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Potential Impacts of Wind Farms on Shipping in the Bay of Bothnia

An pre-study carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse, published May 2026

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Potential Impacts of Wind Farms on Shipping in the Bay of Bothnia

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Summary

Winter navigation in the Bay of Bothnia relies on a highly adaptive routing system coordinated by icebreaker services, where commercial vessels follow routes instructed by icebreaker officers based on prevailing ice concentration, thickness, ice drift, and operational constraints. Planned offshore wind farms (OWFs) introduce fixed structures into this dynamic environment, raising concerns that they may constrain routing flexibility, alter local ice conditions, and increase operational risks during winter navigation. At present, however, systematic knowledge on how OWFs spatially interact with winter shipping routes in the Bay of Bothnia is limited.

The aim of this pre-study is to provide an initial, evidence-based assessment of the potential interactions between planned OWFs and winter navigation. Specifically, the study seeks to identify where OWF areas overlap with winter shipping routes, examine how these overlaps change under different winter severity conditions, and capture operational concerns and risk perceptions from experienced winter navigation stakeholders.

The analysis combines AIS-based reconstruction of winter ship trajectories with ice-condition data and stakeholder input. Cargo vessels and tankers are analysed using an intersection rate, defined as the percentage of unique vessels whose winter routes intersect each OWF area each winter month. The icebreaker activity is analysed separately. Ice conditions are characterised using Copernicus Marine Service data on ice concentration, thickness, and drift, together with a winter-severity indicator derived from multiple sampling points across key traffic corridors and OWF zones. In parallel, qualitative insights are collected via an online questionnaire and in-depth interviews with shipmasters with experience in winter navigation. The study covers four representative winters, spanning mild, normal, and severe ice conditions.

The results show that traffic in the Bay of Bothnia is consistently concentrated along a limited number of entry and exit corridors that shift geographically in response to ice conditions and wind-driven ice drift. OWF areas located along these dominant corridors experience the highest interaction with winter shipping. Under mild ice conditions, traffic is more dispersed. In contrast, during normal and especially severe winters, routing options become increasingly constrained, leading to pronounced concentration of vessel traffic through specific corridors and, consequently, through certain OWF areas. In contrast, OWF areas characterised by persistently heavy ice tend to experience reduced traffic during severe conditions, as vessels divert toward more navigable coastal or icebreaker-assisted routes.

Stakeholder feedback reinforces these findings and highlights loss of manoeuvring space as the primary concern associated with OWFs in winter conditions. Shipmasters emphasise that routing flexibility is essential to ease winter navigation, convoy operations, and emergencies, and that fixed offshore structures may worsen ice deformation, ridging, and rubble accumulation, particularly when multiple structures are located in confined areas.

Sammanfattning

Vinternavigation i Bottenviken bygger på ett starkt adaptivt ruttvalssystem som samordnas av isbrytartjänsten, där kommersiella fartyg följer rutter som instrueras av isbrytarnas befäl baserat på rådande iskoncentration, istjocklek, isdrift och operativa begränsningar. Planerade havsbaserade vindkraftsparker (OWF) introducerar fasta strukturer i denna dynamiska miljö, vilket väcker oro för att de kan begränsa ruttflexibiliteten, förändra lokala isförhållanden och öka de operativa riskerna under vinternavigation. I dagsläget saknas dock systematisk kunskap om hur OWF:er rumsligt samverkar med vinterliga sjöfartsleder i Bottenviken.

Syftet med denna förstudie är att ge en initial, evidensbaserad bedömning av potentiella interaktioner mellan planerade OWF:er och vinternavigation. Mer specifikt avser studien att identifiera var OWF-områden överlappar med vinterliga sjöfartsrutter, analysera hur dessa överlapp förändras under olika grader av vinterstränghet samt fånga operativa erfarenheter och riskuppfattningar hos aktörer med lång erfarenhet av vinternavigation.

Analysen kombinerar AIS-baserad rekonstruktion av vinterliga fartygsrutter med isdata och aktörsinput. Lastfartyg och tankfartyg analyseras med hjälp av en korsningsgrad, definierad som andelen unika fartyg vars vinterrutter korsar respektive OWF-område under varje vintermånad. Isbrytarverksamheten analyseras separat. Isförhållanden karakteriseras med data från Copernicus Marine Service avseende iskoncentration, istjocklek och isdrift, tillsammans med en indikator för vinterstränghet som härleds från flera provpunkter längs centrala trafikstråk och inom OWF-zoner. Parallellt samlas kvalitativa insikter in via en webbaserad enkät och fördjupade intervjuer med befälhavare med erfarenhet av vinternavigation. Studien omfattar fyra representativa vintrar som spänner över milda, normala och stränga isförhållanden.

Resultaten visar att trafiken i Bottenviken konsekvent är koncentrerad till ett begränsat antal in- och utpassagekorridorer, vilka förskjuts geografiskt i respons till isförhållanden och vinddriven isdrift. OWF-områden som är lokaliserade längs dessa dominerande korridorer uppvisar den högsta graden av interaktion med vinternavigation. Under milda isförhållanden är trafiken mer utspridd. Under normala och i synnerhet stränga vintrar blir ruttalternativen successivt mer begränsade, vilket leder till en tydlig koncentration av fartygstrafiken genom specifika korridorer och därmed genom vissa OWF-områden. OWF-områden som kännetecknas av varaktigt svåra isförhållanden tenderar däremot att uppvisa minskad trafik under stränga vintrar, eftersom fartyg i högre grad väljer mer navigerbara kustnära rutter eller rutter med isbrytarassistans.

Återkoppling från aktörer bekräftar dessa resultat och pekar ut förlust av manöverutrymme som den huvudsakliga farhågan kopplad till OWF:er under vinterförhållanden. Befälhavare betonar att ruttflexibilitet är avgörande för säker vinternavigation, konvojtrafik och hantering av nödsituationer, samt att fasta havsstrukturer kan förstärka isdeformation, råkbildning och ansamling av issörja, särskilt när flera strukturer är placerade inom begränsade områden.

Contents

1 Introduction

Offshore wind power is expanding rapidly across the Baltic Sea as part of national and EU strategies to achieve climate neutrality by 2050. Several Baltic Sea countries have committed to jointly accelerating offshore wind development, aiming to increase capacity from 3.1 GW to 19.6 GW by 2030 (WindEurope, 2023).

Northern Sweden's industrial transformation, including fossil-free steel initiatives such as HYBRIT, is expected to require large volumes of renewable electricity, positioning offshore wind as a key future energy source (HYBRIT, 2023). The Bay of Bothnia is central to this energy transition but also presents unique challenges. It supports year-round maritime transport to major industrial ports, and winter navigation is essential for maintaining uninterrupted supply chains. Ice conditions in the region are highly dynamic and influenced by wind direction, drift, and ice pressure, requiring flexible route selection and coordinated Swedish–Finnish icebreaking operations (Porathe, 2023). At present, such flexibility is possible because no offshore wind farms or other major offshore structures exist in the area. However, planned wind farms may reduce this flexibility, as their fixed locations could limit the ability to adjust shipping routes in response to rapidly changing weather and ice conditions.

Existing offshore wind farm site-selection models, while considering factors such as energy capacity, grid access, investment potential, and environmental impact (Chaouachi et al., 2017; Barzehkar et al., 2024), overlook two important aspects relevant to the Bay of Bothnia: sea ice and frequent navigation. These factors introduce additional operational challenges and costs that must be accounted for to optimise OWF deployment in ice-prone areas and ensure coexistence with shipping (Salo & Syri, 2014).

Operating OWFs in ice-infested waters involves several challenges. Sea ice dynamics can threaten turbine integrity through varying ice velocities, failure mechanisms, and extreme loads (Kärnä et al., 2004). Sjöfartsverket (2023) has highlighted that several proposed OWF areas within the Swedish economic zone overlap with, or lie close to, current winter fairways. OWFs may also interfere with maritime navigation by obstructing existing routes and influencing local ice formation, complicating both navigation and icebreaking operations (Ceder et al., 2024) and potentially leading to rerouting, longer itineraries, increased fuel consumption, and operational delays.

The aim of this pre-study is to identify where and how planned offshore wind farms may interact with winter navigation in the Bay of Bothnia. The study adopts the methodology presented by Ceder et al. (2024) and extends it to include additional years as well as OWF in Finnish waters. The analysis combines Automatic Identification System (AIS) traffic data, historical ice charts, and OWF layouts with expert insights from shipmasters. The findings provide a foundation for future modelling, experimental studies, and coordinated planning with Finnish authorities to support the safe coexistence of offshore wind development and winter maritime operations.

1.1 Objectives and goals

This pre-study focuses on the potential impacts of OWFs on winter navigation in the Bay of Bothnia. While the broader expansion of offshore wind power is central to Sweden's long-term energy transition, its implications for winter navigation in ice-infested waters remain insufficiently explored. This pre-study, therefore, aims to build an initial knowledge base that clarifies where and how planned OWF areas may affect maritime operations during winter conditions.

The purpose of the work is to identify potential challenges, spatial conflicts, and operational risks that may arise when permanent offshore structures coincide with variable ice conditions and the established Swedish–Finnish winter navigation system. The applied methodology follows that presented by Ceder et al. (2024). The results will support future research efforts by highlighting priority topics for ship-sea ice-offshore wind farm modelling, operation optimization, and cross-agency coordination. The specific goals of the project are as follows:

1. To identify and map potential spatial interference between planned OWFs and shipping routes, by considering historical AIS data and ice maps, with a focus on locating and characterizing shipping route–OWF intersections under mild, normal and severe winters.
2. To statistically quantify multi-year winter shipping traffic at identified shipping route–OWF intersections using AIS data, in order to characterize traffic intensity, vessel types, temporal variability, and associated ice conditions, including ice drift, ice thickness, and ice concentration.
3. Considering the ice conditions at the intersections between wind farms and shipping routes, review the existing literature and interview ship masters to identify potential impacts on navigation caused by the possible wind farm–ice interactions.
4. Initiate a discussion with Finnish maritime authorities to seek solutions if the planned areas of wind farms interfere with today's routes of Swedish–Finnish icebreaking strategy/tactics.

Together, these goals frame the scope of the pre-study and define its contribution: to map potential interactions between OWFs, ice, and shipping; to collect and synthesise existing knowledge; to document expert operational insights; and to identify needs for future detailed investigations.

1.2 Assumptions and limitations

This pre-study is designed to identify and close critical knowledge gaps related to the interaction among OWFs, winter shipping activities, and ice conditions in the Bay of Bothnia. The following assumptions and limitations apply.

1. The study is limited to qualitative and statistical analyses based on historical data. No new physical experiments, numerical simulations, or coupled ice–structure–ship modelling are conducted. In particular, the study does not include dynamic ice–structure interaction modelling, ship performance simulations in ice, or icebreaker operation simulations.
2. The analysis is confined to the Bay of Bothnia, focusing on the planned OWF areas considered in the project. Only cargo vessels, tankers and icebreakers are included, as these ship types are considered representative of the main commercial traffic and the established winter navigation system in the region[1]. Other vessel categories, such

[1] In this study, cargo vessels include general cargo ships, Ro-Ro vessels, and bulk carriers, while tankers include chemical/product tankers, bitumen tankers, LNG tankers, and LPG tankers. These categories are based on AIS ship type data, refined by matching IMO numbers against the IHS database.

as passenger vessels, fishing vessels, and non-commercial vessels, are excluded, as they may follow different routes and operational patterns.

3. The AIS- and ice-chart-based analyses are limited to the selected winter seasons for which complete and consistent datasets are available, covering four winter periods included in the study. Of these four winter periods, only one covers the entire Bay of Bothnia, whereas the other three are limited to the Swedish Exclusive Economic Zone (EEZ). The study therefore reflects past ice conditions and associated operational patterns. Potential future changes in ice behaviour driven by climate change, altered ice dynamics due to OWFs, or long-term shifts in winter navigation practices cannot be fully captured within the scope of this study.
4. The stakeholder perspectives incorporated in this study are derived from a group of highly experienced maritime professionals and provide valuable operational insight into winter navigation challenges. However, they do not encompass the full range of viewpoints across all operators, vessel classes, or organisational roles active in the Bay of Bothnia. The online questionnaire was completed by only 10 respondents. While the depth of their experience strengthens the qualitative relevance of their feedback, the limited sample size constrains the extent to which the results can be generalised. Therefore, the questionnaire findings should be interpreted as informed expert judgments rather than statistically representative evidence of broader stakeholder consensus.
5. The analysis is based on currently proposed OWF areas and layouts. As OWF planning processes are ongoing, future changes in turbine placement, array configuration, or project boundaries may result in spatial conditions that differ from those considered in this study.

1.3 Outline of the report

This report is structured into six chapters. **Chapter 1** introduces the background, objectives, and scope of the study. **Chapter 2** reviews relevant literature on offshore wind farms, winter navigation, and ice–structure interactions, and identifies key knowledge gaps. **Chapter 3** describes the methodology applied in the study, including AIS data analysis, ice data processing, and stakeholder engagement through an online questionnaire and interviews with maritime actors in the Bay of Bothnia. **Chapter 4** presents the results of the spatial analyses and statistical assessments for the selected winter periods. **Chapter 5** summarises the findings from the questionnaire and interviews with shipmasters and other experienced practitioners. **Chapter 6** concludes the report and outlines identified knowledge gaps and directions for future research.

2 Literature review

Industrial growth in northern Sweden, driven by major transformation initiatives such as HYBRIT, will require a substantial increase in renewable electricity production (HYBRIT, 2023). In addition to industrial electrification, other emerging electricity-intensive activities, such as large data centres, are expected to contribute significantly to future electricity demand in Sweden, further reinforcing the need for expanded renewable power generation. Offshore wind farms (OWFs) are expected to contribute significantly to this expansion, supporting both direct electrification and the production of hydrogen and electro-fuels such as ammonia and methanol. However, the Bay of Bothnia presents unique challenges for OWF deployment due to its long winter season, characterised by sea ice formation and break-up from November to May (Ronkainen et al., 2018).

In the Bay of Bothnia, where winter navigation is dynamic, ice conditions are unpredictable, and routing decisions depend on rapidly changing ice drift and pressure, OWFs could further constrain the flexibility that currently underpins the Swedish–Finnish icebreaking system (Porathe, 2023). The presence of fixed offshore structures in drifting-ice environments may intensify ice deformation, create ridges, or block natural ice pathways, potentially leading to more hazardous operational conditions for shipping.

Operating offshore wind infrastructure in ice-infested waters introduces technical, environmental, and navigational risks. Sea ice can exert high loads on turbine foundations, affect structural integrity (Heinonen & Rissanen, 2017), and cause atmospheric icing on blades and towers, reducing energy production (Byrkjedal et al., 2015). Beyond structural concerns, OWFs located in or near important shipping routes may reduce manoeuvring space and increase navigational complexity, especially during winter. Studies show that proximity to offshore structures can lead to route deviations, increased travel distances, delays, and increased fuel consumption and emissions (Olauson & Forsman, 2024).

This chapter summarises existing knowledge on OWF development, ice conditions, winter navigation, and ice–structure interactions. It highlights research gaps relevant to planning offshore wind deployment in the Bay of Bothnia.

2.1 Offshore wind farm development in the Bay of Bothnia

The Bay of Bothnia is emerging as a key region in Sweden's long-term offshore wind development plans. National strategies aim to increase renewable generation capacity to meet industrial electricity demand, with the northern coastline identified as particularly suitable due to high wind resources and proximity to major industrial energy users. Current plans include several large-scale OWF projects on both the Swedish and Finnish sides of the bay.

Today, winter navigation is unconstrained by fixed offshore structures because no OWFs currently operate in the region. However, analyses show that many proposed Swedish OWF areas overlap with or lie near winter fairways that are essential for maintaining supply chains during the ice season (Sjöfartsverket, 2023; Ceder et al., 2024). Similar concerns exist in Finland's maritime spatial planning, where the need for safe corridors in ice conditions is emphasised.

Modern offshore wind turbines typically consist of a seabed foundation, a transition piece, a tubular steel tower, and the nacelle–rotor assembly (BVG Associates, 2019). The foundation transfers structural loads to the seabed and is typically surrounded by rock armor or other scour-protection measures, which alter local bathymetry and can reduce under-keel clearance, potentially affecting the safe passage of deep-draught vessels in the vicinity. The transition piece elevates the access platforms and boat landings high enough to stay above the highest sea levels, ensuring safe access in all conditions. It also includes attachment points for ladders and fenders (which protect vessels when docking) and J-tubes that guide electrical cables and internal systems that allow technicians to move between the foundation and the turbine tower. Above this, the tower supports the nacelle and rotor at hub heights with blade tip heights that can approach or exceed 200 m. According to the US Department of Energy, turbine capacities have rapidly increased beyond 11 MW, corresponding to hub heights of roughly 140 m (Ahlström et al., 2023). As turbines grow larger, they require greater spacing and larger overall OWF footprints, which in turn influences the size and type of vessels that can safely operate within or near the wind farm area (Ahlström et al., 2023).

During the construction phase, offshore wind farms generate heavy, project-driven marine traffic, including installation jack-up vessels, heavy-lift ships, cable-laying vessels, barges, tugs, and crew transfer vessels (BVG Associates, 2019, April). These operations are highly weather- and sea-state-sensitive and often occur on tight schedules, increasing the demand for temporary exclusion zones, dynamic safety corridors, and detailed coordination with existing shipping lanes. For nearby commercial traffic, the main challenges can include temporary loss or restriction of traditional routes and anchorages, increased crossing situations with slow and partially manoeuvring construction vessels, and limited sea room around installation sites. Efficient planning of staging ports, transit routes, and construction sequencing is therefore critical to minimise interference with merchant shipping and to maintain acceptable levels of navigational safety.

Once an OWF enters operation, traffic patterns shift from heavy installation activity to regular service and maintenance operations conducted by crew transfer vessels and, for larger projects, service operation vessels (BVG Associates, 2019, April). The wind farm becomes a quasi-permanent obstruction field, with turbine rows, foundations, and associated subsea cables defining areas where deep-draught ships may be restricted or excluded. For passing traffic, key operational challenges include reduced manoeuvring space, altered options for emergency anchoring or drift management, and more complex routing when fairways run parallel to or between wind farm clusters. At the same time, service and maintenance vessels must transit to and from the site in a range of meteorological and oceanographic (metocean) conditions, perform close-quarters manoeuvring at turbine foundations, and coordinate their movements with nearby commercial traffic, which may further increase collision and allision risk if not adequately managed through traffic separation, routeing measures, and clear regulatory frameworks.

