Image by Claudia Hinz from Pixabay

The impact of wind farms on winter navigation

Project leader: Professor Jonas W. Ringsberg
Authors: Victor Ceder, Nils Helgesson, Basil P. Thomas, Jonas W. Ringsberg
Report date: 2024-10-22

Chalmers University of Technology
Department of Mechanics and Maritime Sciences
Division of Marine Technology
SE-412 96 Gothenburg
SWEDEN

Summary

In 2022, the Swedish Government adopted the first Swedish marine spatial plans. At the same time, The Swedish Agency for Marine and Water Management (SwAM) was assigned to bring forth proposals for amended marine spatial plans to meet the need for increased electricity production. These plans include and identify several areas in the Gulf of Bothnia that may be suitable for offshore wind power installations in the form of dense wind farms. These farms are planned geographically based on several parameters, including minimizing the impact on commercial shipping in the area, which follows predictable routes during the summer. The Gulf of Bothnia, especially the Bay of Bothnia, is completely or partially covered with ice of varying thickness and concentration during the winter. The ships that operate in these areas during winter therefore require the assistance of icebreakers. Requirements for economic and environmental sustainability are the basis for effective icebreaker planning where, due to the dynamics of the ice, the routes vary greatly from week to week. Offshore wind power hinders and blocks the choice of ship routes and also risks affecting ice formation and the nature of the ice.

The project has carried out a literature study to compile current knowledge about ice formation in the vicinity of offshore wind farms. It shows that there is a large knowledge gap in the area. There is therefore a great need for further research to understand if and how the ice formation at wind farms develops to ensure safe installations and how the ice formation may affect, for example, winter navigation. The project has developed a generally applicable methodology for assessing how shipping is directly affected by offshore wind farms both in summer and winter by limiting the range of available shipping routes. The methodology uses historical tracking data (AIS data) of maritime traffic in the years 2018, 2022 and 2023. It has been applied to geographical areas that SwAM specified as areas of special interest in the Gulf of Bothnia. Through a proprietary script in the Python programming language, the data has been filtered, processed and presented ship tracks on maps of desired areas that contain sub-areas where wind farms are planned to be installed. Based on this, the wind farms' impact on shipping was visually analyzed to identify problematic areas and periods. This has been compared with ice data (thickness, concentration and movement) to explain why ship routes follow different patterns at different time periods (eg, months). To systematically track and compare areas, the proportion of ships within an area whose routes cut through the various wind power areas has been calculated. Statistics have been produced for the analyzed years and areas as specified by HaV.

All the years that have been analyzed have limited ice extent in the Sea of Bothnia and thus the analysis was limited to summer traffic in this sub-area as the routes do not need to be adapted to the ice and without the need for icebreaker assistance. Potentially problematic areas are identified here: B164 with a crossing frequency of 40% in the third week of November 2023, B149 with 40.4% in the last week of October 2023. In the Bay of Bothnia, large parts are covered by ice in winter and there winter traffic with icebreaker assistance could also be analysed. Here, the results show relatively stable intersection frequencies in summer but highly variable, and generally higher frequencies in winter. This is due to the adaptation of routes due to the dynamics of the ice. Potentially problematic areas are identified here B111 with a cut rate of 60% in the first week of April 2023, B113 with 45.6% in the first week of May.

Keywords: AIS data, Gulf of Bothnia, icebreaking, offshore wind farm, winter navigation.

Sammanfattning

Under 2022 tog regeringen beslut om de första svenska havsplanerna. Samtidigt fick Havs- och vattenmyndigheten (HaV) i uppdrag att ta fram förslag till ändrade havsplaner med syftet att skapa förutsättningar för ökad energiutvinning i havet, i form av havsbaserad vindkraft. Förslag till ändrade havsplaner ska lämnas till regeringen senast den 31 december 2024. Dessa planer inkluderar och pekar ut flera områden i Bottniska viken som kan lämpa sig för havsbaserad vindkraft i form av täta vindkraftsparker. Dessa parker planeras geografiskt utifrån flertalet parametrar, däribland att minimera påverkan på den kommersiella sjöfarten i området som under sommartid följer förutsägbara rutter. Bottniska viken, särskilt Bottenviken, är under vintertid helt eller delvis täckt med is av varierande tjocklek och koncentration. Fartygen som trafikerar dessa områden under vintertid kräver därför assistans av isbrytare. Krav på ekonomisk och miljömässig hållbarhet ligger till grund för en effektiv isbrytarplanering där rutterna, på grund av isens dynamik, varierar kraftigt från vecka till vecka. Havsbaserad vindkraft hindrar och blockerar valet av fartygsrutter och riskerar även att påverka isbildning och isens karaktär.

Projektet har genomfört en litteraturstudie för att sammanställa nuvarande kunskap om isbildning i närheten av vindkraftsparker till havs. Den visar att det råder ett stort kunskapsgap inom området. Det finns därför ett stort behov av vidare forskning för att förstå om och hur isbildningen vid vindkraftsparker utvecklas för att säkerställa säkra installationer samt hur isbildningen kan komma att påverka t ex vintersjöfarten. Projektet har utvecklat en generellt applicerbar metodik för bedömning av hur sjöfarten påverkas direkt av vindkraftsparker till havs både under sommar- och vintertid genom att utbudet av tillgängliga fartygsrutter begränsas. Metodiken använder sig av historiska spårningsdata (AIS-data) av sjötrafik under åren 2018, 2022 och 2023. Den har applicerats på geografiska områden som HaV specificerade som områden av särskilt intresse i Bottniska viken. Genom ett egenutvecklat skript i programmeringsspråket Python har data filtrerats, bearbetats och presenterat fartygsspår på kartor över önskade områden som innehåller delområden där vindkraftsparker planeras bli installerade. Utifrån detta analyserades vindkraftsparkernas påverkan på sjöfarten visuellt för att identifiera problematiska områden och perioder. Detta har jämförts med isdata (tjocklek, koncentration och rörelse) för att förklara varför fartygsrutter följer olika mönster vid olika tidsperioder (t ex månader). För att systematiskt kunna spåra och jämföra områden har andelen fartyg inom ett område vars rutter skär igenom de olika vindkraftsområdena beräknats. Statistik har tagits fram för de analyserade åren och områdena som HaV specificerat.

Samtliga år som analyserats har begränsad isutbredning i Bottenhavet och därmed begränsades analysen till sommartrafik i detta delområde då rutterna ej behöver anpassas efter isen och utan behov av isbrytarassistans. Här identifieras eventuellt problematiska områden B164 med en skärningsfrekvens på 40% tredje veckan i november 2023, B149 med 40.4% sista veckan i oktober 2023. I Bottenviken täcks stora delar av området av is vintertid och där kunde även vintertrafik med isbrytarassistans analyseras. Här visar resultaten relativt stabila skärningsfrekvenser sommartid men kraftigt varierande, och överlag högre frekvenser vintertid. Detta på grund av anpassningen av rutter på grund av isens dynamik. Här identifieras eventuellt problematiska områden B111 med en skärningsfrekvens på 60% första veckan i april 2023, B113 med 45.6% första veckan i maj.

Nyckelord: AIS data, Bottniska viken, havsbaserad vindkraft, isbrytning, vintersjöfart.

Table of contents

Nomenclature and abbreviations

AIS	Automatic identification system, positional and identification information required to be transmitted by most commercial vessels
CCTV	Closed-circuit television, video surveillance
CSV	Comma-separated values, structured text format for data
SwAM	Swedish Agency for Marine and Water Management
IMO	International Maritime Organization
In-situ	In place, in the real world
OWF	Offshore wind farm
Pandas	Software library for Python for data manipulation and analysis
Python	Script programming language
SAR	Synthetic aperture radar, imaging radar
SIC	Sea ice concentration
SIT	Sea ice thickness
SIV	Sea ice velocity
SOLAS	International Convention for the Safety Of Life At Sea
TDR	Turbulence dissipation rate
TKE	Turbulent kinetic energy
TSS	Traffic separation scheme
VHF	Very high frequency, radio communication system
VLSFO	Very low sulphur fuel oil
WRF	Weather research and forecasting model
WIPAFF	WInd PArk Far Fields project

Preface

The project was carried out from 8 January to 30 September 2024 at Chalmers University of Technology, the Department of Mechanics and Maritime Sciences, the Division of Marine Technology.

Professor Jonas Ringsberg has been appointed project leader. Other faculty members who have contributed to the project are Professor Wengang Mao, Professor Hua-Dong Yao, and Dr Zhiyuan Li. Three project assistants were hired to work on the project: Victor Ceder, Nils Helgesson, and Basil P. Thomas.

The authors acknowledge Frida Åberg at The Swedish Agency for Marine and Water Management (SwAM), and Niklas Hammarkvist at the Swedish Maritime Administration, for fruitful discussions and proof-reading of the report.

Through discussions with Associate Professor Arttu Polojärvi at Aalto University (Finland), the project team at Chalmers has identified the need for a stronger collaboration between Sweden and Finland. This is particularly important as both countries face similar challenges in our respective research areas, but currently, we seem to be working on solutions independently.

1. Introduction

The Swedish Energy Agency, together with the Swedish Agency for Marine and Water Management (SwAM), have been given the mission of updating the recently decided ocean plans to enable 90 TWh/year in offshore wind farms (OWF) in addition to the current 20-30 TWh/year included in earlier plans. This comprehensive extension imposes the risk of interfering with winter navigation by impeding the icebreaking in the Gulf of Bothnia. Several problems could arise, e.g., re-routing around OWFs, ships getting stuck in the ice and drifting into OWFs, and other disturbances in the traffic close to an OWF. Furthermore, the wind turbine’s foundation imposes the risk of interfering with ice movement such that icebreaking is adversely affected. This information is not only specific to interactions between shipping traffic and OWFs in the Gulf of Bothnia. However, it could be relevant for any geographical location where shipping traffic and offshore windfarms may affect each other in combination with sea ice.

