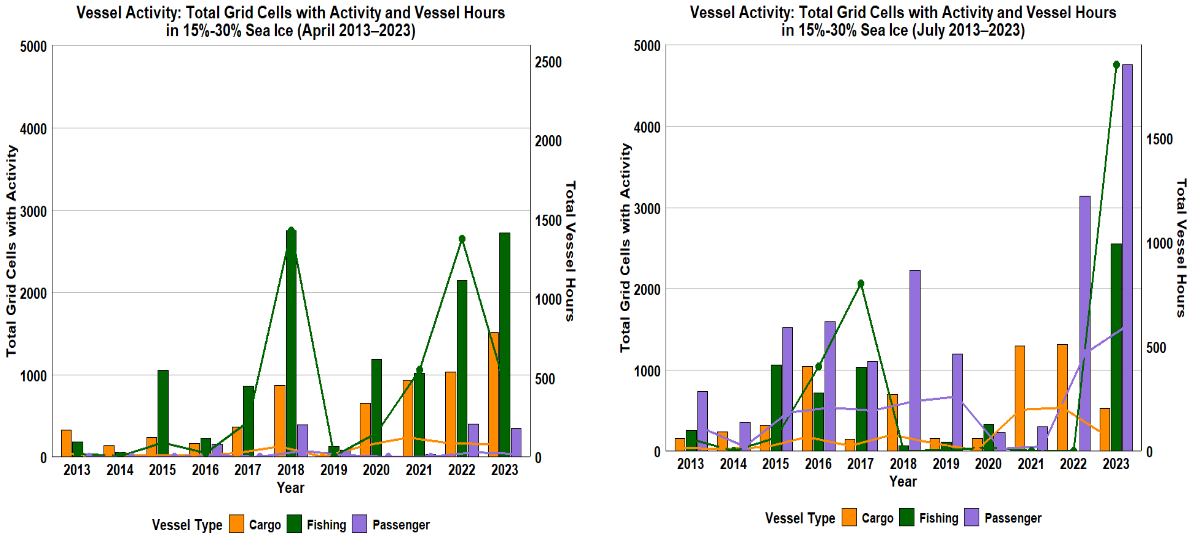

Figure 6: Total vessel density activity (in hours)in 15-30% sea ice concentration (per km^2) (for passenger, cargo and fishing vessels) in April and July around Svalbard in 2013-2023

DISCUSSION

Navigational Risks and Safety Concerns

The retreat of Arctic sea ice has expanded maritime access, yet operating in ice-covered waters remains unpredictable and hazardous (Johannessen et al., 2020).

Forecasting limitations remain a critical challenge. Short-term sea ice predictions are highly uncertain due to seasonal variability and inconsistencies in climate models, making voyage planning difficult and increasing the likelihood of ice-related incidents (Wu et al., 2023). In years with high ice variability, vessels faced unexpected access restrictions, while in low-ice years, an extended season led to higher traffic density within marginal ice zones, raising collision risks.

Between 2013 and 2021, 42% of the 55 maritime incidents recorded in Svalbard involved fishing vessels, primarily due to groundings, human error, and ice-related mechanical failures (Babb et al., 2023). The limited Search and Rescue (SAR) infrastructure further increases these risks, as harsh Arctic conditions and long response times significantly reduce the chances of rapid emergency intervention (PAME, 2020).

In addition to sea ice retreat, Atlantification has disrupted Arctic ice dynamics, delaying winter freeze-up and accelerating summer melt (Johannessen et al., 2020). This phenomenon has led to greater interannual ice variability, with some years experiencing unexpected ice re-expansion, temporarily restricting maritime access. These shifting ocean currents create unstable ice conditions, making Arctic navigation increasingly unpredictable and further highlighting the need for reliable short-term ice forecasts (Jakobsen et al., 2012; Wu et al., 2023).

Environmental Concerns

While declining ice cover has opened new shipping opportunities, increasing vessel traffic raises environmental concerns. One key issue is black carbon emissions, which reduce ice albedo and accelerate regional warming (PAME, 2024). The growing presence of ships also contributes to underwater noise pollution, disrupting Arctic marine species such as narwhals, walruses, and polar bears, which rely on sound for navigation and communication (AMAP, 2017).