Despite the strategic importance of offshore wind, existing site-selection studies for the Baltic Sea rarely consider winter navigation or sea-ice dynamics. Multi-criteria assessments typically prioritise technical potential, environmental constraints, grid access, and investment feasibility (Chaouachi et al., 2017; Barzehkar et al., 2024). Nevertheless, in regions with extensive winter ice cover, these factors alone are insufficient. The combination of seasonal ice, limited manoeuvring space, and high traffic density requires specific attention to the coexistence of OWFs with winter maritime operations.

2.2 Winter navigation and icebreaking operations

Winter navigation in the Bay of Bothnia is organised under a long-standing joint Swedish–Finnish icebreaking system, in which the two national fleets operate as a common resource, coordinated through shared procedures and IT tools such as IBNet (BIM, 2021; Ojala & Nylander, 2023). This cooperative strategy aims to guarantee year-round maritime access to northern Finnish and Swedish ports. A core principle of the Swedish–Finnish winter navigation model is operational flexibility. Icebreakers and merchant vessels routinely adjust their routes in response to rapidly changing conditions.

The most significant operational challenges in Bay of Bothnia winter navigation arise during ice compression events, when persistent strong winds drive drifting ice floes against coastlines or shallow bathymetry, inducing rapid formation of pressure ridges and consolidated ice blockages that obstruct primary routes. Even during a mild winter, such as the 2024–2025 season, significant ice-related challenges can still occur in the Bay of Bothnia (Aker Arctic, 2025). Although temperatures were generally above average and ice formation was delayed, persistent winds repeatedly pushed drifting ice toward the Bothnian coast, causing extensive ridging, compression, and shifting ice fields. These wind-driven dynamics led to blocked routes, difficult navigation conditions, and continued reliance on icebreakers, including temporary suspensions of assistance (Aker Arctic, 2025). The winter's ice extent eventually peaked at 85,000 km², demonstrating that mild thermal conditions do not prevent the development of hazardous ice situations when strong winds and ice drift patterns align unfavorably (Aker Arctic, 2025).

2.3 Interactions between OWFs and shipping in Ice

The interaction among offshore wind farms (OWFs), sea ice, and maritime traffic in the Bay of Bothnia remains poorly understood, as the existing literature primarily focuses on ice–structure behaviour at the scale of individual turbines or offshore platforms rather than on full-scale wind farms operating in heavy, drifting ice. Studies on ice mechanics demonstrate that stationary structures can induce ice crushing, bending failure, wake-induced weakening of the ice sheet, and the formation of rubble and ridges under compression (Heinonen & Rissanen, 2017; Kärnä et al., 2004). Such deformation processes are known to intensify under fast drift and intense pressure, conditions characteristic of mid-winter in the northern Baltic, and similar effects have been documented around Arctic offshore platforms. From a navigational perspective, OWFs may introduce additional risks by reducing manoeuvring space, altering ice patterns, obstructing drift-aligned winter routes, and potentially interfering with radar systems, with studies already showing route elongation and efficiency losses from OWFs even in open-water conditions (Olauson & Forsman, 2024). Despite these concerns, integrated analyses of combined ice–structure–ship interactions in heavy ice are nearly absent from the scientific literature. Conceptual work by Porathe (2023) suggests that advanced route exchange systems might mitigate some risks, but such ideas remain untested in environments where complex ice deformation governs navigability.

Several studies have raised concerns regarding the coexistence of offshore wind farms and maritime traffic in the Baltic Sea, particularly in regions with high traffic density and challenging winter conditions (Ahlström et al., 2023; Olausson & Forsman, 2024; Ceder et al., 2024). The key issues under investigation include the following:

1. **Increased voyage lengths and reduced efficiency**

Offshore wind farms may force vessels to take longer routes, leading to higher fuel consumption, longer transit times, and reduced logistical efficiency. This can undermine the commercial viability of some routes, especially when deviations are frequent or occur under time-sensitive operations. In some cases, route extensions of 4–6 nautical miles have been documented, which, when repeated across numerous sailings, can significantly affect operational costs and scheduling (Olausson & Forsman, 2024; Ahlström et al., 2023). Moreover, OWFs placed near established routes can limit vessels' ability to divert during severe weather or ice conditions.

2. **Impact variability based on traffic characteristics**

The extent of route deviation or navigational disruption is not uniform. It varies depending on ship type, size, traffic volume, and the proximity of the OWF to critical shipping lanes. High-density traffic areas or routes used by larger vessels are more sensitive to spatial constraints introduced by OWFs.

3. **Winter navigation risks**

During the ice season, OWFs may influence ice behaviour by altering drift pathways and encouraging ridge formation near structures. This can reduce navigable space and hinder vessel movement, potentially increasing the demand for icebreaker support (Lang et al., 2019). The proximity of wind farms to key winter fairways is a concern, as it could obstruct routing flexibility needed under rapidly changing ice conditions, thereby reducing maritime safety (Ahlström et al., 2023; Ceder et al., 2024).

4. **Restricted manoeuvring space**

Ships require ample sea room to manoeuvre safely, particularly when executing full turns, usually to starboard. The turning radius of a ship is closely linked to its length, and OWFs reduce available space, especially for large vessels. According to IMO guidelines, sufficient separation distances must be maintained to ensure safe navigation and emergency manoeuvring. Additionally, the presence of turbines may restrict access for emergency and rescue operations, despite a potentially lower baseline risk of incidents (Ahlström et al., 2023; International Maritime Organisation, 2002).

5. **Radar interference and situational awareness**

Wind turbine towers can disrupt radar signals, causing false echoes, signal dropouts, and target swapping. This can make it harder to detect and track nearby vessels accurately, undermining situational awareness and increasing the risk of misjudgement or collision, particularly in reduced visibility or congested waters (Ahlström et al., 2023).

6. **Impacts on anchorage, shelter, and emergency routing**

The development of offshore wind farms (OWFs) in coastal zones can restrict access to traditional anchorage areas and natural shelters, which are essential for vessels during mechanical failures or severe weather. A well-documented example is the Julietta D incident in January 2022, when the Maltese-registered bulk carrier's port anchor cable parted while the vessel was anchored in IJmuiden Anchorage Area No. 7 during storm conditions (Transport Malta, Marine Safety Investigation Unit, 2023). The vessel subsequently drifted, colliding first with the anchored tanker Pechora Star before entering the under-construction Hollandse Kust Zuid offshore wind farm, located approximately 1.8 nautical miles south of the anchorage. At the time, 34 wind turbine foundations had already been installed.

It is common engineering practice for wind farms to connect turbine cables to an offshore transformer platform, which then transmits power to an onshore substation via subsea cable. This setup emphasises the need for careful spatial planning in OWF development, as associated infrastructure, such as export and inter-array cables, must be routed to avoid key navigational areas, anchorage zones, and port approaches. Doing so helps minimise the risk of mechanical damage, reduce interference with emergency manoeuvres, and prevent hazardous interactions with maritime traffic.

3 Methodology

3.1 Analysis of planned OWFs impact on winter shipping routes

To assess the potential impacts of planned OWF areas on winter navigation in the Bay of Bothnia, this study adopts a multi-step analysis framework combining qualitative trajectory inspection, quantitative intersection statistics, and ice condition analysis. The study adopts the methodology presented by Ceder et al. (2024) and extends it to include additional years as well as OWF in Finnish waters. The methodology is designed to systematically link ship traffic patterns derived from AIS data, with spatial OWF layouts and sea ice conditions, thereby enabling a robust assessment of ship navigation–OWF interactions under different winter severities.

3.1.1 Plotting ship trajectories using AIS data

AIS data are used to reconstruct and visualize the trajectories of commercial vessels, and icebreakers operating in the Bay of Bothnia during the selected winter periods. The AIS dataset contains time stamps, vessel information, including ship identification (IMO number), geographical position, speed, course, and ship type, transmitted at regular intervals by vessels equipped with AIS transponders.

For the trajectory analysis, **Figure 1** illustrates the methodology used to integrate planned OWF polygons with AIS ship trajectory data. The planned OWF areas and AIS data are first subjected to spatial and temporal filtering, restricting the analysis to the Bay of Bothnia and to the investigated winter periods. Only cargo vessels and tankers are retained for the main traffic analysis, while icebreakers are extracted and analyzed separately in order to characterize ice-assisted navigation. Individual AIS position records belonging to the same vessel are subsequently linked in chronological order to reconstruct continuous ship trajectories.

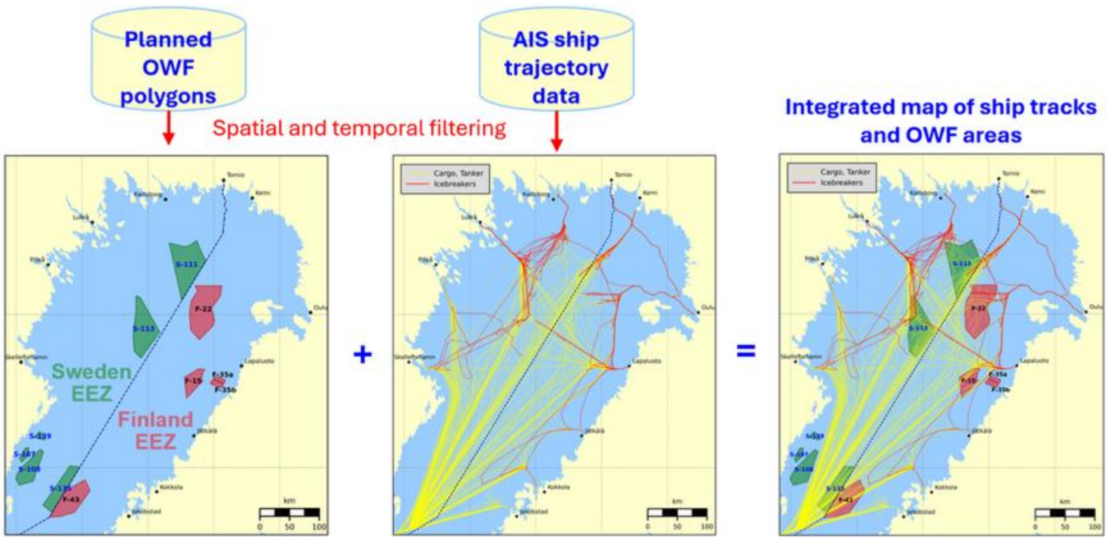

Figure 1: Schematic illustration of the methodology for integrating planned OWF polygons with AIS ship trajectory data.

Ship trajectories are visualized on georeferenced maps together with the planned Swedish and Finnish OWF polygons. Cargo and tanker tracks are displayed using lightcolored lines (yellow) to represent traffic density, whereas icebreaker tracks (red tracks) are highlighted separately to indicate regions requiring frequent ice assistance. This visual inspection provides an understanding of the spatial organization of winter shipping traffic, identifies major navigation corridors, and highlights OWF areas that may be exposed to intensive vessel traffic under various ice conditions.

In this study, AIS data from four winter seasons (October to March) are available, namely 2010–2011, 2014–2015, 2022–2023, and 2023–2024. However, only the 2022–2023 winter provides AIS coverage for the entire Bay of Bothnia, whereas the remaining winter seasons are limited to data within the Swedish EEZ. These four winter seasons therefore constitute the investigated winter in this study.

3.1.2 Ship/OWF intersection statistics using AIS data

While trajectory plots provide valuable qualitative information, a quantitative measure is required to objectively assess the degree of interaction between shipping routes and OWF areas. Therefore, a statistical intersection analysis is conducted.

For cargo vessels and tankers, an intersection is defined as a ship trajectory intersecting the polygon representing a given OWF area. As AIS transmissions are discrete in time, vessel trajectories are approximated by connecting successive AIS position records in chronological order. This approach provides a sufficiently accurate representation of the actual sailing route for statistical analysis.

To enable comparison across different OWF areas, winter months, and winter severity levels, a non-dimensional intersection rate is employed and defined as the percentage of vessels crossing an OWF area:

$$\text{Intersection rate} = \frac{N_{\text{inter}}}{N_{\text{total}}} \tag{1}$$

where N_{inter} is the number of unique cargo or tanker vessels whose trajectories intersect a specific OWF area during the reference period, and N_{total} represents the total number of cargo or tanker vessels operating within the Bay of Bothnia (2023–2024) or Swedish EEZ (2010–2011, 2014–2015, 2022–2023) during the same period.

Icebreaker traffic is treated separately due to its fundamentally different operational characteristics. For icebreakers, intersections are defined on a passage basis rather than on a vessel basis. A passage is identified as a complete icebreaker route entering and subsequently exiting an OWF area, as illustrated in **Figure 2**, where 3 distinct passages are shown as an example. Multiple passages by the same icebreaker within a month are counted individually, as they reflect repeated ice-assisted navigation through the OWF area.

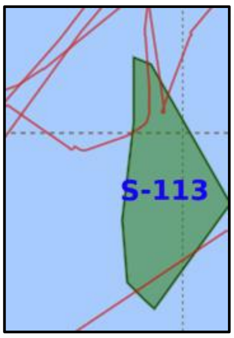

Figure 2: Illustration of the definition of icebreaker passages through an OWF area.

The resulting intersection statistics are presented as monthly bar charts. For cargo and tanker vessels, the charts show the proportion of vessels intersecting each OWF area relative to the total number of vessels operating within the Bay of Bothnia. For icebreakers, the charts report the total number of passages through each OWF area. Together, these statistics enable direct comparisons between different OWF areas, between winter months, and across winters of varying severity.

3.1.3 Analysis and presentation of ice data

To interpret the observed ship routing behaviour and OWF intersection patterns, sea ice conditions are analysed in parallel using publicly available historical ice datasets. Sea ice concentration, sea ice thickness, and sea ice velocity (ice drift) are obtained from Copernicus Marine Service. The specific datasets used in this study, together with their sources and spatial and temporal resolutions, are summarized in **Table 1.**

Table 1: Sea ice datasets used in this study, including data sources, origins, and spatial and temporal resolutions.

Variable	Dataset	Provider	Origin	Resolution
Sea ice concentration	Baltic Sea ice concentration, extent, and classification time series (https://doi.org/10.48670/moi-00131)	Copernicus Marine Service	FMI/SMHI	1km×1km, daily
Sea ice thickness	Baltic Sea ice concentration, extent, and classification time series (https://doi.org/10.48670/moi-00131)	Copernicus Marine Service	FMI/SMHI	1km×1km, daily
Sea ice velocity	Global Ocean Physics Reanalysis GLORYS12V1 (https://doi.org/10.3389/feart.2021.698876)	Copernicus Marine Service	ERA5	0.083°×0.083° (9.2km×9.2km), daily

For each winter period, ice conditions are visualized using representative days with relatively severe ice conditions to illustrate the spatial distribution of ice concentration, thickness, and drift. In addition, time series of ice concentration and thickness are extracted at 12 sampling points (see **Chapter 4.1**) distributed across the Bay of Bothnia, covering both main navigation corridors and planned OWF areas. The daily mean across all sampling points is used as an indicator of overall winter severity.

The ice maps and time series are jointly analysed with ship trajectories and intersection statistics to identify systematic relationships between ice conditions and routing behaviour. This integrated assessment supports the interpretation of why vessels preferentially select certain corridors during specific months and winter types, and how these choices influence interactions with planned OWF areas.

3.2 Stakeholder engagement: online survey and in-person interviews

To capture expert perspectives on winter navigation, offshore structures, and the potential impacts of offshore wind farms (OWFs) in the Bay of Bothnia, the study employed a mixed-method qualitative approach consisting of (1) an online questionnaire and (2) in-person semi-structured interviews with experienced shipmasters.

3.2.1 Online questionnaire

An online questionnaire was developed to obtain structured qualitative and quantitative input from professionals with operational experience in winter navigation and icebreaking activities. The survey was distributed to stakeholders in the Swedish maritime sector, including shipping companies, maritime administrations, and icebreaking services. The questionnaire consisted of four sections, each covering a distinct topic:

1. **Background information (6 questions)**

Captured education level, professional role, years of ice navigation experience, and vessel types.

2. **Ice navigation and icebreaking operations (4 questions)**

Included rating-based assessments of operational priorities, risk factors, usefulness of navigational tools, and key environmental factors influencing decision-making.

3. **Impact of offshore structures on ice and navigation (2 questions)**

Asked respondents to estimate the proportion of vessels requiring assistance near offshore structures and to rate the severity of specific ice- and navigation-related risks.

4. **Potential impacts of OWFs on winter navigation (3 questions)**

Assessed the perceived severity of OWF impacts, e.g., on icebreaker convoys, priority of mitigation measures, and risks associated with different planning options.

Across these sections, respondents answered rating-based questions using a 1–5 numerical scale, where 1 represented the lowest level (e.g., low priority, low risk, or not useful) and 5 represented the highest (e.g., high priority, very high risk, or critical usefulness). Additional multiple-choice and open-ended questions allowed participants to elaborate on their operational reasoning.

A total of ten respondents completed the questionnaire. Of these, 60% were from the shipping industry and 40% from the maritime administration. The respondent group was highly experienced: 40% had more than 20 years of winter navigation experience in the Bay of Bothnia.

Quantitative responses were analysed by calculating mean scores and standard deviations to identify areas of consensus and variation. The online questionnaire provided a broad overview of stakeholder perceptions, supporting the identification of key risk factors, operational challenges, and potential mitigation strategies relevant for winter navigation in areas with planned offshore wind farms.

3.2.2 In-person interviews

To complement the questionnaire and obtain more detailed operational insights, semi-structured in-person interviews were conducted with four experienced icebreaker masters actively operating in the Bay of Bothnia. These interviews provided in-depth qualitative information on day-to-day practices, decision-making processes, and safety considerations during winter navigation. The interview framework covered three major thematic areas:

1. Ice navigation and icebreaking operations, including risk management, meteorological influences on routing, and technological developments;
2. Impacts of existing offshore structures on ice behavior and navigation, such as the influence of lighthouses, beacons, and other fixed installations on ice drift, ridging, and vessel maneuverability;
3. Anticipated effects of offshore wind farm waters on shipping in the Bay of Bothnia, including collision risk, corridor design, turbine spacing, radar performance, and the feasibility of navigation within OWF areas.