At the start of the project, OWF areas, as planned on 2023-09-14, were used to develop the methods and data processing scripts; see Figure 1. The green areas indicate the main planned areas, and the yellow areas indicate alternative areas. However, the early results from the analysis of these areas are no longer useful to the project since the areas were changed on 2024-05-16; see Figure 2. Hence, the results presented in the report refer to the areas presented in Figure 2. Note that no alternative areas are presented in Figure 2.

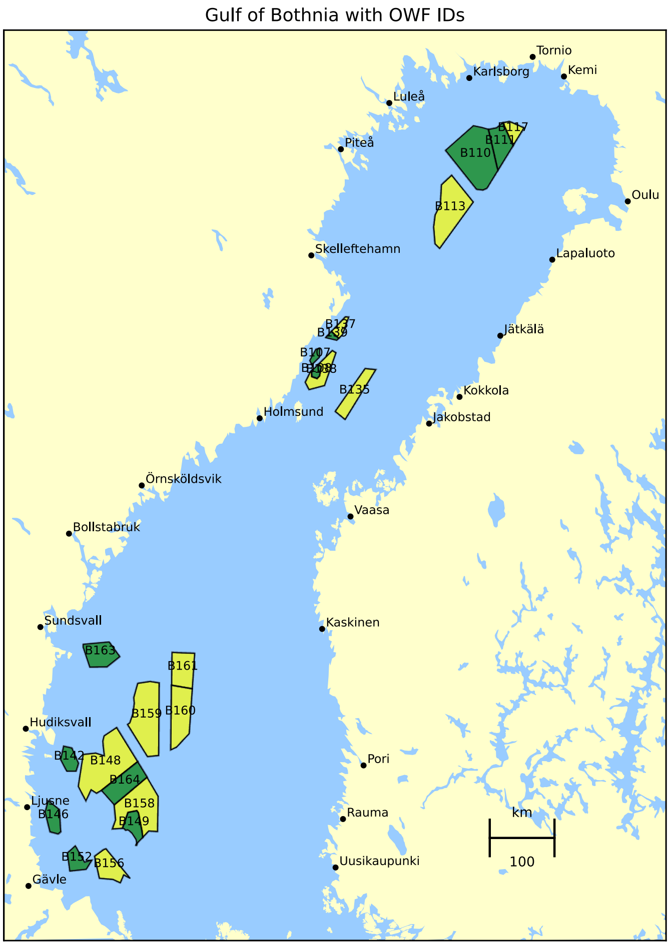

Figure 1: OWF areas planned 2023-09-14.

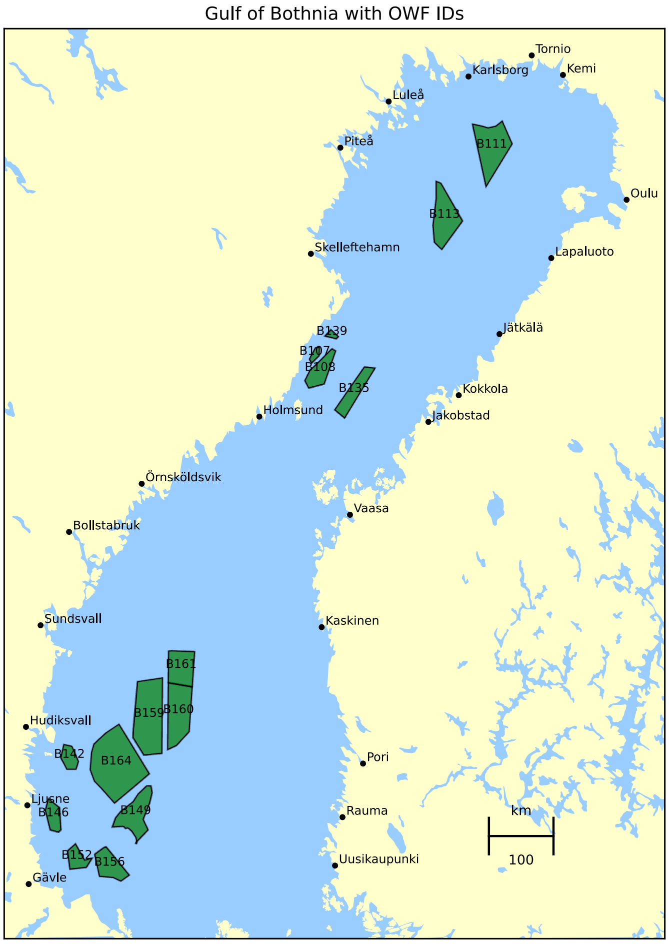

Figure 2: OWF areas planned 2024-05-16.

1.1. Objectives and goals

The objectives of the project were to perform a pilot study to develop a method to better understand offshore wind farms' impact on ice formation and corresponding consequences for winter navigation and to inventory the current knowledge about OWFs' impact on ice formation and how they affect shipping and icebreaking during winter in the Gulf of Bothnia. SwAM defined three questions which the project should has as a goal to answer:

1) How are the shipping lanes affected by offshore wind farms?
2) How will the extension of offshore wind farms in ice covered seas change the conditions for winter navigation with regards to: (a) Available routes, (b) icebreaker operations and the demand for icebreakers, and (c) optimized planning of traffic and icebreaking?
3) How will the formation of ice (with regards to, e.g., thickness, hardness, movement, and growth of ice ridges) be changed if offshore wind farms are installed?

1.2. Assumptions and limitations

As a pre-study, the project is limited to identifying and closing knowledge gaps by compiling information. This is completed with an in-house developed methodology for data analysis of shipping, described in a later chapter of the report. In that sense, no new scientific research is conducted nor included in the project. The compilation of information is limited to a literature study and gathering information from Finnish experts within the field. The Finnish and Swedish icebreaker operations are heavily co-dependent and both nations are facing the same knowledge gaps before implementing offshore wind farms. In addition to this, the geographical vicinity entails similar ice behaviour and that the routes used by commercial shipping cross the border.

One of the outcomes of the project is a methodology and platform developed during the project for generating qualitative and quantitative information and statistics that can be used as a support for decision making. Thus, the project will neither include recommendations for placement of OWFs nor will any icebreaking tactics or strategies be recommended. Rather it provides concrete statistics on the currently proposed areas. It should be noted that the project's data collection is limited to the geographical area of the Gulf of Bothnia and more specifically the OWF areas specified by SwAM in Figure 2.

The analysis of trading patterns is performed on Automatic Identification System (AIS) data, a system that most commercial ships are equipped with. The system is based on a transponder on a ship that sends out its positions and other data and is collected by a receiver. The data used in the project is historical data that has been saved for the years 2018, 2022 and 2023. It should be noted that complete sets of data that were needed to do the analyses in the project were only available for these three years. The ice winter 2017-2018 was classed as a "Normal Ice Winter" (between 115 000 km² and 230 000 km²) while the winters 2021-2022 and 2022-2023 were classed as "Mild Ice Winter" (less than 115 000 km² ice coverage) by the Swedish Meteorological and Hydrological Institute. The project does therefore not include an analysis of a "Severe Ice Winter" (230 000 km² or more ice coverage) (Sjöfartsverket, 2023). Hence, the findings and recommendations made in this report can only be referred to the ice conditions classed as mild and normal ice winters. It is likely that a severe ice winter will have even adverse impact on shipping's winter navigation, especially in the Bay of Bothnia, but also in the Sea of Bothnia. Due to lack of access to data, a winter with severe ice conditions was not analysed.

An initial analysis of the AIS data in the early phase of the project lead to a decision to only include the ship types 70-89; TANKER and CARGO. These are deemed to be representative of the normal shipping traffic, and this assumption was approved by SwAM. Passenger vessels, fishing vessels, non-commercial vessels and other vessels have been excluded since they may not follow the typical shipping routes. This assumption was made to more clearly see the typical shipping routes for commercial vessels.

The study is conducted using "deterministic" winter navigation and icebreaker assistance (routes), "common knowledge" and praxis for ice navigation as well as "assumed/uncertain" (because of possible knowledge gaps) mechanical properties for the sea plan area Gulf of Bothnia. In addition, there are uncertainties and knowledge gaps concerning ice formation in OWFs. The project aimed to identify the most critical knowledge gaps and give suggestions for further studies to minimize the effects of the uncertainties in a reliable decision-making process. Finally, the project does not include validation or verification of results from ship performance or icebreaker simulations since it was out of the scope of the project. This can be carried out in a continuation of the project; see Chapter 7.

Fuel consumption calculations are presented in case studies as a measure of energy consumed for different ship routes. It was out of this project's scope to present the indirect impact of air pollution on the environment from shipping, e.g., CO2 emissions.

1.3. Outline of the report

The report continues with a literature study in Chapter 2 which presents what research has been done previously and to find what important factors need to be considered in the project and in future research. In Chapter 3, the methodology developed in the project is described followed by a more detailed description in Chapter 4 of the different case studies to which the method was applied. The results from simulations and analyses are presented in Chapter 5, followed by the conclusions in Chapter 5 and suggestion to future work in Chapter 7.

2. Literature study

A literature study was conducted to identify prior research and knowledge about OWFs in relation to shipping traffic and ice infested waters. The aim was to find research papers to help answering the questions formulated in Chapter 1.1. In addition to this, a research group active in this project's research area at Aalto University in Finland were contacted to give a summary of their research projects. A brief summary of their research projects is included in this chapter.

2.1. Offshore wind farms' influence on shipping – risk perspective

If OWFs are placed close to established shipping routes, the shipping routes will be affected. Previous studies are reviewed to understand how they are affected and to learn what methods can be used to assess the placement of OWFs.