Expanding shipping routes also increases the risk of oil spills, particularly in ice-covered waters, where cleanup operations are extremely difficult due to slow oil degradation and logistical challenges (Johannessen et al., 2020). Without stronger regulatory measures, the environmental consequences of Arctic maritime expansion could further accelerate climate change impacts and disrupt fragile Arctic ecosystems.

Improving Ice Forecasting and Real-Time Monitoring

Navigating Arctic waters remains highly unpredictable due to the dynamic nature of sea ice and the limitations of current forecasting models, which often lack sufficient spatial resolution and struggle with accurate short-term predictions. Consequently, vessels are at increased risk of encountering unexpected ice formations, compression zones, and drifting floes, leading to a higher likelihood of accidents (Wu et al., 2023). Addressing these challenges requires enhancing real-time ice monitoring and forecasting systems. Recent advances, such as supervised machine learning and deep learning methods, have significantly reduced forecast errors, by as much as 41% compared to traditional models, by integrating AIS data, high-resolution satellite imagery, in situ and satellite-based sea ice thickness observations, and historical ice movement patterns. This comprehensive approach enables large-scale data analysis and the provision of up-to-date ice charts for mariners, resulting in more accurate and reliable predictions for maritime safety and navigation (Palerme et al., 2024; Hutchings et al., 2019; Yang et al., 2023).

Expanding Search and Rescue (SAR) Capabilities

The increasing number of vessels operating in Arctic waters, particularly near the ice edge, poses a significant challenge for emergency response services. The vast distances, extreme weather conditions, and limited SAR infrastructure significantly hinder the ability to conduct rapid and effective rescue operations (PAME, 2020).

To mitigate these risks, it is essential to establish dedicated SAR bases in strategic Arctic locations, equipped with ice-capable rescue vessels, long-range helicopters, and emergency response stations. Strengthening international cooperation among Arctic states through joint training exercises, shared resources, and standardised response protocols would also enhance the effectiveness of cross-border SAR operations (Sydnes et al., 2017). Furthermore, requiring vessels to carry enhanced emergency communication systems and ice survival equipment would improve preparedness in case of ice-related incidents. Expanding SAR capabilities will be crucial as Arctic vessel traffic increases, ensuring that maritime safety keeps pace with the region’s growing navigational activity.

Strengthening Arctic Regulations and Environmental Safeguards

The implementation of the Polar Code (2017) established minimum safety and environmental standards for Arctic navigation, but further regulatory improvements are needed to address emerging challenges (Johannessen et al., 2020). As climate change alters ice conditions and vessel activity expands, regulations must adapt to ensure safe and sustainable Arctic shipping (Huntington et al., 2023).

One crucial area for improvement is tightening emissions regulations to reduce black carbon pollution, which accelerates sea ice melt and contributes to Arctic warming (Huntington et al., 2023; Chen & Wang, 2019). Additionally, mandatory ice navigation training for vessel operators should be enforced to minimise ice-related accidents, ensuring that all ships operating in high-risk ice zones have adequately trained crews. Expanding ice-class vessel requirements would further improve safety, ensuring that ships navigating near the ice edge meet stricter operational and structural standards (Kujala et al., 2024).

Furthermore, regulations should incorporate dynamic navigational restrictions based on real-time ice concentration data, limiting vessel access to unstable ice regions when conditions pose heightened risks. Implementing adaptive regulatory measures will help balance the economic benefits of Arctic shipping with environmental and safety concerns, reducing the likelihood of accidents while ensuring sustainable maritime operations in the region (Lasserre et al., 2023).

CONCLUSION

As Arctic ice conditions evolve, maritime activity near Svalbard continues to increase, presenting both economic opportunities and navigational risks. This study highlights a growing presence of vessels in ice-covered waters, supported by longer sailing seasons and shifting ecosystems. Despite long-term ice retreat, interannual variability remains a key challenge, requiring improved forecasting, enhanced SAR capabilities, and stricter maritime regulations. Strengthening real-time monitoring, investing in emergency response infrastructure, and adapting regulations to dynamic ice conditions will be critical for ensuring safe and sustainable Arctic navigation. As climate change accelerates transformations in the Arctic, proactive policy measures and technological advancements will play a vital role in securing the future of Arctic shipping.

ACKNOWLEDGMENTS

The author would like to thank Nataliya Marchenko for her valuable guidance and insights while developing the research that contributed to this study. Additionally, I would like to thank the NSIDC and the GMTDS for providing the essential sea ice and vessel density data for this analysis.

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