The qualitative insights from these interviews offer a detailed operational perspective that cannot be captured by numerical analysis alone. Together with the online questionnaire results, they form a comprehensive understanding of stakeholder perceptions and practical challenges associated with the coexistence of offshore wind farms and winter navigation in the Bay of Bothnia.

4 Results of OWFs impact on winter shipping routes

4.1 Winter severity and case studies

In addition to expert-based qualitative assessments, the winter severity in the Bay of Bothnia is quantitatively evaluated in this study using historical records of sea ice concentration and sea ice thickness. To ensure spatial representativeness, 12 sampling points are selected and distributed approximately uniformly across the Bay of Bothnia, as shown in **Figure 3**. The selected points are intended to cover the main navigation corridors as well as areas relevant to planned OWF areas. Among them, points P1–P5 are located outside planned OWF areas, while the remaining seven points are within the major Swedish and Finnish planned OWF zones (i.e., S-108, S-135, S-113, S-111, F-43, F-22, and F-15).

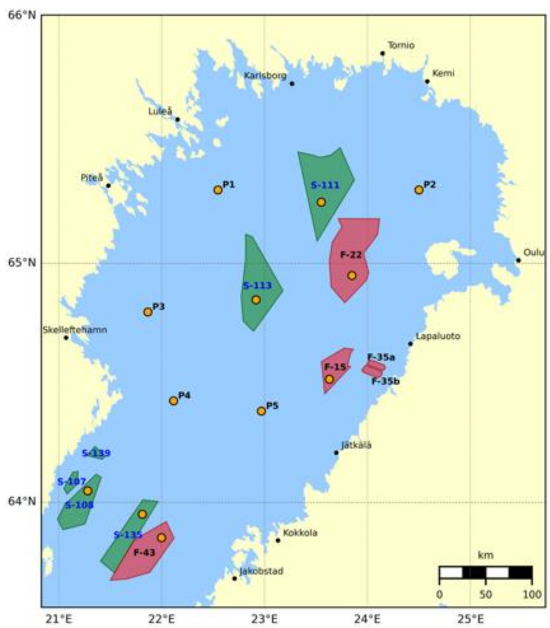

Figure 3: Spatial distribution of the 12 sampling points used for the winter severity assessment in the Bay of Bothnia.

Figure 4 presents the time series of sea ice concentration and sea ice thickness at the 12 sampling points for each investigated winter period. For each day, the individual point values are shown as thin light-blue lines, together with the mean value across all points, which is highlighted by a thick blue line. The mean value serves as an indicator of the overall ice severity in the Bay of Bothnia. The shaded areas in the figures denote periods prior to the onset of sea ice.

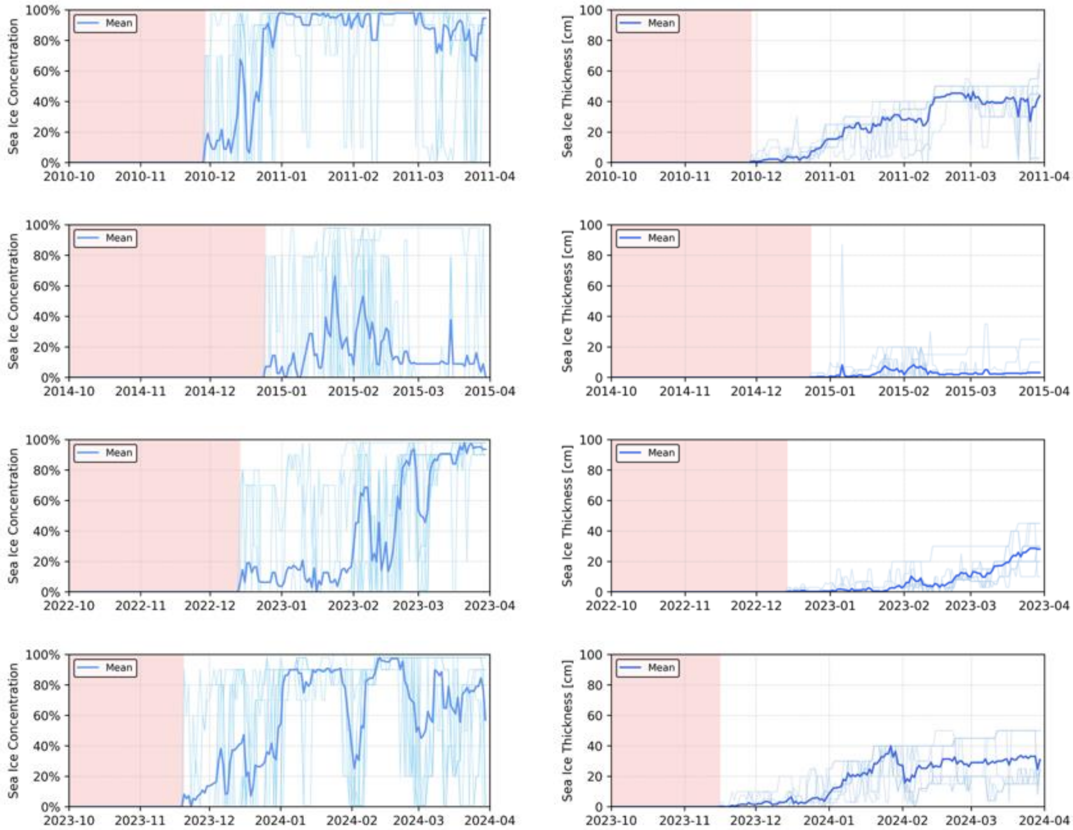

Figure 4: Time series of sea ice concentration (left column) and sea ice thickness (right column) at the 12 sampling points in the Bay of Bothnia for each investigated winter period (October to March), e.g., 2010–2011, 2014–2015, 2022–2023, and 2023–2024.

The key characteristics of these winter periods are summarized in **Table 2**, including the approximate timing of ice formation, the main ice-covered period, the main mean sea ice concentration and thickness, and a description of ice conditions. The winter of 2010-2011 is classified as a severe winter, characterized by an early ice formation in late November, a prolonged ice-covered period extending from late December to late March, and persistently high ice concentration (approximately 80–100%) combined with relatively thick ice (approximately 20–45 cm). In contrast, the winter of 2014-2015 represents a mild winter, with a later ice onset, generally low ice concentration (approximately 10–40%), thin ice (below 10 cm), and a comparatively short ice-covered period. The winter of 2022-2023 is categorized as a normal winter, during which ice concentration gradually increased and remained moderate to high for a shorter period, while ice thickness remained at moderate levels (approximately 10–30 cm). Finally, the winter of 2023-2024 is identified as another severe winter, featuring an early ice formation in mid-November, a long-lasting ice-covered period from January to late March, and consistently high ice concentration (approximately 50–90%) accompanied by moderately thick ice (approximately 20–40 cm). It should be noted that the SMHI classification of winters as mild, normal, or severe is primarily based on the spatial extent of ice cover, and SMHI (2025) classifies the 2023–2024 winter as normal. However, from an icebreaking and winter navigation perspective, 2023–2024 posed substantial operational challenges, and in this study, which focuses on OWFs impact on winter navigation, the winter of 2023–2024 is classified as severe.

These four winter periods collectively span a wide range of ice conditions in the Bay of Bothnia and form the basis for the subsequent case studies. By contrasting vessel trajectories, OWF intersection statistics, and icebreaker operations under mild, normal, and severe winter conditions, the influence of ice severity on winter navigation patterns and potential interactions with planned OWF areas can be systematically assessed.

Table 2: Summary of key sea ice characteristics and winter severity classification for the four investigated winter periods in the Bay of Bothnia.

Winter period	**2010 Oct – 2011 Mar**	**2014 Oct – 2015 Mar**	**2022 Oct – 2023 Mar**	**2023 Oct – 2024 Mar**
Ice begins (approx.)	Late Nov	Late Dec	Mid Dec	Mid Nov
Main ice-covered period	Late Dec – late Mar	Late Dec – late Feb	Feb – March	Jan – late Mar
Main mean ice concentration	≈ 80 – 100%	≈ 10 – 40%	≈ 20 – 90%	≈ 50 – 90%
Main mean ice thickness	≈ 20 – 45 cm	< 10 cm	≈ 10 – 30 cm	≈ 20 – 40 cm
Characteristics	Long, persistent high concentration and thick ice	Mostly low concentration, thin ice	Gradual increase concentration and short period moderate high thick ice	Long period with high concentration and moderate high thick ice
Winter Severity	Severe	Mild	Normal	Severe

4.2 Mild winter

Based on the analysis in **Chapter 4.1**, the winter from December 2014 to March 2015 is classified as a mild winter. For this winter season, AIS data covering the entire Swedish EEZ are available. Our analysis therefore focuses on the intersection between cargo, tanker, and icebreaker traffic and the Swedish OWF areas.

The monthly tracks of cargo ships, tankers, and icebreakers in the Bay of Bothnia are plotted for the period from December 2014 to March 2015, as shown in **Figure 5**. Cargo and tanker traffic is concentrated along a dominant corridor used for entering or leaving the Bay of Bothnia. These routes exhibit high traffic density, illustrated by the dense yellow tracks, and pass through the Swedish OWF area S-135. In contrast, S-108, S-107, and S-139 are located outside the main deep-water fairway, resulting in limited overlap with cargo and tanker tracks. For S-111 and S-113, some vessel routes connecting Finnish and Swedish ports intersect these areas, leading to moderate levels of interaction. At the same time, vessels travelling between the Bay of Bothnia and ports on either the Swedish or Finnish side also pass near these OWF areas, contributing to additional overlaps.

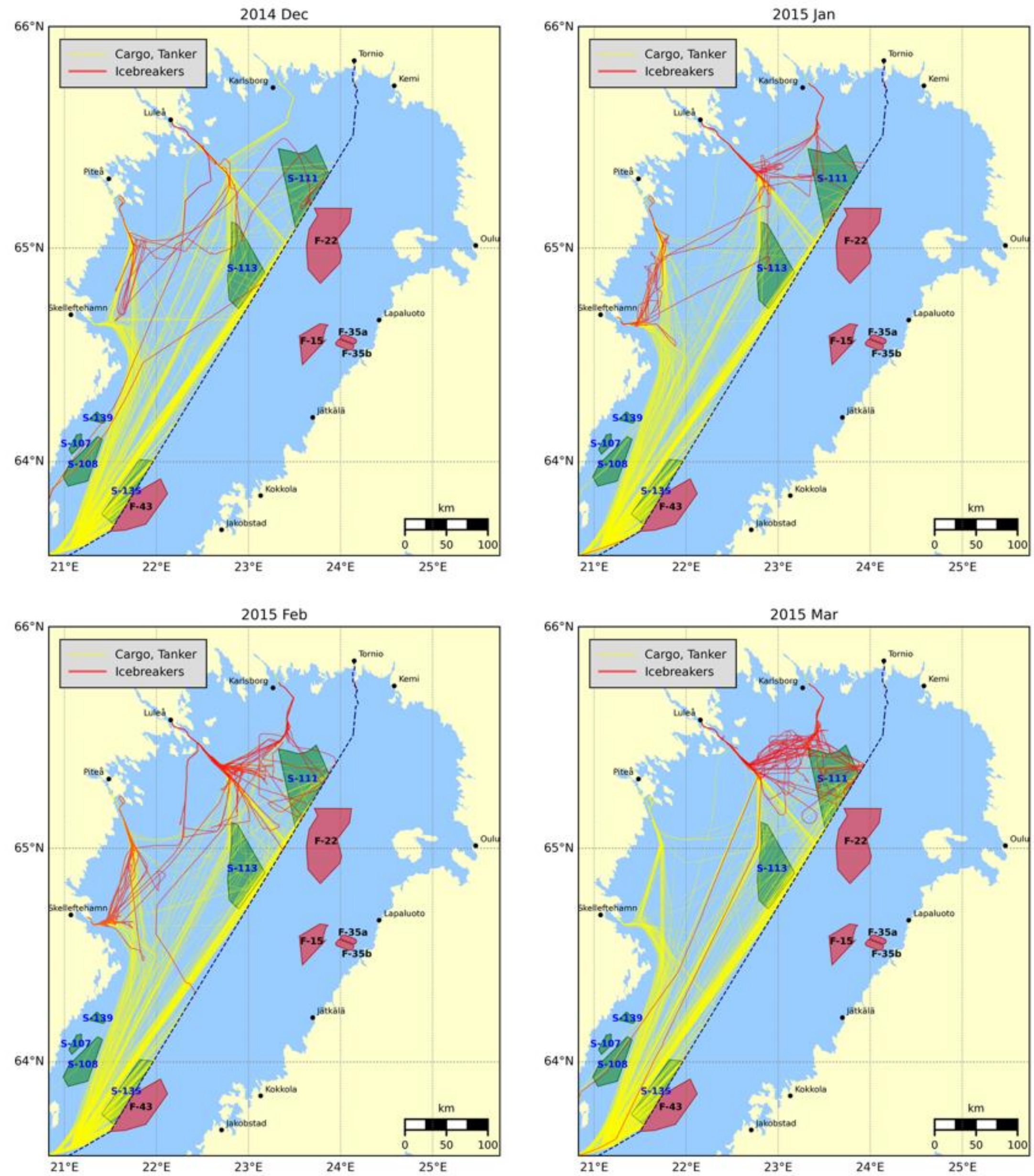

Figure 5: Monthly cargo, tanker, and icebreaker tracks for the mild winter period from December 2014 to March 2015, shown in relation to planned OWF areas.

The intersection statistics for the months considered are presented in **Figure 6**. This winter is classified as a mild winter, and the number of cargo and tanker vessels operating in the Bay of Bothnia shows no substantial variation across months. Among the Swedish OWF areas, S-135 consistently exhibits the highest level of traffic overlap, with 44.9%–50.7% of cargo vessels and 42.9%–60% of tankers passing through this area. This is expected, as S-135 lies directly along the main corridor used by vessels entering and leaving the Bay of Bothnia. S-113 shows the second-highest level of interaction, with more than 25% of cargo vessels and around 30% of tankers crossing the area. The intersection rate for S-111 follows closely behind. For the remaining OWF areas within the Swedish EEZ, the intersection levels are limited and can be regarded as negligible for both cargo and tanker vessels.

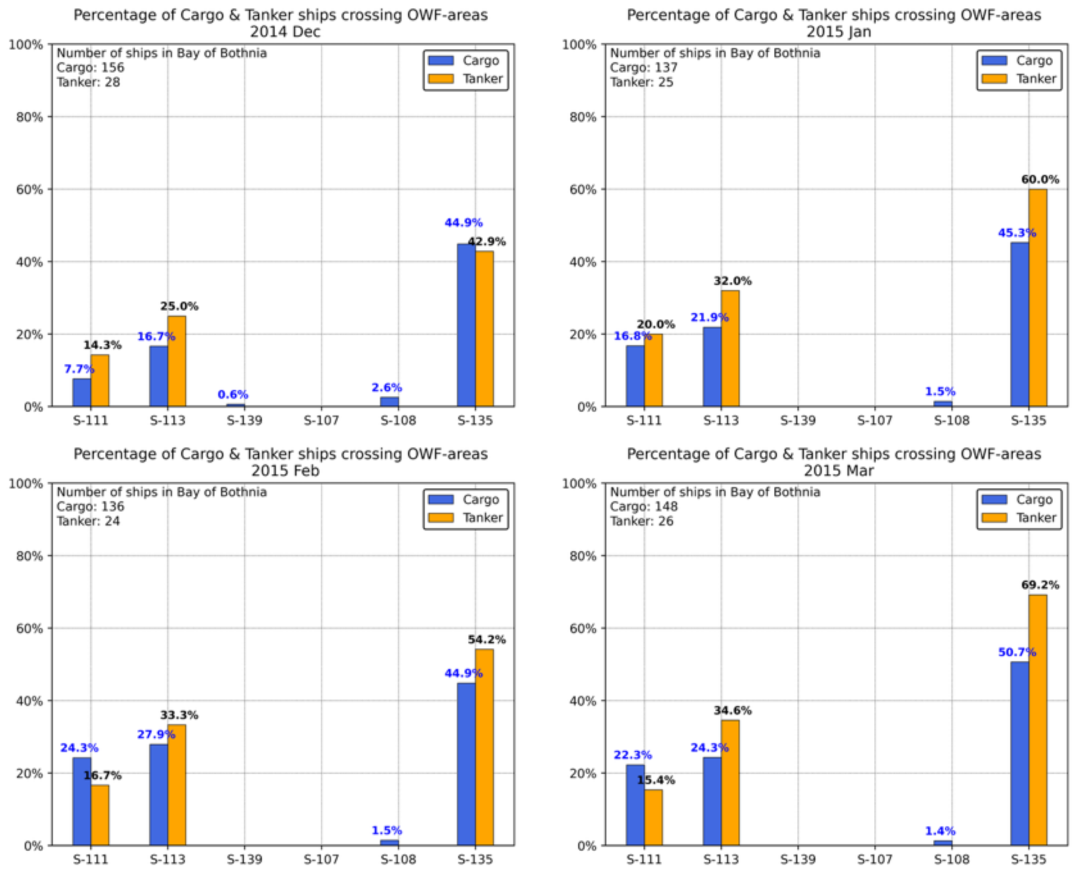

Figure 6: Monthly percentages of cargo and tanker vessels crossing Swedish OWF areas during the mild winter from December 2014 to March 2015. For each month, the proportion of vessels intersecting each OWF polygon is shown relative to the total number of cargo and tanker vessels operating in the Bay of Bothnia.

The following part examines representative ice conditions during the winter and analyzes the overlap between icebreaker tracks and OWF areas. **Figure 7** presents sea ice conditions from December 2014 to March 2015. For each month, a representative day with relatively severe ice conditions is selected to illustrate the spatial distribution of sea ice concentration, thickness, and drift velocity. As shown in the **Figure 7,** in December 2014 sea ice was present mainly along the Swedish and Finnish coasts, with relatively low thickness. Although the extent was limited, several icebreaker-assisted operations still occurred within the Swedish EEZ. By January 2015, the ice cover had expanded considerably, and ice thickness had increased, leading to more frequent icebreaker activity around Skellefteå Port and Piteå, as well as in the area between Luleå and Karlsborg. Ice conditions continued to intensify through February 2015, resulting in even greater icebreaker activity compared with January. By March 2015, the ice cover began to retreat, remaining primarily along the northern coastal zone. Consequently, icebreaker operations were mostly confined to the region near S-111 and the coastal areas between Luleå and Karlsborg.