Zhen et al. (2023) proposes a risk evaluation method for ship navigation in OWF waters based on six factors: visibility, wind, flow, the distance between the route and the wind farm area, number of traffic flows and number of encounter areas. The study also suggests traffic management strategies to reduce the risk in the areas. The work stresses the importance of strengthened monitoring and routing systems in waters close to OWFs. Ship routes should be at as large a distance as possible from the OWF and the number of traffic flows should be reduced as much as possible. The authors stress the importance of monitoring systems such as radar, AIS, VHF and CCTV to monitor the traffic to prevent ships from sailing into the OWF.

Managing risks with ships in proximity is extremely important, it is also important to assess the effect of windfarms on shipping routes. Which in turn will help with the risk assessment. A framework for assessment of the influence of offshore windfarms on existing shipping routes has been proposed by Yu et al. (2020). The framework is based on raw AIS data that is then filtered and put into a statistical model. The framework is applied to *Fujian Putian City Flat Bay Offshore Wind Farm*, on the east coast of China. The authors conclude that the majority (61%) of traffic passes the OWF with a minimum passing distance of 1 to 2 nautical miles. The average speed with which the ships pass decreases, and the spread also decreases. The study was based on AIS data from 2014 (before OWFs were installed) and 2017 (after OWFs were installed). There was a substantial reduction of traffic, 26 645 ships passed the monitored area in 2014, before the OWFs were installed, and 17 444 ships passed in 2017. The study concludes that the ships had to change their trajectory, the speeds of the ships also decreased, and the width of the route became significantly narrower, since the OWFs were built on a previous shipping route.

These studies are good examples if studies that show how OWFs will change the shipping routes, depending on location. They also suggest different strategies to manage risks and to analyse the effects of an OWF on the shipping routes in the vicinity.

2.2. Offshore wind farms' influence on shipping – routes and ice management

Ice conditions have a large influence on winter traffic, since navigation routes should be planned to avoid passing through zones with thick slush belts and pack ice. However, the existing ice data in the open sea without OWFs is not completely reliable for route planning. The reason is that ice conditions are dependent on winds, current and waves, and a large OWF can significantly change the surrounding winds, current and waves.

Vihma and Haapala (2009) concluded that research has increased on the Baltic Sea ice conditions and lists a number of main findings. Ice winters have become increasingly milder in the last 21 years (1988-2009). The atmosphere, sea ice and the sea have large dependencies on each other considering thermodynamic and dynamic processes and the processes are linked together and complex. However, since the study was published, there has been a few severe ice winters.

Ronkainen et al. (2018) showed that the ice thickness variability is large and changes from day to day. Especially broken ice that drifts create ridges that are very unpredictable. The ice in the north is subjected to more severe wind and lower air temperature which leads to older ice in the north which also experiences more deformation and ridging. Heavily ridged ice regions near the fast ice edges had a mean ice thickness that was 0.45 to 0.56 m thicker than purely thermodynamically grown ice, ice that has frozen, in calm waters under time and not been broken. The study emphasizes that the drift ice thickness is often underestimated in the ice charts. The authors state that the ice charts are based on a limited number of undeformed ice observations but that the real ice can be 2 to 3 times thicker than purely thermodynamically grown undeformed ice.

Hüffmeier et al. (2008) conducted ice management studies in winter ports. Ice is managed in ports by port tugs and channels leading to the port are maintained either by the tugs or shipping traffic is keeping the channels open, if there is enough number of vessels visiting the port. The extent to which harbour tugboats manage the ice range from 1 nm to 20 nm out from the port and varies from port to port. Meanwhile, the ice management in the northern Baltic border and open-sea region is handled collaboratively by Swedish and Finnish icebreakers. To establish routes between the OWFs and to tackle the changed ice features, ice management plans should be developed collaboratively with Swedish and Finnish administration.

Goerlandt et al. (2017) conducted studies on accidents in winter navigation in the northern Baltic and observed 11 open-sea accidents between November 2007 to May 2013. With possibilities of accidents, contingency measures might need to be in place to tackle cases such as oil spills especially when it involves spreading to OWF areas.

2.3. Offshore wind farms' influence on shipping – ice formation

Ice formation depends on the surrounding conditions. The air temperature, water temperature, wind, currents and waves will affect the formation of ice. These conditions can be affected by wind farms which would lead to different ice conditions compared to the surrounding sea.

Christiansen and Hasager (2005) used synthetic aperture radar (SAR) to study the wakes from two large OWFs in Denmark. One with 80 turbines is at Horns Rev in the North Sea, and the other with 78 turbines at Nysted in the Baltic Sea. The wakes can propagate 20 km downwind. Platis et al. (2018) carried out the first in-situ measurements for the OFWs in the German Bight. The far-field wakes at the hub height were measured using a special research aircraft in 2016 and 2017. Satellite images from SAR proved that the far-field wakes were extended to at least 45 km when atmospheric stratification is stable. In this situation, the maximum wind speed deficit reached 40%, and the turbulence in the wakes was enhanced. In 27 cases from March to October, the wake length ranged from 10 to 70 km. But the wakes would become local within farms if atmospheric stratification is not stable. These effects were also validated in their numerical simulations.

Temperature can also be changed by OWF wakes, as reported by Wang and Prinn (2011). A surface cooling was caused by increased latent heat flux that was convected from the sea surface to the lower atmosphere. The convection was mainly due to the turbulence mixing effect of the wakes. It was also reported that the effect is significantly dependent on seasonal wind variations. Fitch et al. (2013) simulated the OWF in Walney in the UK that contains 100 turbines in an area of 10 by 10 square km. The turbine hub height is 100 meters, and the turbine diameter is 126 meters. Their simulations predicted that the wakes changed the temperature by 1-2 K. The increase of heat fluxes was affected by surface roughness.

Vautard et al. (2014) assessed temperature changes caused by OWFs in the North Sea through numerical simulations. The WRF model for describing regional climates was used in the simulations, and the additional TKE within the wakes were computed. The temperature change was within ±0.3°C, and statistically more significant in winter.

Aircraft measurements and numerical simulations of the OWFs in the North Sea were carried out by Siedersleben et al. (2018) to understand thermodynamic impacts. There were 26 flights made to measure far-field wakes in the research project WIPAFF. Temperature, as well as sometimes water vapor concentration, were found to be different within and outside of the wakes. The farms influence the atmosphere boundary layer because of turbulence produced. The thermodynamic impacts on temperature and humidity at hub height were in the order of 0.5 K and 0.5 g/kg, and the impacts sustained up to 60 km downwind of the farms. Their simulations further indicated that the wakes of temperature and water vapor in a future real scenario have downwind lengths more than 100 km when the atmospheric stratification is stable.

The TKE and turbulence dissipation rate (TDR) of OWF wakes were analysed based on wind Doppler lidar measurements near the Massachusetts coast for 13 months (Bodini et al., 2019). The TDR was important to affecting the prediction accuracy of the hub-height wind speed and wake evolution. Its magnitudes at offshore regions were two orders smaller than onshore regions. Moreover, wind veer affects the annual period of turbulence, resulting in more significant turbulence in winter. Bodini et al. (2023) analysed 13-month lidar data that were measured the near-coast area of Massachusetts. The turbulence intensity was seasonally dependent and associated with wind veer conditions. The turbulence intensity in summer was less than half of that in winter. Winds came from the open ocean in summer. In contrast, winter winds were from the land located in the north-west, which had lower temperature and increased turbulence due to the land surface. Seasonal winds and their veer conditions are crucial factors that affect the wake development and characteristics.

Akhtar et al. (2022) found that sea surface heat fluxes were changed by the large OWFs in the North Sea over a long period. The net heat fluxes transferred heat from the sea surface to the atmosphere in autumn and winter when the sea is warmer than the surrounding, but in the opposite direction in spring and summer when the sea is colder than the surrounding. The wakes obviously reduced the heat fluxes since wind speeds and TKE were decreased. The deficits of the hub-height wind speeds caused by the wakes were 2.3 m/s in spring, 1.8 m/s in summer, 1.5 m/s in autumn and 1.7 m/s in winter. In addition to this it was showed that the OWFs increased the seasonal low cloud coverage by 4-5% in the wind farm area. These two mechanisms resulted in an annual net cooling of the lower atmosphere.

These studies show how an OWF can change the environment and thus affect the formation of ice. However, the exact mechanics of ice formation are very complex and not well known. No conclusions can be made regarding the specific effects of OWFs on ice formation, further research is needed in this area.

2.4. Research on Aalto University in Finland

Research focus and methods

The Aalto University Arctic Technology and Ice Mechanics research group performs research on offshore wind in ice-covered waters by using two approaches. They develop and apply numerical tools, mostly discrete element method-based, and perform unique experimentation in the Aalto University Ice and Wave Tank.

There are two major challenges, which they have worked to overcome in computational modelling ice and offshore wind turbines and wind farms (Åström et al., 2024; Åström and Polojärvi, 2024; Prasanna et al., 2024; Polojärvi, 2022; Muchow and Polojärvi, 2024):

1. High-resolution models are required, but these models are computationally very demanding. Computational models for predicting ice dynamics or ice conditions operate on a scale of kilometres, but now a scale of meters is required.

2. The modelling requires simulations over long time periods. Combined with the high-resolution requirement, may often necessitate a combination of models. They now have unique capabilities to model sea ice domains of tens of kilometres side length with meter-scale resolution.

Experimentation in the Aalto Ice and Wave Tank also forms an important part of the group's research. The tank is a world-unique basing for model scale ice testing. It is largest in the world by area (40×40 m, 2.8 m deep). It is currently the only experimental facility in the world, where ice-induced vibrations can be reliably produced and analysed in detail in model-scale experiments (Hammer et al., 2024; Hendrikse et al., 2022). Such vibrations are of main concern for structural design of offshore wind turbines and accounting for them is often required in testing. Reaching this goal has taken development of both, model-scale ice properties and experimental set-ups.