The number of icebreaker passages intersecting different OWF areas is summarized in **Figure 8.** As shown in the figure, icebreaker operations at S-111 are significantly more frequent than at any other OWF area. This is because in this mild winter, sea ice tends to accumulate along the coastal zone and particularly in the northern part of the Bay of Bothnia. Consequently, S-111 exhibits the highest level of icebreaker intersections. In March 2015, for example, as many as 28 passages crossed this OWF area. In contrast, the

OWF areas located in the central and southern parts of the bay experience far fewer icebreaker interactions, with at most three passages per month.

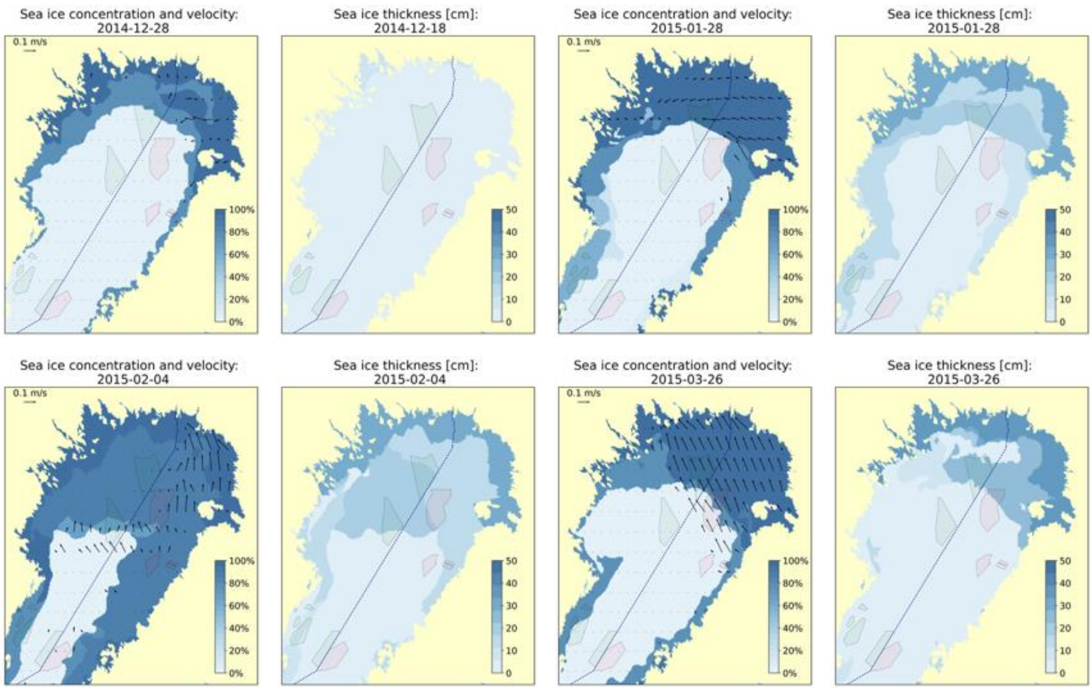

Figure 7: Sea ice conditions during the winter from December 2014 to March 2015. For each month, a representative day with relatively severe ice conditions is selected, showing the spatial distribution of sea ice concentration, sea ice thickness, and ice drift velocity.

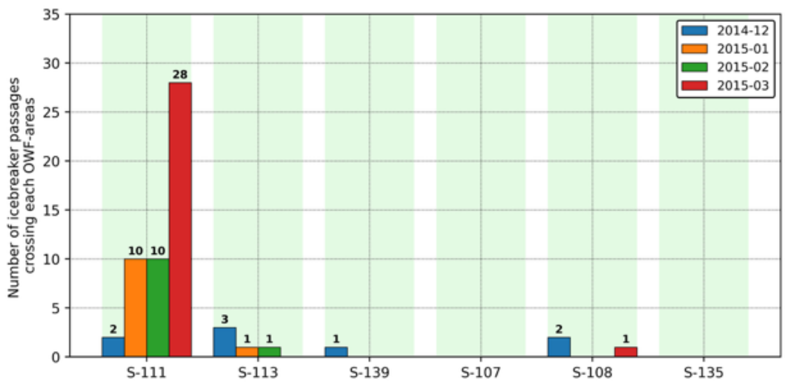

Figure 8: Monthly number of icebreaker passages intersecting Swedish OWF areas during the mild winter from December 2014 to March 2015.

4.3 Normal winter

For the normal winter from December 2022 to March 2023, AIS data are available across the entire Bay of Bothnia, covering both the Swedish and Finnish EEZs. This enables a comprehensive statistical assessment of vessel interactions with the planned OWF areas in both countries. **Figure 9** presents the monthly tracks of cargo ships, tankers, and icebreakers for this period, while **Figure 10** illustrates the sea ice conditions from December 2022 to March 2023. For each month, a representative day with relatively severe ice conditions is selected to show the spatial distribution of sea ice concentration, thickness, and drift velocity.

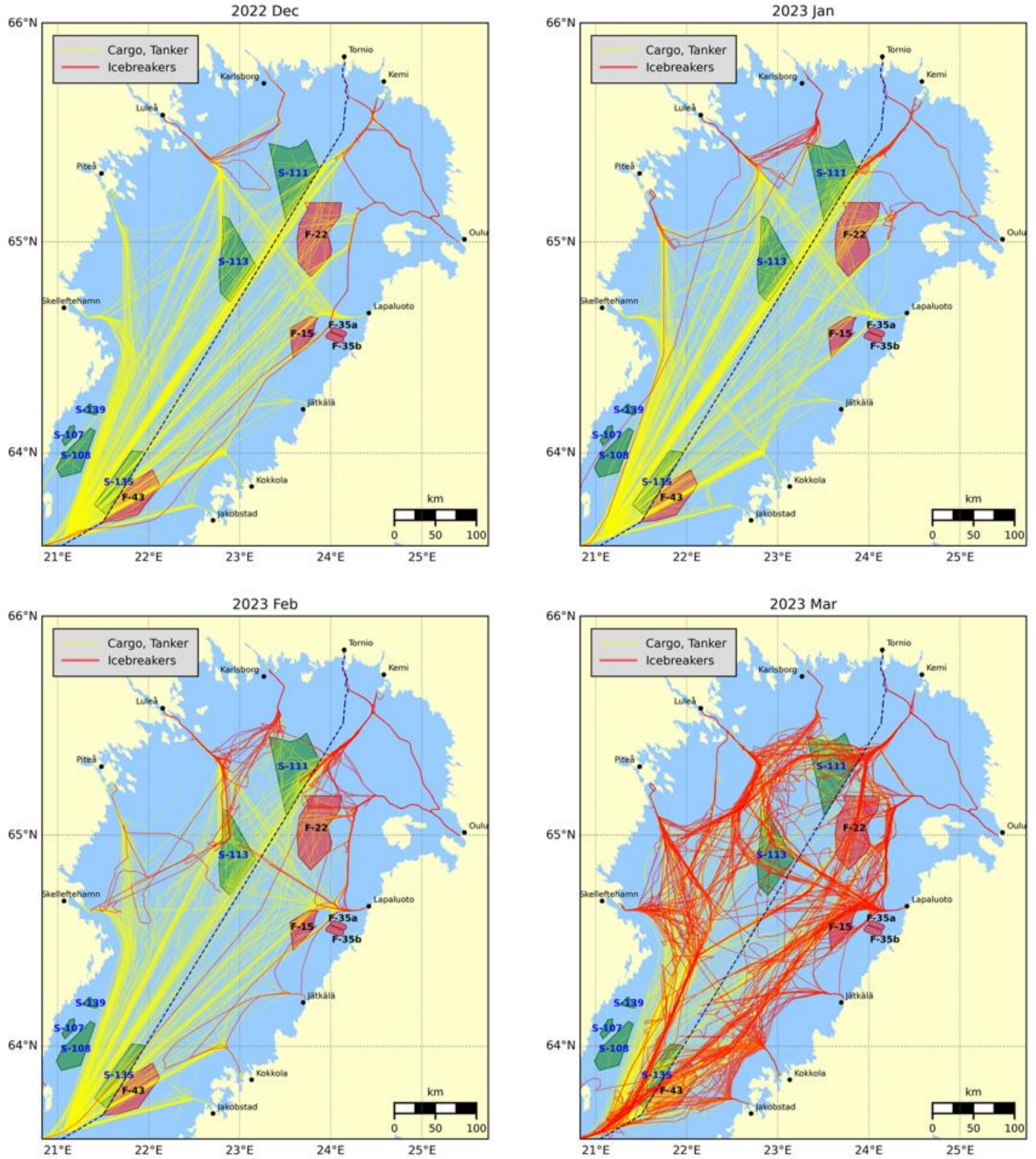

Figure 9: Monthly cargo, tanker, and icebreaker tracks for the normal winter period from December 2022 to March 2023, shown in relation to planned OWF areas.

Figure 9 shows cargo and tanker routes follow the dominant central corridor used for entering or leaving the Bay of Bothnia. These are dense traffic lanes, which result in pronounced intersections with Swedish OWF S-135 and Finnish OWF F-43. The central deep-water fairway also leads to frequent interactions with OWF areas such as S-113 and S-111. In contrast, Swedish OWFs S-107, S-108, and S-139 remain largely outside the high-density traffic corridor and therefore experience only limited overlap with passing vessels. On the Finnish side, intersections with F-15 occur when ships travel between Finnish coastal ports and the main passage corridor, but the overall level of overlap remains moderate. Some vessel routes connecting Swedish and Finnish ports also pass through F-

15. In contrast, no cargo or tanker tracks intersect the Finnish OWF sites F-35a and F-35b.

As ice conditions intensify, most notably in March 2023 as **Figure 10** presents, the spatial pattern of cargo and tanker traffic changes substantially. The central corridor becomes increasingly constrained or temporarily unusable due to thick ice, forcing vessels to deviate toward coastal regions where ice conditions are more navigable. This shift results in reduced traffic in the central basin and a marked concentration of tracks along either the Swedish or Finnish sea, depending on local ice severity. In some situations, when sea ice is lighter along the Swedish coast, vessels first navigated westward to join icebreaker-assisted convoys before crossing toward Finnish ports. Conversely, when the Finnish coastal zone offers more favorable ice conditions, vessels initially travel eastward for assistance before proceeding toward Swedish destinations.

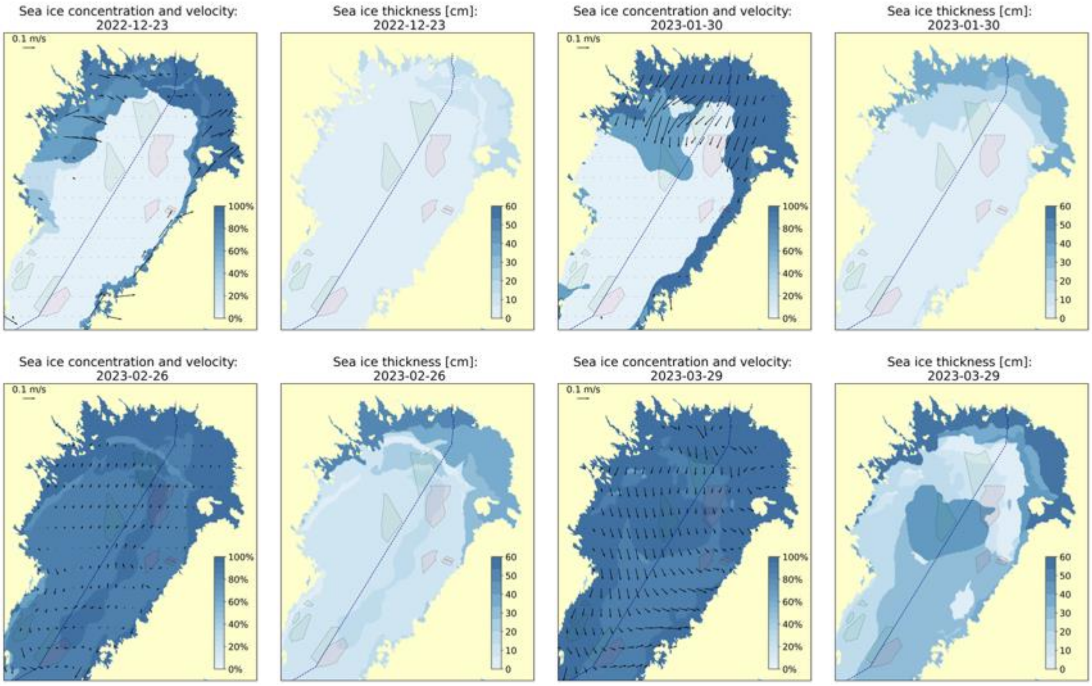

Figure 10: Sea ice conditions during the winter from December 2022 to March 2023. For each month, a representative day with relatively severe ice conditions is selected, showing the spatial distribution of sea ice concentration, sea ice thickness, and ice drift velocity.

The intersection rate for the normal winter period is presented in **Figure 11.** The green shading indicates Swedish OWF, while the red shading represents Finnish OWFs. The two OWF areas located along the main entry and exit corridor of the Bay of Bothnia, Swedish S-135 and Finnish F-43, show the highest percentage overlap with cargo and tanker traffic. For S-135, the overlap under light ice conditions is approximately 40–45%, increasing to more than 70% when ice conditions intensify on the Swedish side, as observed in March 2023. A similar rise is seen for F-43. In contrast, the percentage of passages intersecting Swedish OWF S-113 decreases under severe ice conditions. As shown in **Figure 11,** the S-113 area is characterized by both high ice concentration and increased ice thickness, which discourages vessels from navigating through this region. More ships are forced to deviate toward coastal zones with more navigable ice conditions on either the Swedish or Finnish side. This shift leads to a noticeable increase in passages through the Finnish OWFs F-15 and F-22.

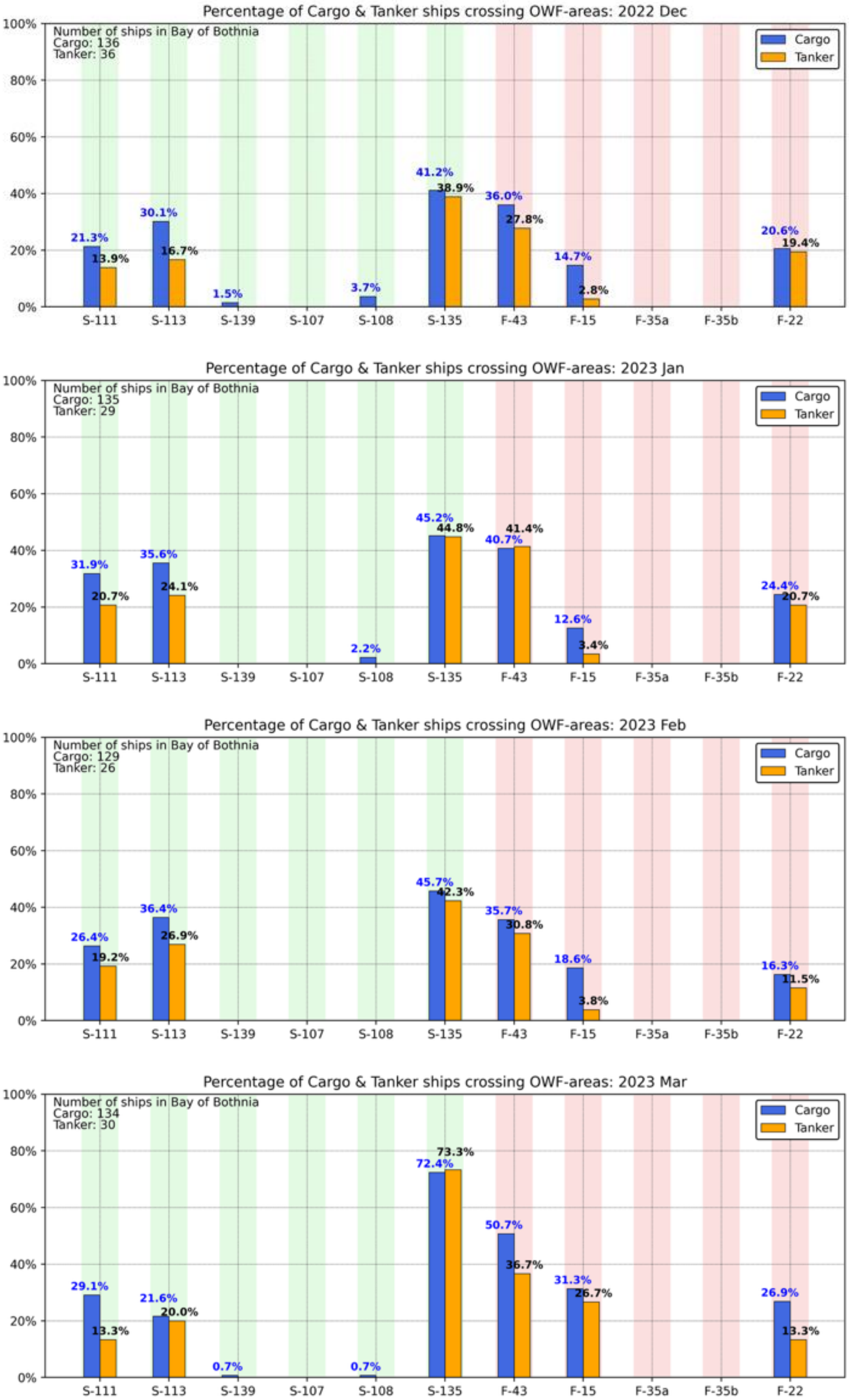

Figure 11: Monthly percentages of cargo and tanker vessels crossing Swedish and Finnish OWF areas during the normal winter from December 2022 to March 2023. For each month, the proportion of vessels intersecting each OWF polygon is shown relative to the total number of cargo and tanker vessels operating in the Bay of Bothnia.

The number of icebreaker passages intersecting different OWF areas is summarized in **Figure 12.** During March, when ice conditions are most severe, the number of icebreaker passages increases substantially, reaching 45 crossings at S-135 and 28 at F-43. In the Swedish OWF S-113, where both ice concentration and ice thickness are high, the number of icebreaker passages likewise exceeds 30. The next most frequently intersected areas are F-15 and F-22. In contrast, negligible or no icebreaker activity is observed in the OWFs located close to the coast, including S-139, S-108, S-107, F-35a, and F-35b.

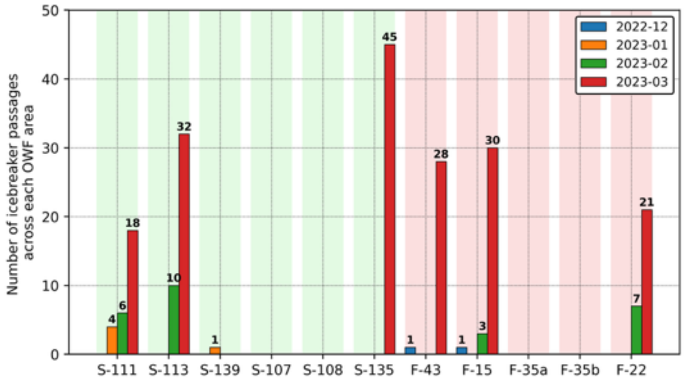

Figure 12: Monthly number of icebreaker passages intersecting Swedish and Finnish OWF areas during the normal winter from December 2022 to March 2023.

4.4 Severe winter

For the severe winter periods from December 2010 to March 2011 and from January to March 2024, AIS data are available only within the Swedish EEZ. Consequently, the analysis focuses exclusively on the planned OWF areas in Sweden. **Figure 13** presents the monthly tracks of cargo ships, tankers, and icebreakers during the winter from December 2010 to March 2011, while **Figure 14** illustrates the sea ice conditions for each month, represented by a day with relatively severe ice conditions.

As shown in **Figure 14**, in December, sea ice is mainly concentrated in the northern part of the Bay of Bothnia and along the Finnish coast, while ice coverage in the central basin remains limited. Consequently, cargo and tanker traffic within the Swedish EEZ is largely unaffected and continues to follow the typical central traffic corridor. Icebreaker operations during this month are mainly confined to coastal areas where vessels require assistance when approaching ports. In January, both the central basin and the northern regions became largely ice-covered. Ice concentration and thickness are relatively lower along the Swedish coast, making this area comparatively more navigable. Thus, cargo and tanker traffic tends to navigate in the Swedish area, where ice conditions are calmer, before proceeding northward. With icebreaker assistance, vessels either continue through the central basin toward Finnish ports or remain within the Swedish area to Swedish destinations. In some cases, when ice conditions along the Finnish coast are more favorable, vessels pass directly through OWF S-135 toward Finland and subsequently cross the central basin to reach Swedish ports. In February, the ice thickness in the central basin and the Finnish EEZ is relatively lower. As a result, many vessels are able to enter the Bay of Bothnia via the central corridor with icebreaker assistance and subsequently navigate to their destinations on either the Swedish or the Finnish side. By March, ice conditions within the Swedish EEZ are comparatively less severe than in other regions. Most vessels preferentially navigate within Swedish waters before crossing eastward toward Finnish ports. This leads to substantial overlap between cargo and tanker tracks and the Swedish OWF area S-113 during this period.

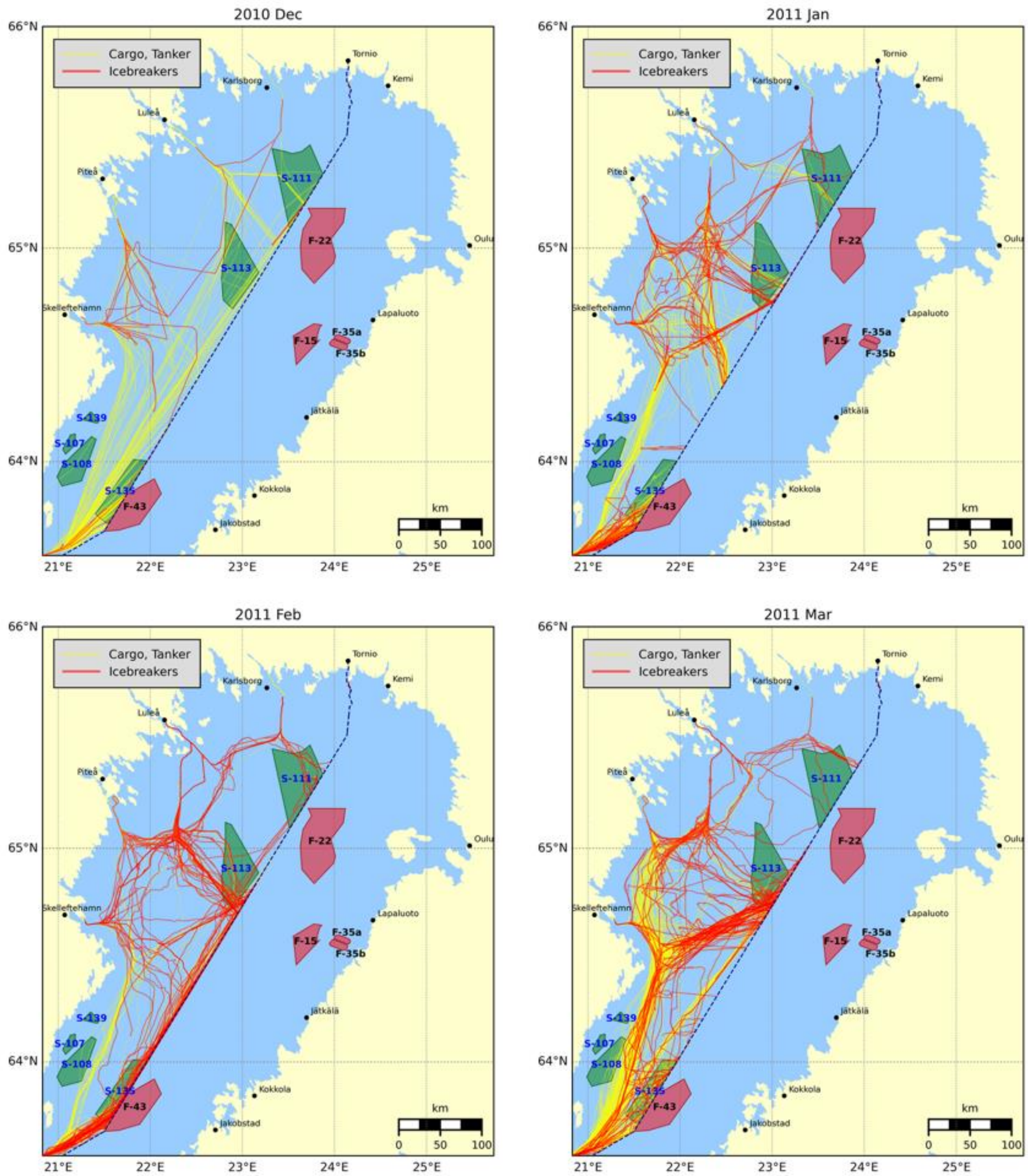

Figure 13: Monthly cargo, tanker, and icebreaker tracks for the severe winter period from December 2010 to March 2011, shown in relation to planned OWF areas.

Figure 15 presents the intersection statistics for the months considered of this severe winter period for cargo and tanker vessels. Overall, the spatial distribution of intersections is broadly consistent with that observed during the mild and normal winter cases, with Swedish OWF S-135 exhibiting the highest number of intersections, as it is located along the primary entry and exit corridor of the Bay of Bothnia. During February 2011, 87.8% of cargo vessels and 96.3% of tankers passed through the S-135 OWF area. This exceptionally high overlap is attributable to the prevailing ice conditions, which constrained vessel traffic to the central corridor. In contrast, from January to March, vessel traffic through Swedish OWF S-111 decreased markedly compared to December 2010, due to the persistently high ice concentration and ice thickness in this region. During this period, no tanker traffic intersected S-111, and the percentage of cargo vessels passing through this area dropped to below 10%. While S-108, which exhibits only limited interaction with vessel traffic during the first three months, shows an increased level of intersection during March. As ice conditions in other parts of the Bay became less navigable, nearly 10% of cargo and tanker traffic was rerouted through this area.

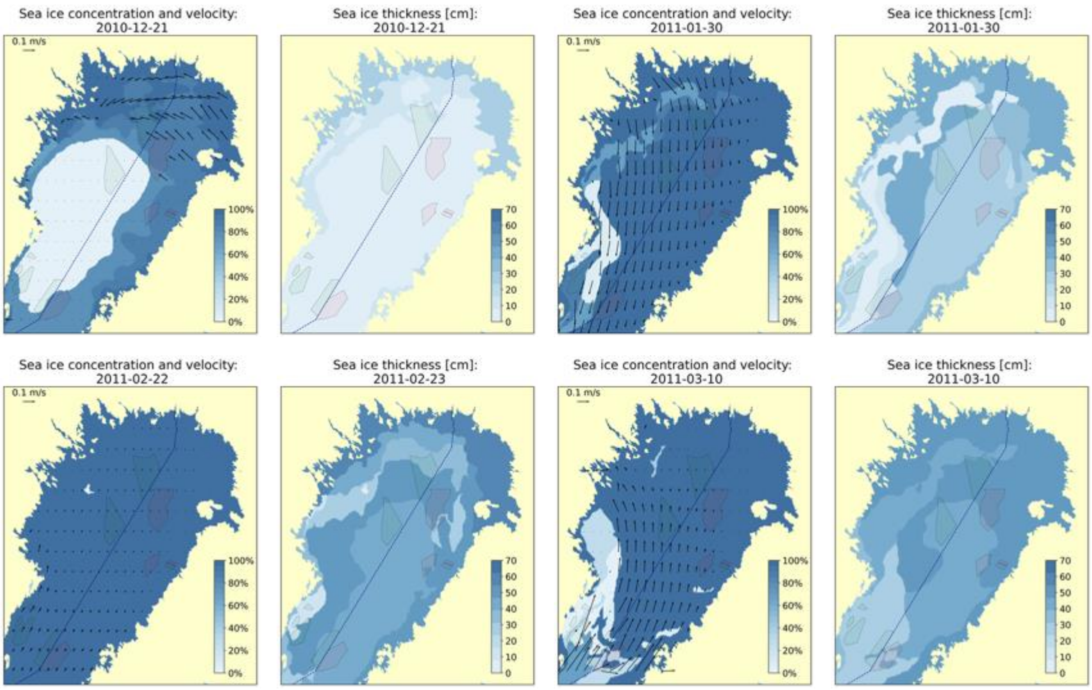

Figure 14: Sea ice conditions during the winter from December 2010 to March 2011. For each month, a representative day with relatively severe ice conditions is selected, showing the spatial distribution of sea ice concentration, sea ice thickness, and ice drift velocity.

Figure 16 illustrates the monthly number of icebreaker passages intersecting Swedish OWF areas during the severe winter period. Overall, OWF S-135 and S-113 experience by far the highest levels of icebreaker activity among all considered sites. In particular, S-135 exhibits an exceptional peak in February 2011, with 143 icebreaker passages. This peak coincides with a period when vessel traffic was strongly concentrated along the central corridor of the Bay of Bothnia or towards to Finnish side, as the ice distribution made this route comparatively more navigable than Swedish area. Although ice conditions remain severe in March, the number of icebreaker passages through S-135 decreases to 30, reflecting a redistribution of icebreaker assistance as vessels are increasingly guided toward coastal routes with calmer ice conditions along either the Swedish or Finnish side. Similarly, S-113 shows consistently high icebreaker activity throughout the severe winter, which can be attributed to relatively thinner ice in the surrounding area compared with adjacent regions.

For the last severe winter considered in this study, covering the period from January to March 2024, **Figure 17** presents the monthly tracks of cargo ships, tankers, and icebreakers in relation to the planned OWF areas. It also illustrates the corresponding sea ice conditions for each month, represented by a day characterized by relatively severe ice conditions.

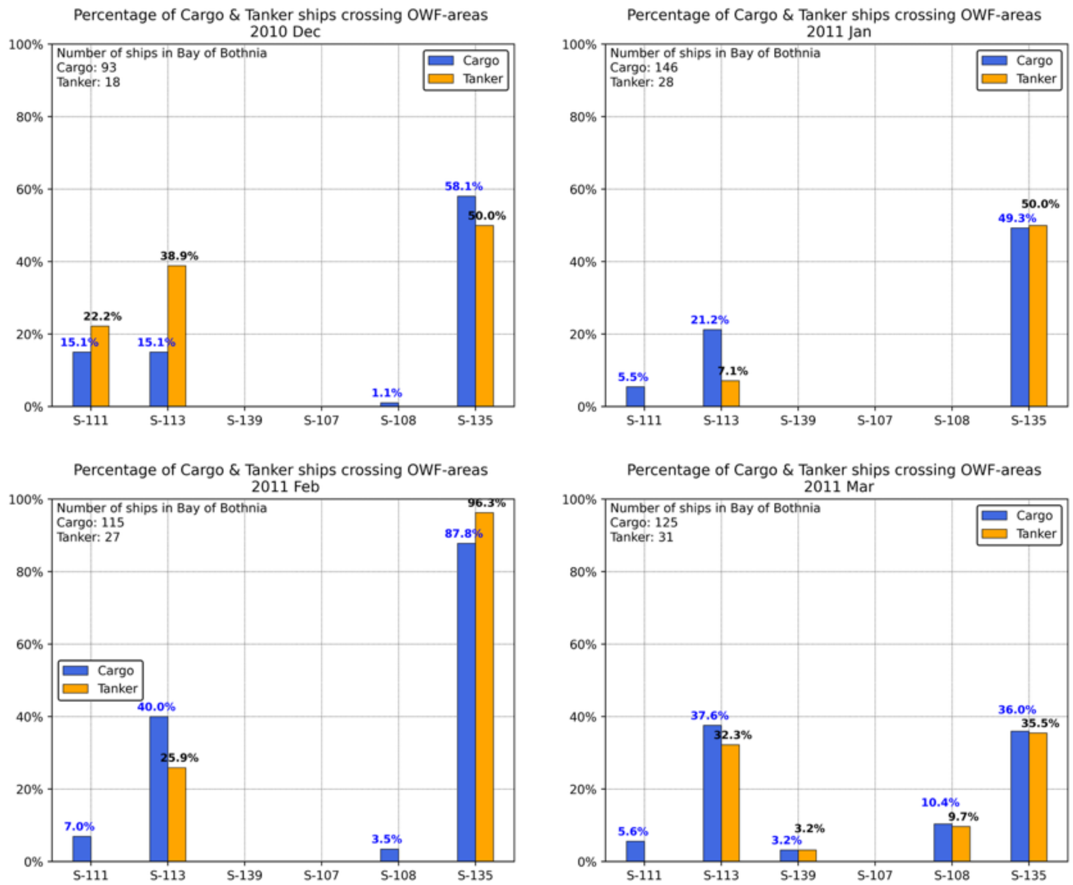

Figure 15: Monthly percentages of cargo and tanker vessels crossing Swedish OWF areas during the severe winter from December 2010 to March 2011. For each month, the proportion of vessels intersecting each OWF area is shown relative to the total number of cargo and tanker vessels operating in the Bay of Bothnia.

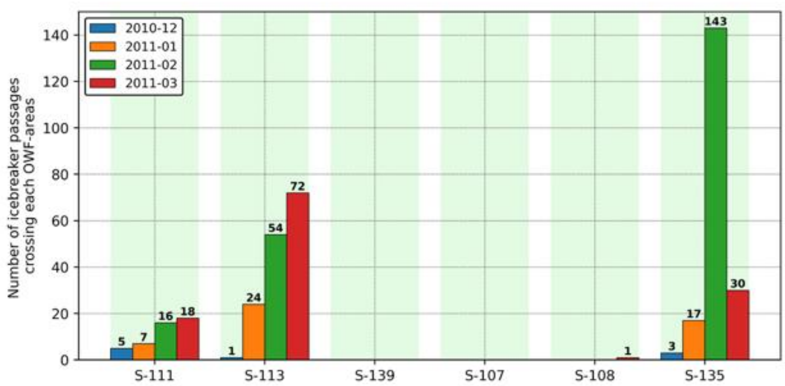

Figure 16: Monthly number of icebreaker passages intersecting Swedish OWF areas during the severe winter from December 2010 to March 2011.

During the latter half of January, ice conditions along the Finnish coast become relatively calmer. As shown in **Figure 17,** many cargo and tanker vessels, assisted by icebreakers, navigate directly through OWF S-135 toward the Finnish side, either to Finnish ports or subsequently cross the central basin toward Swedish ports.

The sea ice condition shown in **Figure 18** corresponds to 10 January, representing conditions during the first half of the month. On this date, ice thickness is lower along the Swedish coast, making this route more navigable. A substantial number of vessels are observed operating within Swedish waters. While a zone of thicker ice persists along the central corridor, prompting vessels to rely on icebreaker assistance to deviate toward the Finnish side, which results in a noticeable number of intersections with OWF S-113. In February, ice conditions moderate to some extent across the Bay of Bothnia, although overall ice coverage remains extensive. Ice thickness in the southern part of the basin is relatively lower, allowing vessels to utilize more southerly routes when travelling between Swedish and Finnish ports. By March, ice conditions in the southern Bay of Bothnia further improved, with large areas becoming nearly ice-free. Under these conditions, most cargo and tanker vessels preferentially navigate through the southern, ice-free regions. As a result, traffic largely bypasses OWF S-113, and virtually no vessel passages intersect this area during March.