The main international collaborators on offshore wind, on general level, have included Delft University of Technology (the Netherlands) and the Norwegian University of Science Technology (NTNU), while our main collaborators within Finland include the Finnish Meteorological Institute and the VTT technical Research Center of Finland, with whom they have worked through several project on sea ice engineering and mechanics throughout the past decades.

Main offshore wind projects
SHIVER (2021-2025): This project focuses on the ice loads on a single wind turbine with a strong focus on ice-induced vibrations (IIV). The project requires developing experimental techniques to study IIV in model scale experiments; SHIVER enabled the group to develop their experimental capabilities towards testing of ice-structure interaction in the case of compliant structures, such as offshore wind turbines and led to first experiments in the world reliably producing IIV in an ice basin. It consisted of two month-long experimental campaigns during spring 2021 and spring 2023 (the results will soon be published in scientific journals). The project is coordinated by Delft University of Technology with Aalto University and Siemens Gamesa as partners.

WindySea (2022-2024): WindySea aimed for a framework for “Digital Twin of an Offshore Wind Farm” for a cold sea area; see Figure 3. This would be a modelling engine for forecasting future marine environmental and ice conditions, with capability to describe interaction between ice and wind farms. The main focus has been in the development and application of large-scale high-resolution sea ice modelling tools, which can be used to estimate the effects of wind farms on sea ice dynamics and deformation, and ice conditions (Åström et al., 2024; Åström and Polojärvi, 2024; Prasanna et al., 2024). The WindySea consortium includes Aalto University (coordinator), VTT and FMI. The project has run over three years (2022-2024) and has had a total budget of about 2 M€, with funding from the Academy of Finland under a call for research on key areas of green and digital transition. The funding is based on European Union's Recovery and Resilience Facility (RRF) - NextGenerationEU.

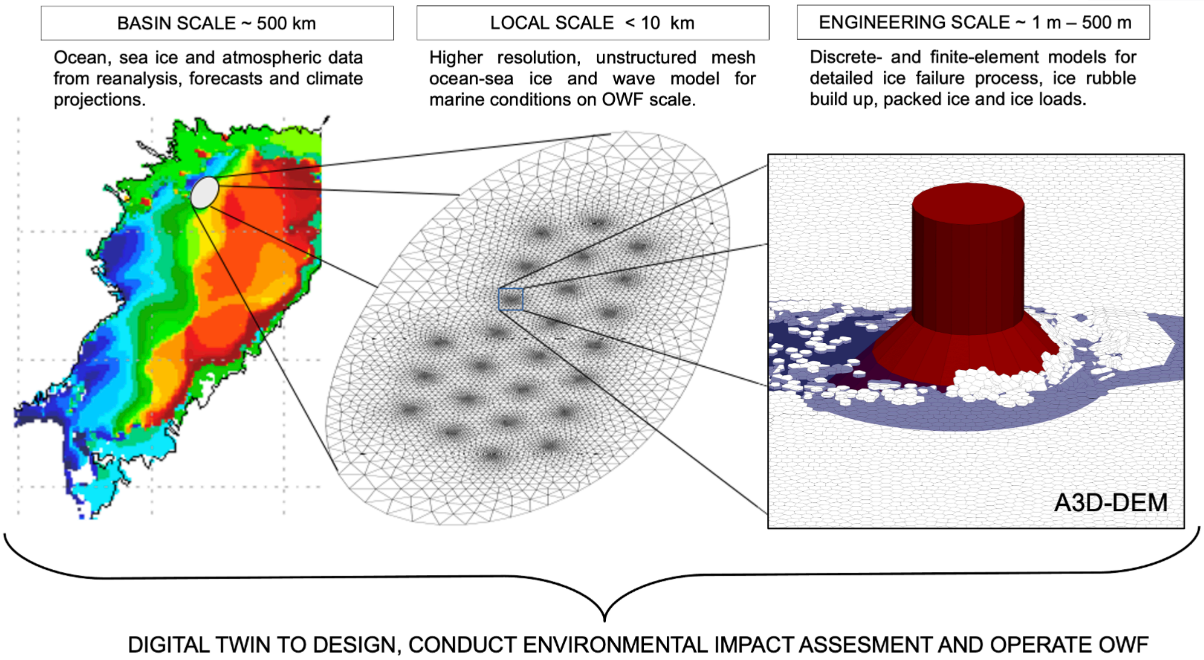

Figure 3: Multi-scale sea ice modelling required framework for modelling wind farms in ice in WindySea project.

SBP IceWind (2023-2025): In this project, VTT, Aalto University, and FMI, in collaboration with industry partners, aim to enhance understanding of offshore wind turbine structures in ice-covered sea areas, enabling reliable investment plans and designs in the northern Baltic Sea. To achieve this, three measurement campaigns are conducted to improve design models. The largest campaign in the Bay of Bothnia focuses on ice conditions and ice-structure interaction using a channel marker or lighthouse. Aalto University's ice tank tests various foundation types, while blade icing is studied on an onshore wind turbine near the coast. The data collected informs model development to support offshore wind turbine design in icy waters. Funding is from Business Finland and the offshore wind industry.

3. Method for analysis of OWFs impact on shipping routes

3.1. Overview of methodology

To understand the influence from an OWF on winter navigation, multiple approaches are combined and applied in this project. The literature study was conducted to gather as much relevant information as possible from existing literature. Studies were found regarding the behaviour of ice around offshore wind turbine support structures in sea; see Chapter 2.

The project has developed a general applicable method for the analysis of consequences on shipping routes from spatial planning of fixed installations offshore. It uses historical data and statistics to evaluate trends. New structures or areas with farms of structures can then be introduced as objects and a re-analysis of historical trends can be used to see if mitigation actions must be considered or if the new installations will have no negative consequences on, e.g., the shipping routes.

AIS data has been used as a data source to plot ships' tracks on a map including the planned OWF areas. A visual analysis of these tracks, hereafter referred to as *Method A*, can qualitatively show if a deeper analysis must follow if ships' tracks pass the planned OWF areas. The AIS data includes, but is not limited to, ship identification codes, position, course, and speed that is transmitted by the AIS. According to the provisions of SOLAS (International Convention for the Safety Of Life At Sea) Ch. 5 Reg 19, all ships of 300 gross tonnage and upwards undergoing international voyages and cargo ships of 500 gross tonnage and upwards not engaged on international voyages and passenger vessels irrespective of size shall be fitted with an AIS. This means that all vessels relevant to the study will have sent AIS information. The AIS information is automatically transmitted to shore stations, other ships and aircrafts. The AIS is also capable of receiving the same information from surrounding ships that assists the watchkeeping officer in navigation. Stored AIS data is a valuable resource that can be analysed to obtain information on the marine traffic, patterns and more.

The visual results from *Method A* does not provide any values. To conduct a proper scientific assessment and comparison of how severe the impact OWFs are on winter navigation quantitative values are needed. The same AIS data is used in *Method B* to generate statistics for assessing the rate of intersections for the different areas, to generate tangible data to assist in decision making regarding OWFs' impact on shipping routes.

Publicly available data has been used in the project to extract metocean and ice data for several years for comparison purposes, ice data for different relevant time periods. The data analysed is the wave height and wave directions, ocean currents and direction, wind statistics, sea ice thickness, sea ice concentration and sea ice velocity (ice drift). The ships' tracks are compared with the suggested OWF areas and ice conditions. The analysis aimed to create an understanding of how ship traffic is affected by ice conditions and to see if there exists any patterns or common routes in the ice infested waters. This assessment is referred to as *Method C*. This in turn assists in determining routes affected by the possible installation of OWF in the areas specified. The ice plots along with bathymetry data gives more understanding of the ice behaviour especially in shallow regions and enhances the capability to suggest alternative routes to avoid OWF areas.

Methods A and C were used together in a qualitative analysis to understand the relation between sea ice and shipping routes. How the sea ice is affecting the shipping routes and traffic were compared with the planned OWF areas to hypothesise about the effects of OWFs on winter navigation in the Gulf of Bothnia. An overview of this methodology is illustrated in Figure 4.

It is of interest to analyse and quantify how ship route changes due to planned OWF areas may affect the emissions from shipping. In *Method D*, the ship performance simulation model ShipCLEAN (Tillig and Ringsberg, 2019) was used to compare the fuel consumption before OWFs were installed and after. It is important to carry out such comparisons to get comparable values for assessment of sources or actions that may have negative climate impacts. That is, will the longer shipping routes lead larger fuel consumptions that can still justify the advantages with renewable offshore wind or not.

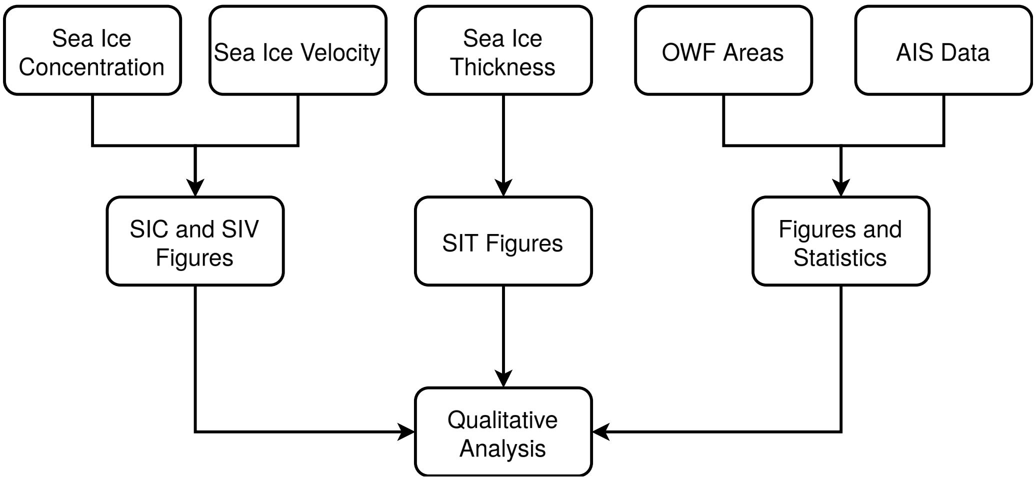

Figure 4: Methodology of the data analysis.