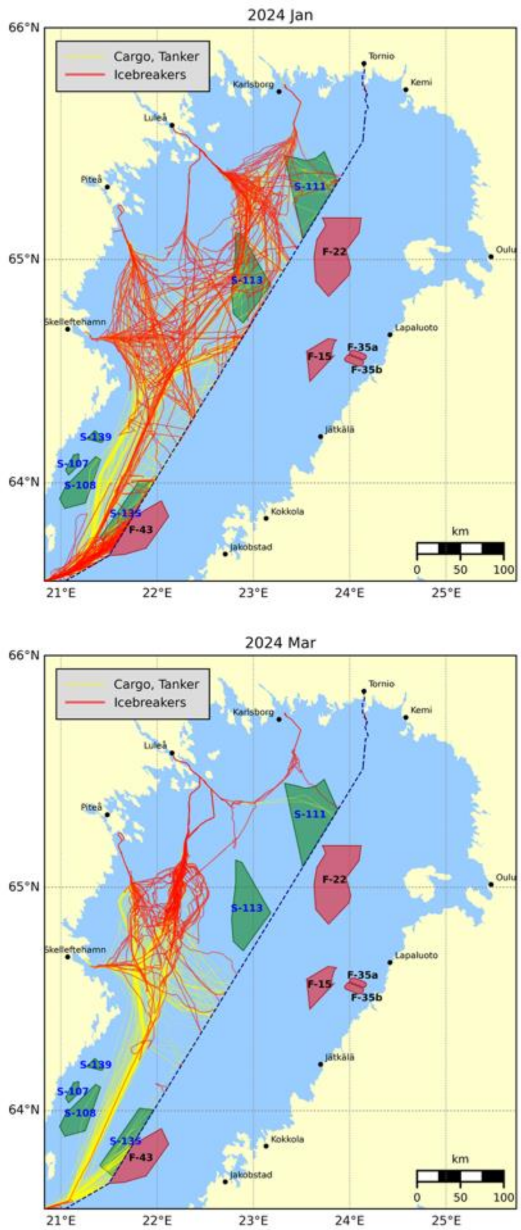

Figure 17: Monthly cargo, tanker, and icebreaker tracks for the severe winter period from January 2024 to March 2024, shown in relation to planned OWF areas.

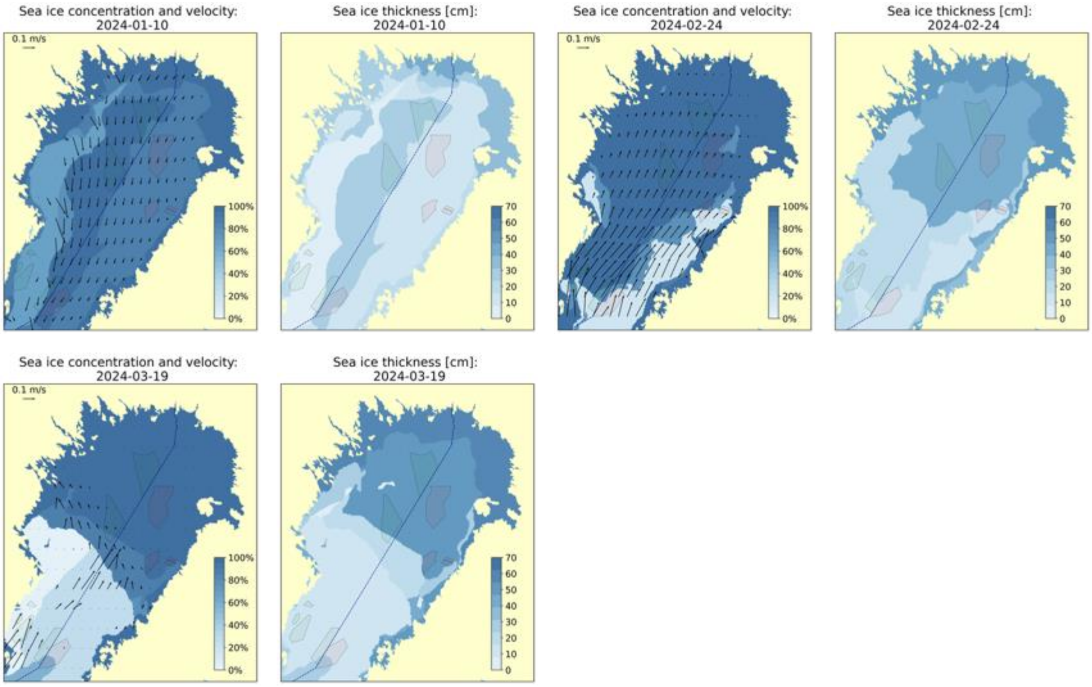

Figure 18: Sea ice conditions during the winter from January 2024 to March 2024. For each month, a representative day with relatively severe ice conditions is selected, showing the spatial distribution of sea ice concentration, sea ice thickness, and ice drift velocity.

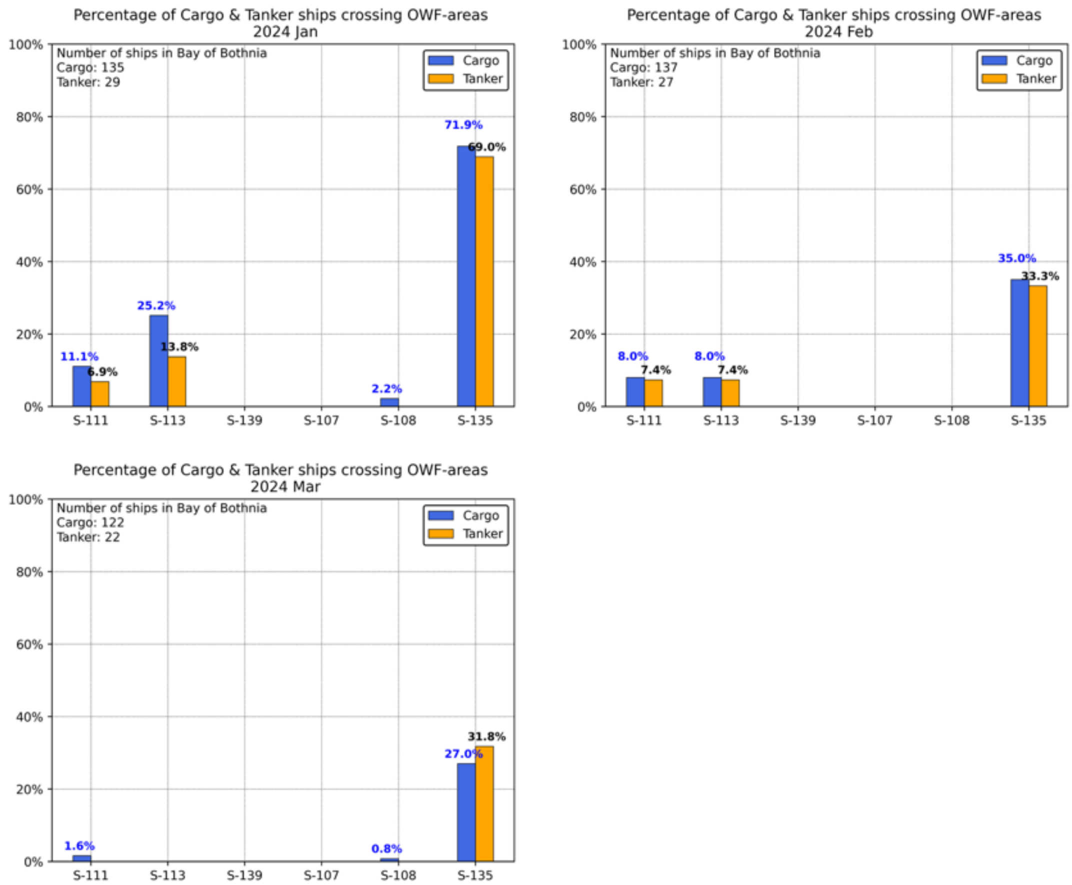

Figure 19: Monthly percentages of cargo and tanker vessels crossing Swedish OWF areas during the severe winter from January 2024 to March 2024. For each month, the proportion of vessels intersecting each OWF polygon is shown relative to the total number of cargo and tanker vessels operating in the Bay of Bothnia.

More detailed statistical results for cargo vessels, tankers, and icebreakers are presented in **Figures 19** and **20**, respectively. These statistics further coincide with the patterns identified in the trajectory-based analysis. Among all OWF areas, S-135 consistently exhibits the highest percentage of intersections with cargo and tanker traffic. In January 2024, when ice conditions along the Finnish coast are relatively more favorable, cargo and tanker vessels frequently traverse S-135 with icebreaker assistance to the Finnish side, with almost of 70% cargo and tanker vessels intersecting this area. During this period, a comparatively high level of intersection is also observed for S-113. This is primarily because the central basin is largely covered by thick ice, limiting opportunities for vessels to optimize their routes toward regions with more navigable ice conditions. As ice conditions evolve in February and March, the percentages of cargo and tanker traffic intersecting both S-111 and S-113 decrease markedly. By March, intersections with these OWF areas are nearly negligible, as vessels increasingly utilize more southerly routes where ice conditions are considerably milder, and navigation becomes less constrained.

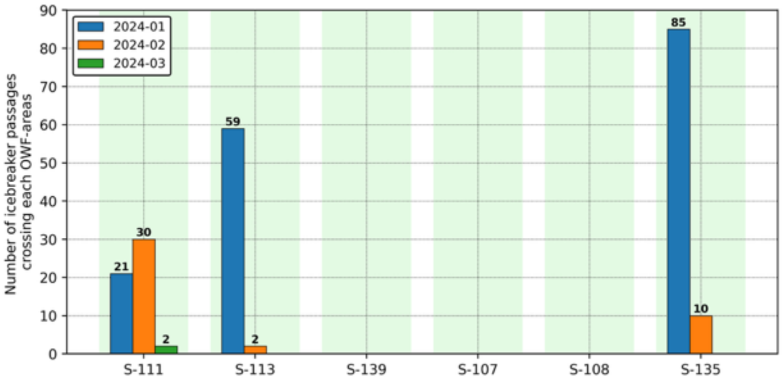

Figure 20: Monthly number of icebreaker passages intersecting Swedish OWF areas during the severe winter from January 2024 to March 2024.

Icebreaker intersections peak in January, reflecting the heightened need for assistance under severe and spatially heterogeneous ice conditions in the central corridor. In the subsequent months, icebreaker activity decreases across most OWF areas as navigable routes expand. An exception is observed for S-111, where icebreaker passages increase in February. This is attributable to traffic serving northern ports, which no longer navigate southward but instead pass through S-111 when ice conditions in this area become sufficiently favorable to support icebreaker-assisted navigation.

5 Results of online questionnaire and interviews

5.1 Online questionnaire

5.1.1 Section 1: Background information

Ten respondents have participated in the online questionnaire, representing highly experienced personnel from the shipping industry (60%) and maritime administration (40%). All respondents possess substantial expertise in winter navigation and icebreaking operations in the Bay of Bothnia. Among the respondents, 40% have more than 20 years of professional experience, while only 10% have five years or less. Similarly, 40% have participated in winter navigation in the Bay of Bothnia for over two decades, indicating that the sample represents professionals with extensive firsthand knowledge of the region's operational challenges.

It is important to note, however, that the sample size is limited to 10 participants, and the results should therefore be interpreted as reflecting the expert opinions and professional judgments of a small but highly experienced group rather than as statistically representative of all stakeholders in the region. While this limitation restricts the generalizability of the findings, it also ensures that the insights derive from individuals with deep operational knowledge and long-term experience in winter navigation in the Bay of Bothnia.

5.1.2 Section 2: Ice navigation and icebreaking operations

The second section of the online questionnaire focused on icebreaking operations in the Bay of Bothnia, comprising four questions on ice navigation and operations within the area.

5.1.2.1 Question 1

Respondents were asked to rate the importance of six aspects on a scale from 1 (low priority) to 5 (high priority), and to identify key areas for improvement. The results indicate that satellite imagery (average score: 5.0), training and crew competence (4.8), and real-time sharing of ice and weather data (4.7) were rated as the most critical aspects for enhancing (see **Figure 21**). These findings underscore the importance of situational awareness tools and well-trained personnel for effective winter navigation.

Coordination between vessels and port authorities (4.2) was also rated as necessary, suggesting that while coordination mechanisms generally function well, continued improvement could strengthen operational efficiency. New ice navigation technologies and unmanned aerial vehicles (UAVs)/drones received lower improvement-priority scores. Overall, stakeholders in the Bay of Bothnia placed greater emphasis on enhancing human competence, satellite-based monitoring, and real-time information sharing.

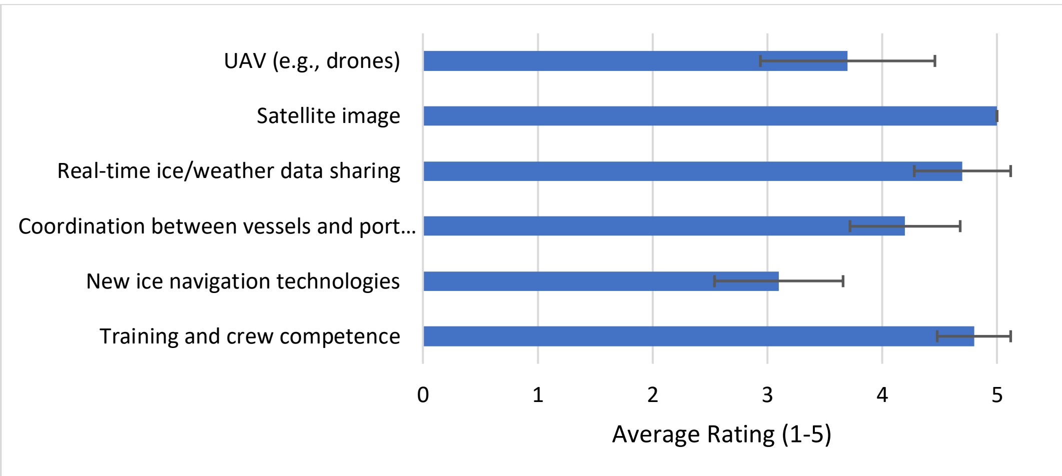

Figure 21. Average ratings of key aspects for improvement in icebreaking operations in the Bay of Bothnia. Respondents rated each aspect on a scale from 1 (low priority) to 5 (high priority). The bars represent the standard deviation, illustrating the variation in respondents' assessments for each aspect.

5.1.2.2 Question 2

The likelihood of various operational accidents and the associated risk factors during winter navigation in the Bothnian Bay were assessed. The results show that human-factor issues, such as fatigue and crew errors, were perceived as the most significant risk (average score: 3.7/5; standard deviation: 0.76), see **Figure 22**. This was followed by mechanical failures in harsh conditions (3.4/5) and collisions with assisted vessels (3.3/5). In contrast, low visibility was rated as a comparatively lower risk (3.0/5). These findings indicate that human factors and mechanical reliability are the two primary safety concerns in winter navigation.

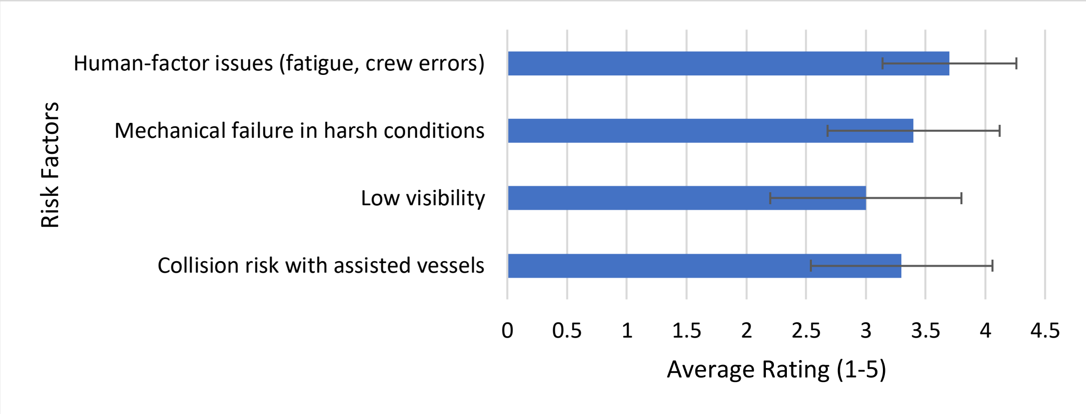

Figure 22. Average ratings of operational risk factors during winter navigation in the Bothnian Sea. Scale from 1 (low risk) to 5 (very high risk). The bars represent the standard deviation.

5.1.2.3 Question 3

Respondents rated the usefulness of different tools for ensuring safe navigation in ice-covered waters on a scale from 1 (not helpful) to 5 (critical). The results indicate that UAVs (4.7 ± 0.7) and AIS (4.6 ± 0.72) were considered critical tools, reflecting strong confidence in these technologies to enhance situational awareness and operational safety (see **Figure 23**). Satellite imagery (4.1 ± 0.42) and personal experience and judgment (4.1 ± 0.18) were also rated highly, highlighting the ongoing importance of both technological and human expertise in ice navigation. Meteorological and oceanographic forecasts (4.0 ± 0.42) and communication with other vessels (4.0 ± 0.8) were viewed as moderately critical. Radar systems (3.6 ± 0.18) and helicopters (3.4 ± 0.68) received lower scores, indicating that respondents perceive these traditional tools as less essential compared with newer, integrated, and data-driven technologies. The findings demonstrate a growing reliance on digital, remote-sensing, and information-sharing systems, complemented by human expertise.

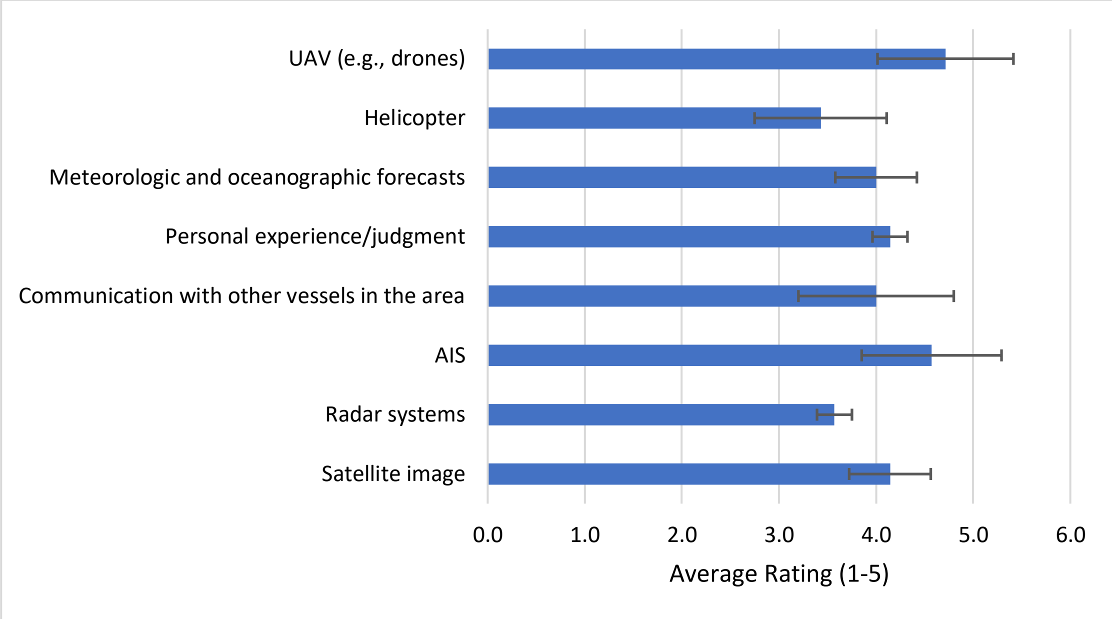

Figure 23. Average ratings of different tools for ensuring safe navigation in ice-covered waters. Respondents rated each tool on a scale from 1 (not helpful) to 5 (critical). The bars represent the standard deviation.

5.1.2.4 Question 4

The last question in this section required respondents to identify the factor that most strongly influences decision-making during winter navigation. Wind and current were cited by 50% of respondents as the dominant factors. Other factors mentioned included ice rubble or drifting ice (10%), sea ice concentration (10%), and ice ridges (10%), while 20% of respondents emphasised that a combination of all factors plays a critical role (**Figure 24**). This distribution reflects the complex interaction between ice, wind, and weather conditions governing navigation in ice-covered waters. While wind and current are the most decisive individual factors, safe decision-making depends on assessing multiple interconnected variables, highlighting the need for integrated ice and weather information systems.

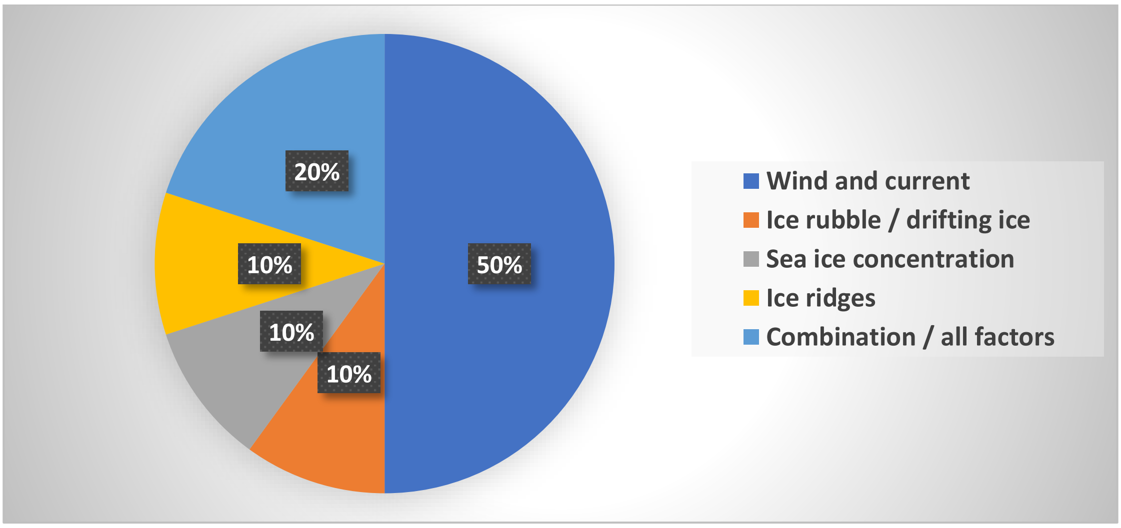

Figure 24. Factors influencing decision-making in winter navigation based on the percentage of responses.

5.1.3 Section 3: Impact of offshore structures on ice and ice navigation

In this section, the online questionnaire addressed two key questions focusing on how offshore structures may influence ice conditions and navigation safety in the Bay of Bothnia. The first question explored the proportion of vessels requiring assistance under varying ice conditions near offshore structures, while the second examined the severity of specific operational risks.

5.1.3.1 Question 1

The responses show an expected correlation between ice severity and the proportion of vessels requiring assistance, see **Figure 25**. Under mild ice conditions, 60% of respondents indicated that 11–20% of vessels typically need icebreaking support. In regular ice conditions, the demand for assistance increases substantially; 50% of respondents reported that 21–50% of boats require support, while another 40% estimated that more than half (over 50%) do. In severe ice conditions, the consensus was nearly unanimous, with 80% stating that more than half of all vessels require assistance. These results show that demand for icebreaking support rises with ice severity, underscoring the importance of coordinated operations for safe and efficient winter navigation in the Bay of Bothnia.

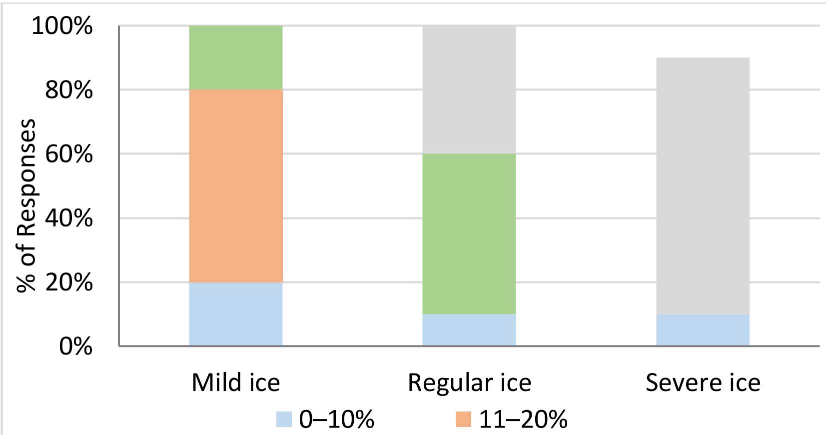

Figure 25. Proportion of vessels requiring assistance under different ice conditions, based on expert assessments.

5.1.3.2 Question 2

Respondents were asked to assess the severity of different risks encountered when navigating near offshore structures under ice conditions, see **Figure 26**. The results show that grounding due to route deviation or drifting near shallow areas (average score: 4.0 ± 0.6) and ice congestion close to shoals (4.0 ± 0.6) were considered the most likely risks. These were followed by radar interference or shadowing from the structure (3.2 ± 1.0) and collision with the foundation or structure (3.1 ± 0.9). The responses indicate that ice-related and navigational hazards, particularly grounding and ice congestion, are perceived as the most critical operational challenges near offshore structures. Meanwhile, risks associated with structural interaction and radar interference are viewed as less severe but still relevant to safe navigation planning.

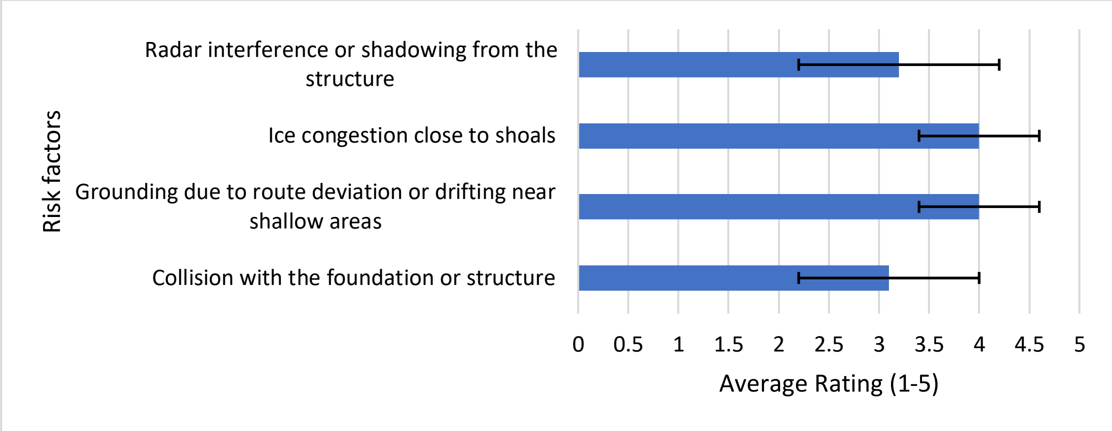

Figure 26. Average severity ratings of different risks associated with navigation near offshore structures. Respondents rated each risk on a scale from 1 (low) to 5 (very high). The bars represent the standard deviation.

5.1.4 Section 4: Impact of OWF on ice and ice navigation

This section examines the perceived impacts of planned offshore wind farms on winter navigation and icebreaker operations in the Bay of Bothnia. Respondents were asked to evaluate how the presence of OWFs might affect navigation safety, manoeuvrability, and operational efficiency under various ice conditions.

5.1.4.1 Question 1

Responses to the question regarding the OWFs' impact on icebreaker operations or convoys indicate that narrower channels, requiring precise navigation, are perceived as having the most severe effects on icebreaker operations, with an average score of 4.8 ± 0.32, indicating strong consensus among respondents (see **Figure 27**). In contrast, radar disruption or shadowing (3.5 ± 0.7) and speed reduction in confined areas (3.1 ± 0.72) were rated as moderate impacts. Both displayed greater variability in responses, reflecting differing perspectives. The responses suggest that restricted navigation space poses the most significant operational challenge for OWFs, as limited manoeuvrability increases risks during convoy and icebreaking operations.

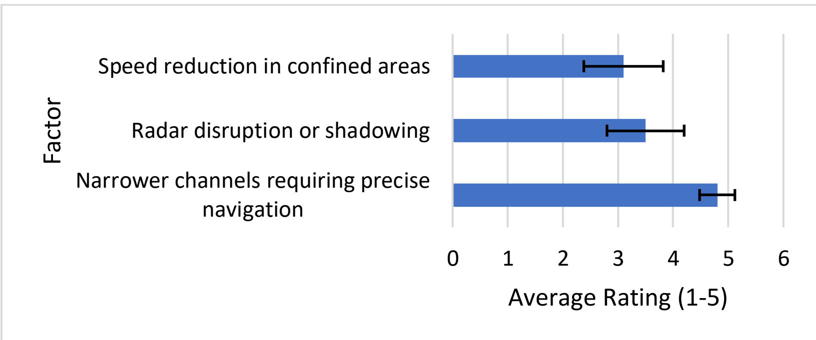

Figure 27. Severity ratings of the potential impacts of offshore wind farms (OWFs) on icebreaker operations or convoys. Respondents rated each factor on a scale from 1 = No effect to 5 = Severe effect. The bars represent the standard deviation.

5.1.4.2 Question 2

In response to the question "Please assign each of the following potential measures a priority rank," respondents were asked to prioritise different strategies for mitigating the impacts of OWFs on ice navigation. The results show that restrictions on OWF construction were given the highest priority (4.2 ± 1.1), indicating strong concern about the placement of wind farms in areas critical for ice navigation (**Figure 28**).

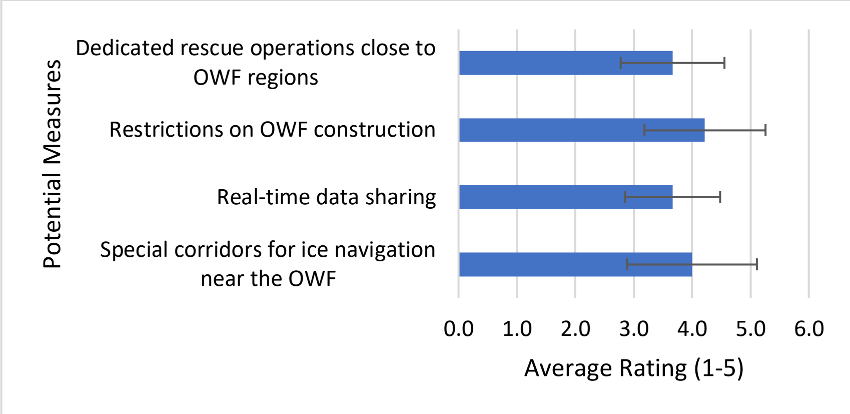

Figure 28. Average priority ratings assigned to potential measures for mitigating the impacts of offshore wind farms on shipping. Respondents rated each measure on a scale from 1 (Low priority) to 5 (High priority). The bars represent the standard deviation.

Special corridors for ice navigation (4.0 ± 0.8) also ranked highly, underscoring the importance of maintaining safe and navigable routes for vessels operating in ice-covered waters within OWF's area. Other measures, including real-time data sharing (3.7 ± 1.0) and dedicated rescue operations near OWFs (3.7 ± 0.9), were still recognised as important components of a comprehensive safety framework. The responses indicate a clear preference for preventive measures, such as route planning and spatial restrictions, underscoring the importance of proactive risk management to ensure safe coexistence between OWF development and maritime operations.

5.2 In-person interviews

This chapter presents insights from interviews with experienced icebreaker masters active in the Bay of Bothnia. The discussions focus on operational practices, decision-making, and safety management in ice-covered waters, as well as the potential impacts of offshore structures and future offshore wind farms on ice conditions and navigation. The interviews cover three main areas: (1) ice navigation and icebreaking operations; (2) the impact of existing offshore structures on ice behaviour and navigational safety; and (3) the anticipated effects of offshore wind farms, including risks, turbine spacing, and corridor design for winter navigation.

5.2.1 Section 1. Ice navigation and icebreaking operations

Q1. Management strategies and decisions for key risks (collision, visibility, mechanical failure, human factors).

All respondents emphasised that effective risk management during ice navigation relies on experience, coordination, and strict procedural discipline.

Collision risk: In lighter ice, vessels can maintain wider spacing, while in heavy, compressed ice, they must operate closer together or use towing for control. There is a need for clear, consistent communication between the icebreaker and the assisted vessel via radio channels. Collision risk is an ever-present concern when assisting vessels, particularly in areas of thick or compacted pack ice. OWFs could worsen this by creating additional ridges and ice rubble.Icebreaking inherently involves a "calculated risk", where close contact with assisted vessels is sometimes unavoidable in heavy, ridged, or compacted ice. During demanding conditions, two officers are always stationed on the bridge, and a third joins when necessary to strengthen situational awareness and decision-making. The experience and crew competence are the foundation for managing operational risks during icebreaking. Minor collisions between icebreakers and assisted vessels occur rarely, typically once per season, and are usually minor incidents.

Low Visibility: ice-breaking operations rely heavily on radar and distance measurement to keep safe separation. Under **low-visibility** conditions, ships being assisted often struggle to see or follow the correct channel, especially when multiple ice tracks or nearby structures are present. Under low-visibility conditions, operations continue but with enhanced caution and vigilance. Multiple radars (including X- and S-band) are used and may assign an additional lookout to monitor conditions visually. Communication with the assisted vessel is critical; if contact fails, the operation is immediately stopped.

During **mechanical failure**, the first response is to manoeuvre away; if that fails, the assisted vessel must stop. Regarding mechanical failures, they occur occasionally, most often when propellers or ballast systems freeze in extreme cold, making vessels unstable and more challenging to manoeuvre, even in light ice. For mechanical failures, it is essential to maintain safe manoeuvring margins, have contingency plans, and account for the age and reliability of icebreaker equipment in risk assessments.

For **human-factor risks**, the importance of team coordination, continuous dialogue, and reliable communication systems was highlighted, noting that equipment or channel failures are among the most serious threats during operations. Inexperience is the a critical risk: some crews are accustomed to ice operations, but others, particularly those new to winter navigation, become overly cautious or anxious, leading to poor decisions and communication errors. It was noted that having two officers per watch reduces errors and enables quicker responses. In addition, maintaining redundant systems, such as multiple sensors and range-measurement tools, is essential to ensure safety in case of equipment or communication failures.

Q2. How do wind and other meteorological factors affect your standard route or speed?

All interviewees highlighted that icebreaking operations are tightly controlled by meteorological conditions, with wind, currents, and ice drift consistently described as the dominant factors affecting navigation.

Wind direction and strength determine ice pressure and ice movement, guiding decisions on which areas to avoid and which routes to use. Captains aim to avoid areas with high ice pressure and move toward regions with lower ice pressure. For example, during westerly winds, open water may form along the Swedish coast, allowing some vessels to travel independently. Route selection is continuously adjusted through coordination among icebreakers, using satellite images, experience, and weather forecasts to identify viable paths.

Meteorological conditions also influence port entry, particularly in locations such as Luleå, which have multiple possible approaches. The choice of approach depends on the current wind direction and ice drift. Rain and snow primarily reduce visibility, complicating radar interpretation.

One respondent emphasised that wind is the "big game changer", noting that water levels in the Bay of Bothnia vary significantly with wind direction, speed, duration, and air pressure. These fluctuations affect navigation planning near ports and shallow areas.

Q3. Can you compare navigation in the Bay of Bothnia during winter and summer?

Interviewees unanimously highlighted significant differences between winter and summer navigation in the Bay of Bothnia. During summer, vessels can navigate freely, choose direct routes, and use any fairway without ice-related constraints.

In winter, navigation is entirely dictated by ice conditions. The shortest path is often the most difficult, and vessels must follow icebreaker-opened channels, resulting in longer and more restricted routes. Captains emphasised that winter navigation requires adapting to natural forces rather than resisting them.

Local ice dynamics add complexity: In one example, several weeks of strong southwesterly and southerly winds pushed ice northward, blocking access to Luleå and closing Kalix port for three weeks, forcing cargo to be moved by land.

In heavy ice conditions, vessels may need to be escorted one by one through alternative fairways, depending on draft and ice conditions.

Infrastructure improvements, such as dredging deeper fairways, were mentioned as measures that could ease winter navigation, enabling deeper-draught vessels to use certain entrances, such as the southern approach to Luleå.

Q4. What is the main difference you have experienced in winter navigation or icebreaking in the Bay of Bothnia that may be related to climate change (e.g., less surface ice but more rigid ice, delayed freeze-up, earlier melting, or changes in ice categories)?

All interviewees reported noticeable changes in winter navigation conditions that they attribute to climate change. A consistent observation was that winters have become windier, with smaller areas of ice cover, while the ice that does form is more rigid, compact, and compressed.

Respondents noted that freeze–thaw patterns have shifted, with strong winds and storms now occurring later in the season (December–January) rather than in autumn. Winters that previously brought stable cold and snow now include rain and wind, contributing to harder, denser ice despite reduced overall ice coverage. As a result, icebreaking remains demanding and requires the same number of icebreakers as before.

It was explained that stable cold periods are now shorter, lasting only days or a week before strong winds return. These winds cause continuous ice drift, rubble, and ridge formation, which complicate navigation.