3.2. Method A – plotting ship tracks using AIS data

The AIS data is delivered in CSV format and consists of all individual transmissions from ships equipped with an AIS transponder. In the files, every row represents a transmission, and the column contains data such as the IMO number, timestamp, destination, ship name, flag state, speed, etc. of the ship at the time of transmission. A simplified example of how the data is built up is presented in Table 1. The column called "ship" is fictional to assist visualization and it is not included in the data and belongs to a unique IMO number. For every "ping", the data contains a timestamp and position in coordinate format. The *type of ship and cargo* is a classification that is used for filtering out ships. The ships are limited to 70-89 (cargo and tanker) and the rest is filtered out.

Table 1: AIS data structure.

Ship	Timestamp	IMO	Latitude	Longitude	Type of ship and cargo	...
A	2022/02/02 00:00:00	9826902	59.8375	25.98403	89	
B	2022/02/02 00:00:00	9279317	53.45175	14.5878883	52	
C	2022/02/02 00:00:00	9294692	54.39959	18.6968317	82	
			…			
B	2022/02/02 00:00:20	9279317	53.45905	14.5508	52	
			…			
A	2022/02/02 00:03:08	9826902	60.0102	26.05	89	
			…			
C	2022/02/02 00:56:02	9294692	54.605	18.7025	82	

The data is used for the AIS plotting. A conceptual flow chart describing the code is presented in Figure 5. The OWF and AIS data are read in separately into Pandas data frames in Python. For every date interval, for example a week, a map is generated using Python basemap for the corresponding area with OWF areas plotted as polygons. The AIS data is filtered geographically to exclude data outside of the region and only ship types 70-89 are included in the analysis. The built-in functions in the Pandas library are used for the filtering the data frame. By identifying the IMO numbers of all relevant ships in the dataset the scattered positions can be compiled to a path and plotted for every ship. Since the raw AIS data is split into different files, a loop is needed to load in the next file and continue plotting on the same generated map. The weekly assessment of data assists in visualising shipping patterns rather than individual and scattered ship routes.

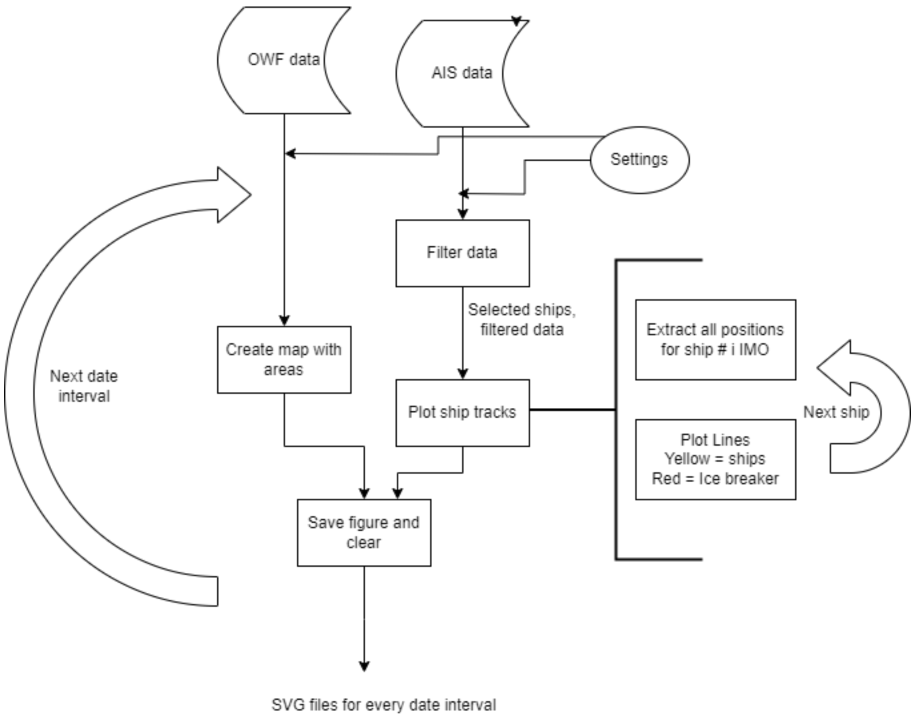

Figure 5: An illustration of the script structure for Method A.

The result is a map of the selected area together with the planned OWF areas in that region. On top of this, the commercial ship tracking data is plotted in with yellow lines. Icebreakers are assessed separately and visualised in red lines such that an indication of relative need of icebreaker assistance is presented.

The AIS plots are divided into two sections, one for the Bay of Bothnia, which also includes The Quark, and the other for Sea of Bothnia. Splitting the Gulf of Bothnia in two parts helps to better visualise data and gives results that are better for presentation as well. The convergence of marine traffic into a regulated traffic lane connecting Sea of Bothnia and The Quark forms a natural boundary for that purpose allowing inspection of the two as independent regions.

3.3. Method B – ship/OWF intersection statistics using AIS data

To assess the severity of each wind farm's influence on the shipping routes, intersection statistics is needed. To be able to compare different areas and time periods a non-dimensional number is needed. The measure *rate of intersection* is defined as:

$$\text{Rate of Intersection} = \frac{\text{Number of intersections}}{\text{Number of ships in the reference area}} \tag{1}$$

A ship's path is considered as intersected with the OWF area if the path from linking all AIS data points intersect the OWF area. Since the AIS does not update continuously this will not guarantee the representation of the exact route but it forms a sufficient approximation. To calculate the non-dimensional number, the number of intersections is divided by the number of ships in the reference area of interest defined by the analyst. It is important that the reference area is defined properly to minimize noise and dilution of data. In Figure 6, four imaginary paths and an OWF area are presented with two different reference areas. Reference area 1 includes a route (the left-most yellow line) that will never intersect the OWF area and can thus be regarded as noise. For this the rate of intersection will be 33% while the smaller reference area 2, which only includes the route in vicinity to the OWF area, will result in a 50% rate of intersection.

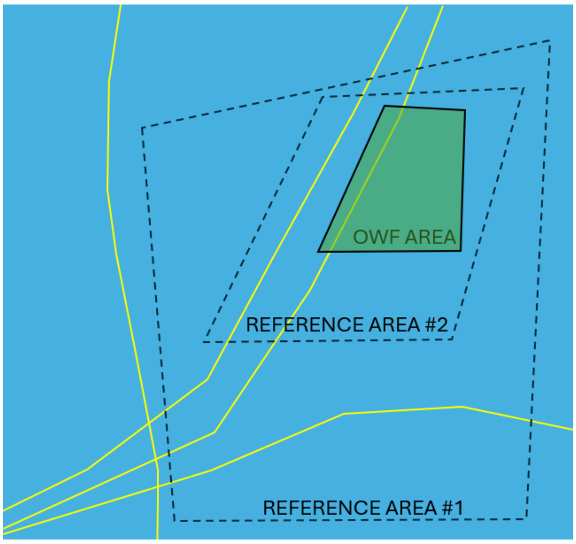

Figure 6: Conceptual description of reference areas, with one smaller and one larger reference area.

It should be noted that a smaller reference area will result in a higher rate of intersection while a larger reference area will result in lower values since more ships will be included that are not in the vicinity of the OWF areas. As the reference area approaches the OWF area the rate of intersection goes towards 100% and when the reference area approaches the entire globe it goes toward 0%.

Figure 7 is a diagram that illustrates the architecture of the script used in the following paragraph. All ships within the reference area at any time during the period is counted to the number of ships. If a ship passes the same area multiple times during the reference period, it is still counted as one intersection since otherwise any area could reach rates of intersection above 100%. The results are presented as bar plots with values of intersection for each area separately related to the same reference area. Along with the intersection statistics, the number of ships (cargo and tanker) passing through the reference area for the period is also calculated and displayed in the plot.

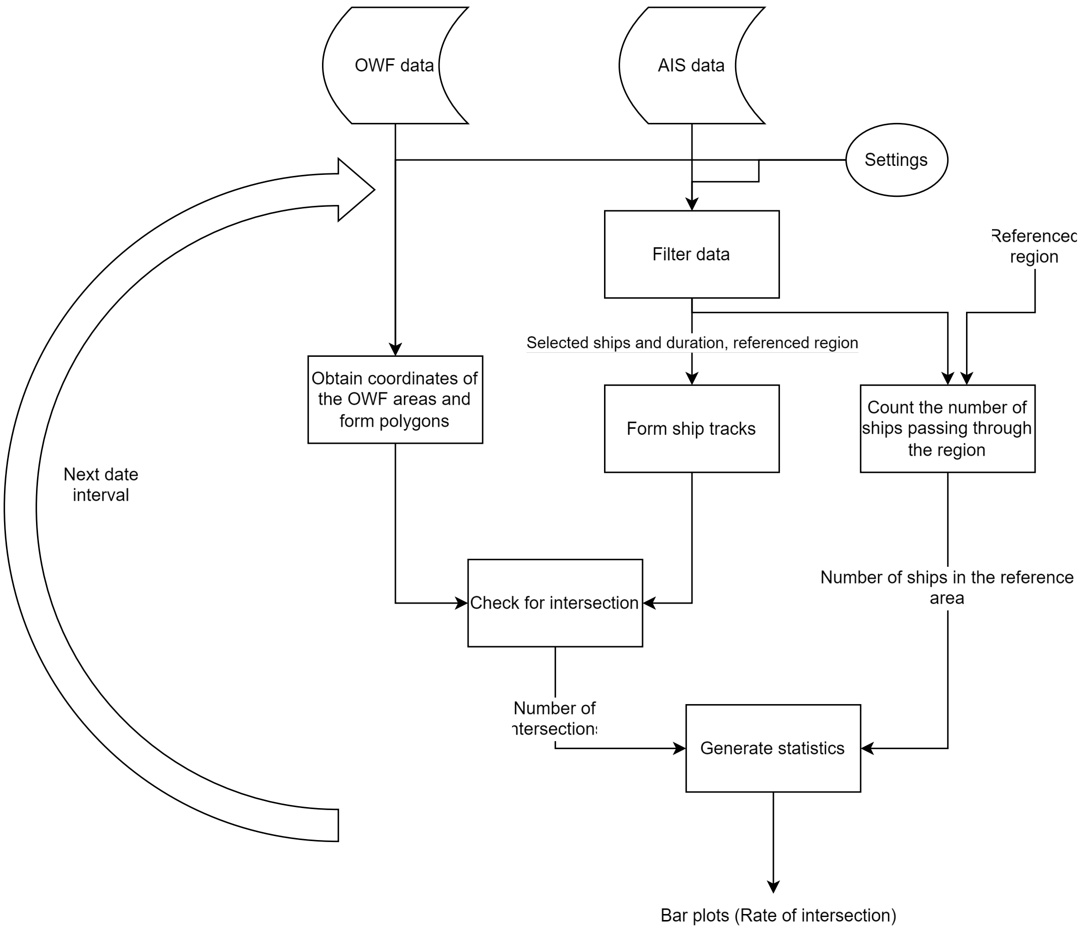

Figure 7: Diagram of the architecture of the script implemented for Method B.

3.4. Method C – analysis and presentation of ice data

To analyse the ice in the Gulf of Bothnia, data from the Finnish Metrological Institute (FMI) and Mercator Océan International are used; see Table 2 for specifics. The sea ice thickness is the thickness of the ice sheets, and it does not account for ice ridges. Sea ice concentration indicates the surface covered by ice compared with open water. The sea ice velocity indicates the movements of the ice. The maps also show vectors for open water, which for open water is the surface velocity of water (surface current).

Ice thickness and ice concentration are based of SAR images whereas the ice drift is calculated from comparing SAR images from two different times, usually 1 to 3 days in between. The data is a daily average for all three variables.

Table 2: Data used for presentation of ice charts.

Data	Dataset	Source	Origin	DOI
Sea Ice Thickness	Baltic Sea - Sea Ice Concentration and Thickness Charts	Copernicus Marine Service	FMI	https://doi.org/10.48670/moi-00132
Sea Ice Concentration	Baltic Sea - Sea Ice Concentration and Thickness Charts	Copernicus Marine Service	FMI	https://doi.org/10.48670/moi-00132
Sea Ice Velocity (1993-01-01 to 2021-06-01)	Global Ocean Physics Reanalysis	Copernicus Marine Service	Mercator Ocean	https://doi.org/10.48670/moi-00021
Sea Ice Velocity (2022-06-01 - up to real time)	Global Ocean Physics Analysis and Forecast	Copernicus Marine Service	Mercator Ocean	https://doi.org/10.48670/moi-00016

The data is specified to the required area and period and downloaded to avoid storing data for areas and time periods that are not analysed. The data is plotted on two maps divided into Bay of Bothnia, including The Quark, and the Sea of Bothnia. The maps with sea ice thickness and sea ice concentration are compared with the public ice charts from FMI to validate the accuracy of the plotting method. The ice drift is unfortunately not possible to verify against the same ice chart. Figure 8 shows the methodology for creating the figures of the ice data. The box indicating ShipCLEAN routes is related to Method D described in Chapter 3.5.

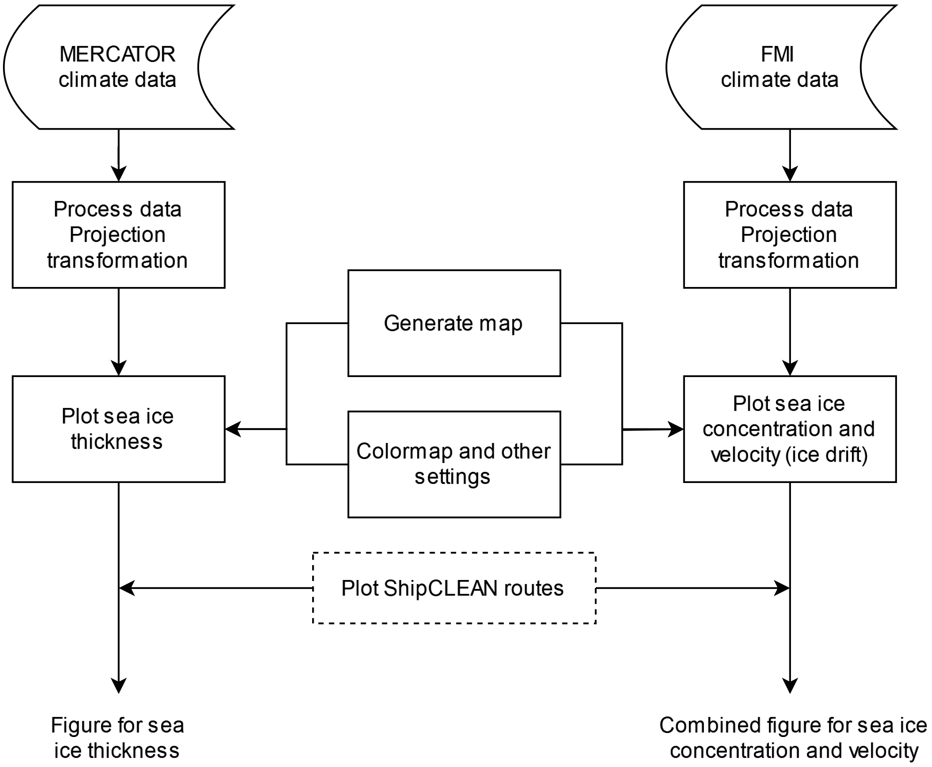

Figure 8: Structure of script for generation of ice data maps.

3.5. Method D – ShipCLEAN ship route simulations

A way of micro analysing how the installation of OWFs will affect the shipping is to study how an existing route will be affected and how much a new route might cost in terms of added duration of transport and fuel consumption. By using the ShipCLEAN code, simulations can be carried out to obtain the duration of a journey, and the fuel consumed for a ship model and its route. The method is useful here where the details are few and vague and cannot be linked to a particular ship or time and results are quick. This enables faster analysis of larger subsets of data to achieve a good overview of the situation. It should be noted that only fuel consumption from the main engine is calculated; auxiliary loads and hotel loads are not included. When the journey time increases, the auxiliary fuel consumption will increase since it is not based on the ship's resistance, thus it will not lower when slow steaming.

An extended version of the ShipCLEAN code is called ChaSE; see Arabnejad et al. (2024). In addition to the capabilities of ShipCLEAN, it offers the possibility of carrying out emission and LCA assessments of different energy carriers (e.g., fuels).

4. Description of case studies

The task to assess the planned OWF areas are on such large scale and geographical extent, with the Gulf of Bothnia spanning 117,000 km2, that to produce usable results the areas needed to be divided into case studies. The case studies are limited examples were the methods developed have been used to generate knowledge to understand the bigger picture.

The Methods A to C have been developed to be used in parallel, where all methods are independent but complements each other with information to better understand the results. These three methods are suitable to use on all OWF areas. The analysis of shipping traffic is separated into three regions, hereafter referred to as “reference areas”, each as a separate case study. The first area being the Bay of Bothnia, the second The Quark, and the third is the Sea of Bothnia. The Quark is a narrow section of the Bothnian Gulf where water depth restrictions force all commercial ships summertime to travel within the traffic separation scheme (TSS). During wintertime, the TSS cannot be maintained due to the ice.

- In the **Bay of Bothnia**, due to its location further up north, the ice formation is more intensive compared to the other areas. The shallow coastal area, that is also close to the OWF areas, is exposed to more severe and thick ice conditions. The distance from the main body of the Baltic Sea also means that water temperature is lower than the average temperature of the Baltic Sea.
- The region of **The Quark** is between the Bay of Bothnia and the Sea of Bothnia. The constraint with a narrow passage leads to shipping routes (at least summertime) that are relatively well defined in pattern, uniform and consistent. The Quark is exposed to significant ice coverage in the peak winter (i.e., the coldest winter months), which affects the winter navigation in the area significantly.
- In contrast to the Bay of Bothnia and The Quark areas, for the mild and normal winters studied in this project, the **Sea of Bothnia** experiences much less ice coverage. Even during the winter months, parts of the Sea of Bothnia are open for self-navigation. Icebreaker activity is almost non-existent (except in the ports where channels have consistent ice management by the tugs). Thus, these three reference areas have navigational characteristics that are unique and require different study approaches.

The AIS data, ice thickness and concentration, are analysed and the percentage of traffic affected by a possible OWF installation in the path is obtained along with the ice thickness and concentration plots.

The case studies examining the three areas by using the Methods A to C are only able to conclude whether the areas overlap the current shipping lanes and winter routes or not. To understand the consequence of implementing an OWF and needing to re-route ships, a fourth case study was conducted using Method D together with Method C with an example area that was found to be problematic from the earlier case studies by evaluating an alternative, longer route.

4.1. Case study A – the Bay of Bothnia

For the areas B111 and B113, located in the northern part of the Bay of Bothnia, a reference area for the intersection statistics was defined according to Figure 9 which has a southern border in line with Skelleftehamn and Jätkälä. The reason for not including ships in the entire Bay of Bothnia is that ships going to ports such as Jakobstad and Kokkola from the south are irrelevant for the statistics concerning B113 and B111.