Another key change is the shorter duration of complete ice cover. In the past, both the Bay and the Sea of Bothnia froze entirely, whereas now the Bay of Bothnia may freeze for only a week or two. Increased open water leads to more frequent ice barriers near ports, driven by wind and currents. Consequently, icebreaker assistance is increasingly focused on short-term clearing near harbours rather than full-bay operations. Melting often occurs earlier, ending the icebreaking season several weeks ahead of historical patterns.

Q5. What would you consider the top 2–3 technological or operational improvements in winter navigation, and how have these changes affected operational efficiency or safety (e.g., reduced travel time, fewer incidents, smoother coordination, etc.)?

Across all interviewees, the IBNet system was identified as the most significant improvement in winter navigation. The system has evolved into a central platform for sharing routes, monitoring vessel movements, and coordinating operations between icebreakers and assisted vessels. It replaces older manual methods, such as transmitting coordinates via VHF, and has greatly improved efficiency, accuracy, and safety.

Improved satellite imagery, with higher frequency and better quality, was highlighted as another significant advancement, providing enhanced situational awareness and supporting route planning. Several interviewees noted ongoing efforts to integrate satellite data, port information, and potentially drone-based ice mapping directly into IBNet for real-time updates.

Enhanced communication systems, such as the adoption of Starlink, have eliminated previous coverage gaps and significantly strengthened coordination at sea. Better radios and more reliable connectivity improve information flow and enhance safety.

The AIS was also emphasised for improving vessel tracking, and coordination between ships and icebreakers.

Some interviewees highlighted operational improvements in the icebreaker fleet, including the use of azimuth thrusters on modern Finnish icebreakers, which provide better manoeuvrability than conventional propellers.

Interviewees also discussed the potential of artificial intelligence as a future tool. They stressed that AI could support route planning by analysing data from weather forecasts, satellite imagery, AIS, ice charts, and port operations. However, they emphasised that AI should complement, never replace, human judgment, particularly given the importance of experience, crew culture, and vessel-specific performance in winter operations.

5.2.2 Section 2. Impact of offshore structures on ice and ice navigation

Q1. What management strategies or decision-making approaches do you use when assisting vessels near offshore structures?

Interviewees explained that navigating near offshore structures is primarily dictated by ice conditions, weather, ice drift, and expected changes in these factors. Decision-making focuses on maintaining a safe distance, avoiding areas where drifting ice forms ridges, and passing structures from the side opposite the ice drift to reduce risk.

Existing structures in the Bay of Bothnia are mostly lighthouses, which serve as reference examples. These are often located near shallow waters, making them natural no-go areas that require heightened caution. Some masters noted that areas around offshore installations are generally treated as shallow-water hazards, with 500 m restricted zones, which is the maximum safety zone around offshore installations, according to UNCLOS.

Q2. Please explain how the above approaches vary with different ice conditions.

Interviewees emphasised that strategies near offshore structures change with ice severity. Under light ice conditions, navigation resembles open-water sailing. Under thicker, drifting, or compacted ice, risk awareness increases. Vessel assistance becomes more critical to avoid drifting into shallow or restricted areas, and routes must be adjusted based on ice drift direction, ridging, and pressure zones. In severe winters with extensive ice cover, offshore structures intensify ice deformation, creating ridges and pressure areas. These interactions depend strongly on seasonal severity.

It was also noted that predicting the presence of grounded or compacted ice around structures is challenging and may require ice-basin testing to better understand how different ice types interact with offshore installations.

Q3. How do offshore structures influence local ice conditions based on your experience

• Which types of offshore structures (e.g., lighthouses, beacons, offshore platforms, etc.) tend to cause the most noticeable impacts?

• What type of ice seems to be most affected, and within what approximate distance (e.g., X NM) do you typically notice these changes?

Interviewees explained that offshore structures, especially lighthouses, beacons, and buoys, influence local ice conditions by creating tracks, ridges, and deformation zones as drifting sea ice presses against them. Drifting ice is the most affected, becoming compressed and ridged around fixed structures, while stable fast ice is less influenced.

Lighthouses are generally robust and designed to withstand heavy ice pressure, though older ones may show damage, and in one case (Björnklack), a lighthouse was toppled by ice movement. Floating beacons and buoys are more vulnerable; they may become submerged, drift away, or disappear due to ice forces, requiring seasonal removal and reinstallation.The degree and distance of impact depend mainly on wind direction, wind duration, ice drift speed, and currents. In prolonged strong winds, significant accumulations of rubble ice can build up on the side opposite the prevailing drift.

Some interviewees noted that lighthouses located near shallow waters form natural no-go zones, as vessels risk getting stuck if they pass too close and are pushed toward them by wind and ice drift. Poor navigational decisions, such as taking shortcuts, can increase these risks.

Q 4 & 5 Do you typically apply a safety buffer zone (e.g., X NM) around offshore structures during icebreaking operations? Under which ice conditions might that buffer need to be larger (e.g., X NM in severe conditions)?

All interviewees stated that a safety buffer zone is always maintained around offshore structures, mainly due to shallow waters, grounding risks, and ice behaviour near fixed installations.

The required buffer distance cannot be fixed, as it depends on current weather, ice drift, ice severity, and pressure ice conditions. Masters emphasised that the buffer is adjusted dynamically to prevailing circumstances. In severe ice or during strong winds with fast-moving ice, the buffer must be increased to ensure safe manoeuvring.

Strategies also include passing structures on the side where the ice drifts away, reducing the risk of vessels being pushed toward them. When risk remains high, towing may be used to maintain control.

Interviewees noted that typical minimum distances around offshore structures are around 500 m, but in practice, buffer zones can extend to several nautical miles depending on the situation.

Interviewees noted that experience from lighthouses showed that even in light ice, vessels generally keep 5–10 cables (≈900–1800 m) distance, and can come as close as 0.2 NM only under icebreaker escort.

5.2.3 Section 3. Impact of offshore wind farms on ice and ice navigation

Q1. What is your current knowledge of OWFs' impact on ice and navigation? Consider ship routing, radar, space availability (manoeuvre), radar system, safety, anchoring during an emergency, etc.

All interviewees noted that current knowledge of offshore wind farms and their effects on ice and navigation in the Bay of Bothnia is limited, as no OWFs currently operate in the region. Existing experience comes mainly from environments with mild or thin ice, offering little insight for northern conditions.

Several respondents emphasised that maintaining sufficient manoeuvring space and safe distances will be essential if vessels are required to navigate near or through OWFs. Corridors between turbines must be wide enough to prevent ships from drifting into structures or becoming stuck in moving ice, and adequate icebreaker availability would be necessary to assist vessels under challenging conditions.

Interviewees compared potential OWF impacts to those observed around Arctic oil platforms and other fixed structures, where drifting ice forms rubble and ridges as it interacts with the installations. Anchoring was considered irrelevant in ice-covered waters, as vessels typically drift with the ice rather than anchor.

Some participants noted that radar performance near turbines in southern regions has not been a problem, with turbines remaining visible on radar. However, they stressed that such observations may not apply to the Bay of Bothnia's heavy-ice environment. Overall, assessments of OWF impacts on winter navigation in this region remain largely theoretical.

Q2. Do you see potential benefits from OWFs for winter navigation? How might they be used?

Interviewees largely agreed that offshore wind farms do not provide direct benefits for winter navigation. Instead, their presence would introduce new operational demands. Icebreakers would need to monitor vessel movements in and around wind farms, respond to emergencies, and assist ships that drift too close to turbines under difficult ice or wind conditions. This would expand the area of responsibility for national icebreaker services and increase their workload. Some interviewees noted that this burden could be reduced if OWF developers maintained their own fleet of support or icebreaking vessels to handle turbine access and emergency assistance.

Although no clear navigational advantages were identified, a few respondents discussed theoretical or speculative potential effects. It was suggested that offshore wind farms could cause ice to become more stationary rather than drifting, thereby creating more navigable conditions on the lee side of the farm. However, this idea remains unverified and would require controlled testing to understand how turbine structures influence ice drift and deformation.

Several interviewees stated that coexistence between OWFs and winter navigation might be more manageable if wind farms were located closer to shore, where ice often remains fixed. In such areas, interactions between drifting ice and turbine structures might be reduced, although nearshore siting could face local opposition from residents in archipelago regions.

Some respondents noted that OWFs would likely increase demand for icebreakers, which could be seen as an indirect operational benefit if it led to a larger, more capable fleet.

A consistent conclusion across interviews was that the effects of OWFs on ice conditions, such as ice drift, thickness, and ridge formation, need to be examined through small-scale or modelling studies, as current understanding is limited and cannot be inferred from the few installations in regions with mild ice.

Q3. Do OWF structures influence ice ridging or concentration? How?

Interviewees agreed that offshore wind farm structures will influence ice ridging and concentration in the Bay of Bothnia. The turbines would interfere with the natural drift of sea ice, causing it to break, and to accumulate around the foundations.

Respondents also compared these processes to ice behaviour around lighthouses and other fixed structures. As drifting ice passes such stationary objects, it leaves a weakened track in the ice cover that becomes a focal point for ridge formation when wind or current direction changes. Multiple respondents explained that this effect could occur around each turbine, leading to a large wind farm generating numerous intersecting tracks and ridges. This would create a complex, uneven ice field with more rubble, compacted ice, and areas of pressure ridges. Some interviewees described this cumulative effect as turning the wind farm area into an "ice machine." Interviewees noted that the severity and width of ridge formation depend on factors such as ice thickness, drift speed, wind direction, and compression forces, with ridges potentially reaching several metres above the sea surface.

Another assumption could be that thin ice may move relatively freely through a wind farm, but as ice thickness increases, its movement would slow, deform, and eventually stop, depending on drift speed and prevailing conditions. This may lead to difficult navigation around and between turbines.

Q4. If navigation is required within OWFs during winter, what risks do you foresee? Are these higher than usual?

All interviewees agreed that navigating within offshore wind farms during winter will involve much higher risks than usual.

OWF areas would likely become restricted zones, with access limited mainly to maintenance vessels, which would face significant challenges reaching the turbines due to ice conditions. Dedicated icebreakers would be necessary to support these operations, as existing icebreakers cannot be assigned solely to wind farm assistance.

Emergencies could require entering wind farms, which would be a nightmare scenario for icebreaker captains due to restricted manoeuvring space and collision risk. For example, rapid ice movements could push vessels into turbine structures, increasing collision risk. Ice conditions, currents, and turbine spacing would critically determine operational safety, with smaller icebreakers being the only practical option for rescue or assistance within such areas.

Drifting vessels or mechanical failures (e.g., ice in rudders or propellers) would be complicated to handle within such constrained environments, making rescue operations challenging and dangerous. Risks in these situations are clearly higher than usual.

Q5. In your opinion, how should turbines be spaced or arranged to minimise winter shipping disruptions (e.g., corridors, buffer zones, alignment with dominant ice drift)?

Interviewees stressed that offshore wind farms should be designed to minimise interference with winter navigation. A common view was that turbines should be placed as far offshore as possible and positioned to minimise the total area affected by ice–structure interactions. Some participants recommended tightly clustered turbine arrangements, which confine ice impacts to a smaller region. Although such clustering may trap ice between structures and create zones of stationary ice, this was considered preferable to widely spaced turbines that could generate multiple ice tracks and ridges across a broader area. The question of what spacing and foundation size turbines begin to block ice movement significantly is an important area for further investigation.

Another recommendation was to cluster turbines while maintaining broad, well-defined navigation corridors. These corridors should remain flexible to allow vessels and icebreakers to manoeuvre safely. Accessing the lee side of a wind farm was noted as advantageous when winds shift.

Some interviewees emphasised that the placement of OWFs outside main shipping routes and icebreaking paths is the most critical measure for reducing winter navigation disruptions.

Another perspective was that wind farms should include a designated no-go or buffer zone, similar to a traffic separation scheme, where vessels are prohibited from entering during winter.

Q6. If typical convoy widths or turning radii require a certain corridor, how wide would an ideal corridor be? For instance, is an X NM separation enough for two icebreaking convoys to pass simultaneously? Could narrower corridors be acceptable in mild ice conditions but not in severe ones?

Interviewees explained that the ideal corridor width for winter navigation depends on ice conditions and location. In open areas, convoys can sometimes use the same track, but near ports or constrained areas, spacing becomes more critical.

One respondent stated that 1 to 1.5 nautical miles could be sufficient for icebreaker convoys to meet safely in certain conditions. For channels between OWFs, a much wider corridor of about six nautical miles was suggested to allow safe manoeuvring and provide a margin for drifting ice. Finnish authorities have suggested a 6 NM corridor along the EEZ border (3 NM on the Swedish side and 3 NM on the Finnish side). Sweden has not yet decided on any distance requirement.

Another respondent stated that narrower corridors may work in mild ice, but in severe ice, significantly more space is required. For two convoys to pass safely, a corridor of at least three nautical miles would be necessary. Under challenging conditions, vessels may have to wait and be assisted one by one using temporary staging areas.

Another interviewee noted that, in normal operations (without wind farms), two convoys typically maintain a five-cable separation in good ice conditions. However, near the turbines, defining a safe corridor was considered too difficult due to the risks.

A different respondent estimated that 10–15 nautical miles might be required in challenging winter conditions. Convoys may include up to 11 vessels, and if one becomes immobilised, significant space is needed for drifting, assistance, and manoeuvring.

Q7. What minimum inter-turbine spacing (in NM) ensures safe two-way ice navigation in the Bay of Bothnia, considering vessel beams, ice drift angles, and icebreaker operations?

Interviewees expressed differing views on the minimum inter-turbine spacing required for safe two-way navigation in the Bay of Bothnia, but all agreed that the necessary distance depends heavily on ice conditions, ice drift behaviour, vessel operations, and turbine characteristics.

Some respondents suggested specific distances. One indicated that around six nautical miles between turbines would be necessary to allow icebreaker convoys to manoeuvre, pass each other, and manage drifting ice without excessive risk. Another proposed a minimum of three nautical miles, ideally expanding up to six nautical miles, to create two-way corridors and safety buffers for both merchant vessels and icebreakers. This spacing would need to accommodate ice drift angles and whether vessels are navigating independently or with icebreaker assistance, which requires additional clearance.

One respondent emphasised that turbine spacing must also consider turbine width and the potential effects of ice dislodged or thrown from turbine blades. They noted that determining safe spacing will require simulation and field testing to understand how ice interacts with turbine structures under different conditions.

6 Conclusion and future work

This pre-study has provided an initial assessment of how planned OWFs may interact with winter navigation in the Bay of Bothnia. The assessment is based on three complementary sources of evidence: AIS-based reconstruction of vessel traffic and ship–OWF intersections, analysis of sea-ice conditions including concentration and thickness, and stakeholder perspectives collected through an online questionnaire and in-depth interviews with experienced shipmasters.

Taken together, the literature review, AIS-based analyses, ice-condition assessment, questionnaire responses, and interviews reveal a consistent overall pattern. The main challenge associated with planned OWFs in the Bay of Bothnia is not only their spatial overlap with shipping routes, but their potential to reduce the operational flexibility on which winter navigation depends. Existing literature has already highlighted that offshore structures may restrict manoeuvring space, complicate navigation, and in some cases alter local ice behaviour. However, previous studies provide only limited knowledge of how such effects may develop under ice-cover conditions in the Bay of Bothnia. This study helps close part of this gap by showing that maritime traffic is repeatedly concentrated into a limited number of navigable corridors, and that these corridors shift with winter severity (ice conditions). This means that the significance of a planned OWF area cannot be assessed solely from its fixed location on a map, it must also be understood in relation to the dynamic redistribution of vessel traffic and icebreaker support under changing winter conditions. The detailed findings are summarized below.

In the mild winter (2014–2015), Swedish OWF S-135 shows the largest overlap with cargo and tanker routes (roughly 45–51% of cargo and 43–60% of tankers intersect), reflecting its location on the main corridor. S-113 and S-111 show moderate interaction, while several other Swedish OWFs have negligible overlap. Icebreaker passages concentrate most strongly near S-111 (coastal/northern ice), with peaks such as 28 passages in March 2015.

In the normal winter (2022–2023) (with Swedish and Finnish EEZ coverage), intersections intensify for OWFs placed on the main corridor, especially S-135 (Sweden) and F-43 (Finland). When ice conditions become more constraining, traffic shifts toward more navigable coastal zones and/or icebreaker-assisted convoys, increasing intersections for some areas (e.g., F-15, F-22) while reducing passages through regions with harsher local ice (e.g., S-113 in some months). Icebreaker passages rise sharply in the most challenging month, reaching peaks such as 45 crossings at S-135 and 28 at F-43.

In severe winters (2010–2011, 2023–2024) within the Swedish EEZ, the intersection patterns become more extreme and more sensitive to where "easier" or more manageable ice develops (often controlled by wind-driven drift/pressure). In 2010–2011, S-135 reached exceptionally high traffic overlap (e.g., ~88% of cargo and ~96% of tankers in February 2011) and an icebreaker-passage peak of 143 through S-135. In 2023–2024, S-135 remains dominant, while intersections with S-111 and S-113 vary strongly month-to-month as the usable corridor migrates southward and/or toward the Swedish or Finnish side depending on ice and wind.

Respondents and shipmasters consistently emphasise that winter operations depend on situational awareness, real-time information sharing, and crew competence, and that wind-driven ice drift and compression are decisive in route choice. In the questionnaire, priorities for improving winter navigation emphasise satellite imagery, training, and real-time data sharing; perceived risk is highest for human factors and mechanical reliability. For offshore structures, stakeholders rate grounding and ice congestion near shoals as major concerns; for OWFs specifically, the most severe expected impact is restricted space/narrower channels for convoy and icebreaker operations. Interviews reinforce that fixed structures can create ice tracks, rubble, and ridges; participants warn that a wind farm could create cumulative deformation effects ("many structures → many ridging/weakness lines"), complicating both routine routing and emergency response.

Future work will build on this pre-study by moving from descriptive intersection statistics toward an operational, actionable decision-support system. This will require multi-source data fusion, combining AIS, projected ice conditions, and icebreaker/port operational data, to enable simulation of channel navigability and winter traffic flows. Building on these capabilities, physics-informed digital twins (Lang et al., 2024) and decision-support tools can be developed to support icebreaker coordination under dynamic ice, port, and traffic conditions. Finally, the framework can be extended to evaluate marine planning scenarios (e.g., offshore infrastructure deployment, traffic regulations, and climate change) to optimize winter route planning and icebreaker dispatching while maintaining safe and reliable access to northern ports.

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