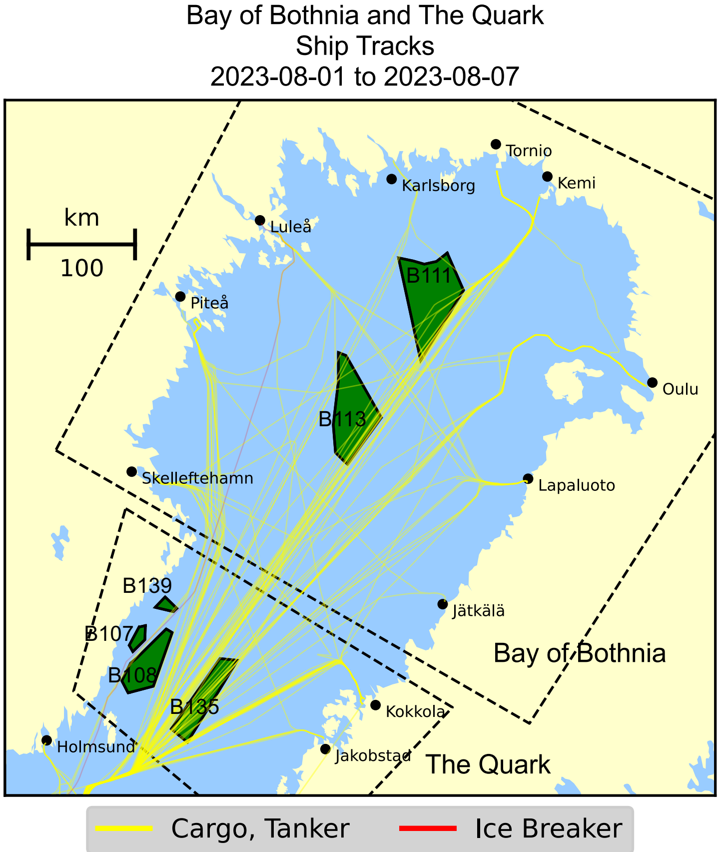

Figure 9: Reference areas for Cases A and B for Bay of Bothnia and The Quark.

4.2. Case study B – The Quark

For the areas located in The Quark, i.e., B107, B108, B135 and B139, the reference area borders are parallel to the previous reference area in the north and Holmsund in the south. This is to exclude ships going across the Bay of Bothnia from the intersection statistics. The Quark area is also shown in Figure 9, the southern of the two reference areas.

4.3. Case study C – the Sea of Bothnia

The cluster of OWF areas outside the coast from the Gulf of Gävle in the south and Sundsvall in the north is treated separately with a reference area as shown in Figure 10. The eastern boundary for the reference area is set by analysing the ship traffic and has been marked to exclude the ships passing through the Sea of Bothnia just to get to ports further up north. Thus, only the ships sailing to and from the ports along the eastern seaboard of Sweden are included in the statistics.

Sea of Bothnia
Ship Tracks
2023-08-01 to 2023-08-07

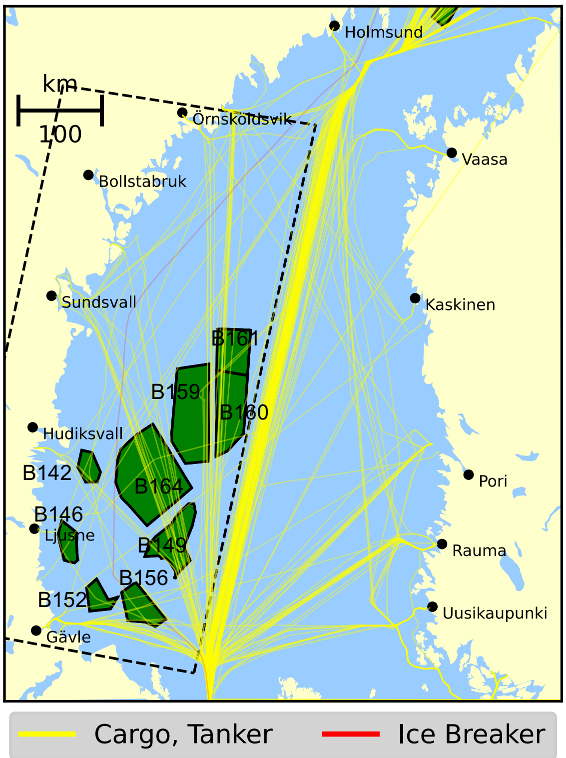

Figure 10: Reference areas for Case C for the Sea of Bothnia.

4.4. Case study D – re-routing of a ship crossing the OWF area B111

In this case study, a medium range tanker, with length overall of 183 m, breadth 32 m and draught 11 m heading from Luleå to Brahestad, was re-routed to avoid traversing an OWF earmarked area (ID number: B111). The ShipCLEAN code was used to create a simulation model of the MR Tanker and run simulations that gave data for comparative analyses with respect to changes in fuel consumption and voyage duration due to the different routes. The routes and voyage parameters considered can be described as follows.

- **Summer route:** a route consistent with the summer AIS tracks (August 2023) between Luleå and Brahestad was used, see Figure 11, and the ship was set to sail with a target speed of 14 knots in a wave field of height 1 m; wind and current were disregarded. To avoid shallow water effects a depth of 50 m was set for the whole route for both winter and summer. This route was also used as an alternative during winter.
- **Winter route:** 2023 AIS tracks from the first week of April were used to obtain a route between the two ports. It was noted that most ships sailing between ports in the northern reaches of the Bay of Bothnia, for the period observed, crossed the OWF area B111, owing to the thicker ice in the central parts of the region.

- **Alternative winter voyage:** an alternative route was defined which avoided the OWF area by going further north. This still allowed the ports north of Lapalouto to utilize the same channel, assuming similar icebreaker operations as the actual shipping route described above. The sea ice conditions are based on the ice charts and are similar to those of the actual winter route.

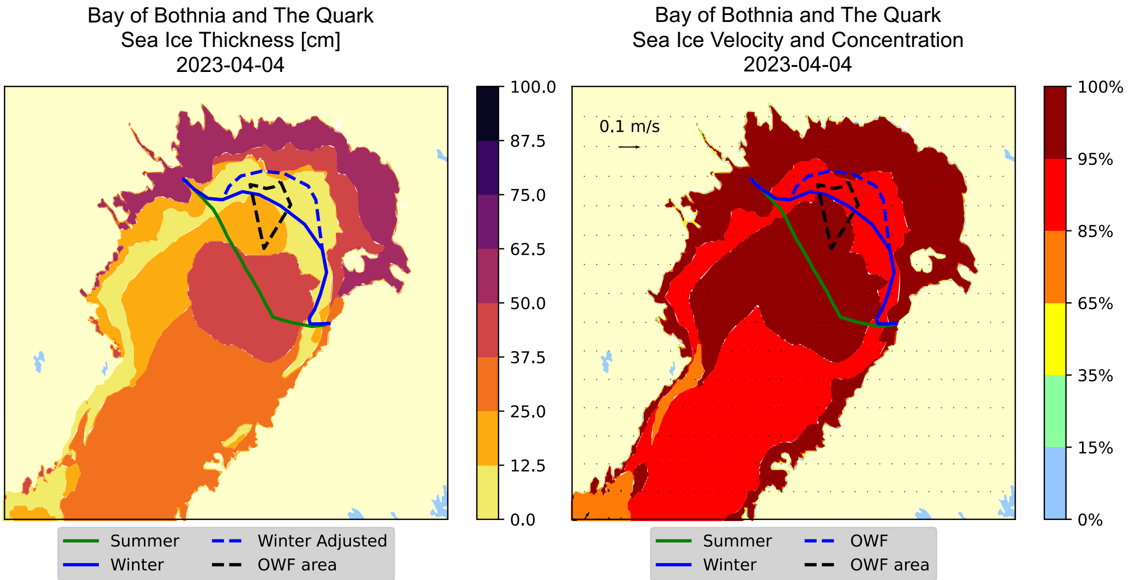

Figure 11: Re-routing a ship crossing an OWF area.

For the voyages in winter, two target speed cases of 5 knots and 10 knots were simulated to consider the operational conditions in conjunction with icebreaking activities in the region. It could either mean that the ship is sailing in a convoy or an ice-broken channel. For simplified initial analysis, the following conditions were assumed: a wave height of 0.1 m for the whole routes, no wind, and no current. It was assumed that the ice concentration was 20% in channels broken by an icebreaker. Ice thicknesses along the route were obtained from the sea ice thickness plots for the middle of the corresponding week in April.

For the case of re-routing, the water is assumed to be deep (a depth of 50 m was set for the whole route). However, based on bathymetry data (see Figure 16), the route with relatively low ice thickness and concentration passes through shallow regions with a depth decreasing down to 10 to 20 meters, which would make the passage require careful navigation and affect the fuel consumption due to the squat effect.

5. Results

The chapter presents results from data analyses and the case studies presented in Chapter 4. Chapter 5.1 gives a brief description as an introduction to the main challenges with ice infested waters in relation to ship traffic and the bathymetry of the sea.

For the analysis of AIS traffic and interaction with OWF areas, weeks with considerable traffic conforming to a pattern and much traffic intersecting the OWF areas are discussed in the results. The project's focus is on winter navigation, and hence, three winter weeks and only one summer week are discussed in the results for each case study:

- **Case study A – the Bay of Bothnia**
  Areas B111, and B113
- **Case study B – The Quark**
  Areas B107, B108, B135, and B139
- **Case study C – the Sea of Bothnia**
  Areas B142, B146, B149, B152, B156, B159, B160, B161, and B164
- **Case study D – re-routing of a ship crossing an OWF area**
  Area B111

5.1. Ice conditions and bathymetry

Ice conditions are ever changing which means that the traffic conditions and routes are different each week in wintertime. In this chapter, an example is presented to illustrate the complexity and variability of the sea ice conditions.

In the first week of April 2023, the ice concentration and thickness allows for channels on both the west and east side of the Bay of Bothnia, see Figure 12. The ice is thicker on the southeast side below the thicker part in the middle. This restricts ship traffic from the south to reach the northern east part of the sea. Icebreakers made channels along the west and north to reach the east side of the bay.

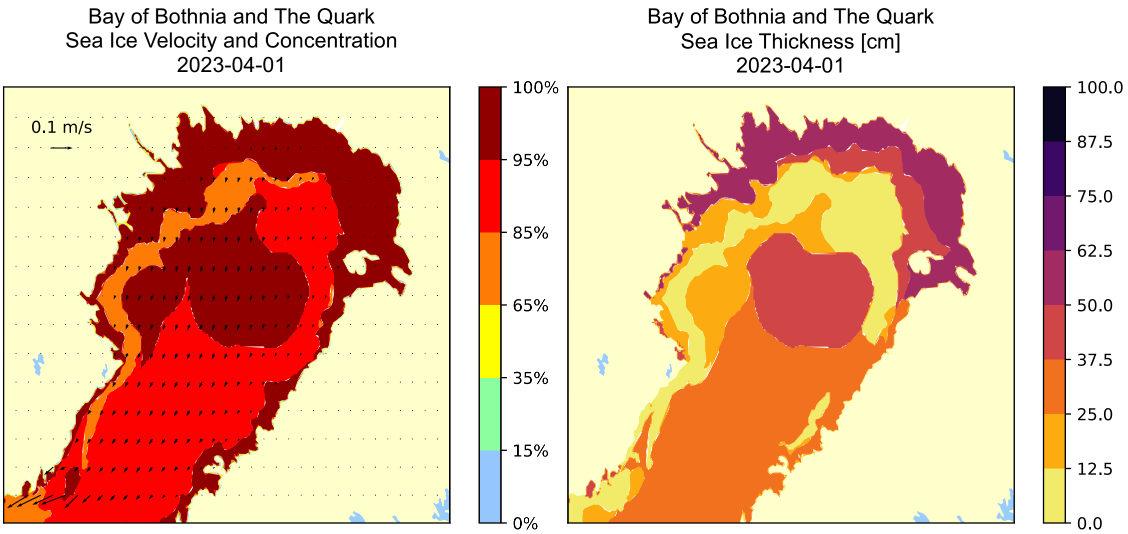

Figure 12: SIV, SIC to the left and SIT to the right (date: 2023-04-01).

Figure 13 shows that the ice thickened and got even more concentrated in the second week of April which hindered the icebreaking on the east side.

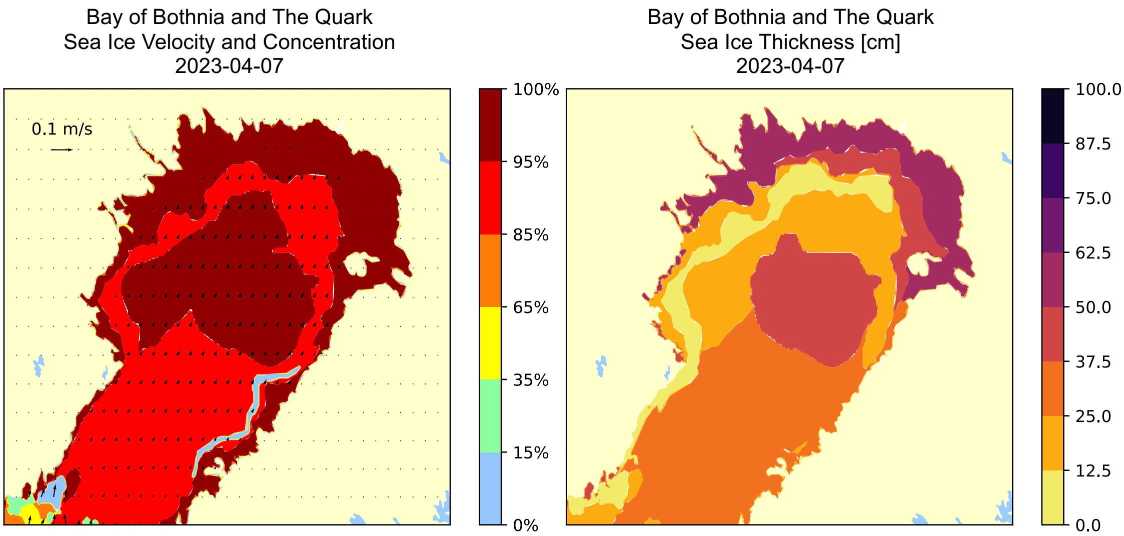

Figure 13: SIV, SIC to the left and SIT to the right (date: 2023-04-07).

In the third week of April, the ice has thickened considerably, and the concentration reached close to 100% in the western part, see Figure 14. The ship traffic in the following week was routed along the east side of the bay instead of the west as seen in the beginning of April. This large difference in routing occurred in only three weeks' time.

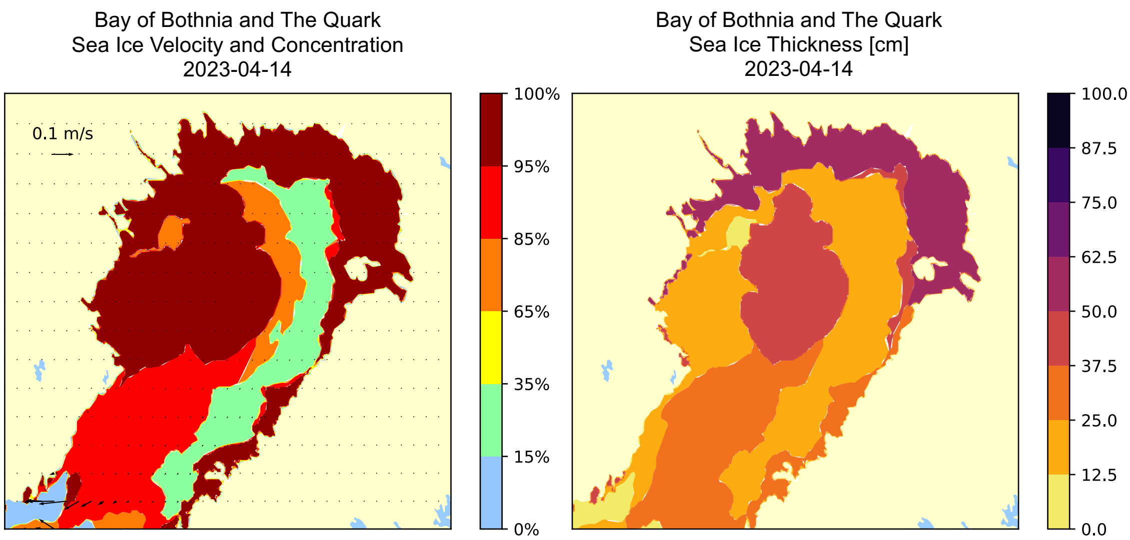

Figure 14: SIV, SIC to the left and SIT to the right (date: 2023-04-14).

In the beginning of the last week of April the ice started to melt and break up, especially in the northern part, see Figure 15. The ship traffic started to move more "freely" independent of icebreakers in the region and many of the ships were able to navigate without icebreaker assistance.

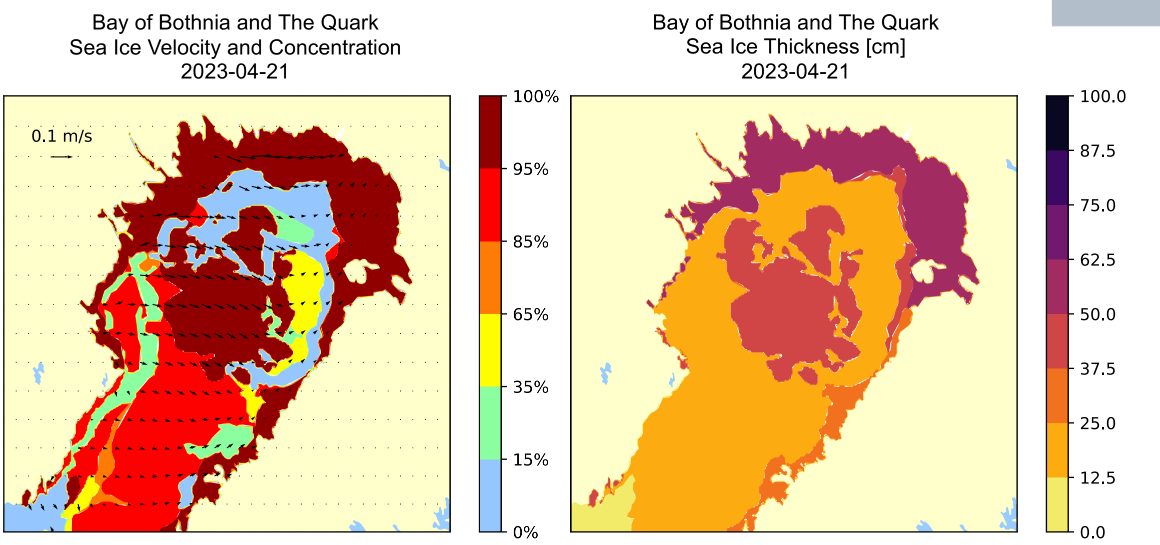

Figure 15: SIV, SIC to the left and SIT to the right (date: 2023-04-21).

Figures 12 to 15 illustrate the complexity of ice management and winter traffic well. This is a complex problem where the ship traffic needs to adjust according to the sea ice conditions. Figure 16 shows the depth in both Bay of Bothnia, The Quark and Sea of Bothnia. The black lines outline the planned OWF areas. Some of the areas are close to regions with low water depth, which needs to be considered. The ships and icebreakers will need to consider the water depth when navigating. Some OWF areas could either force ships into shallow waters or force long detours to be able to navigate around an OWF.

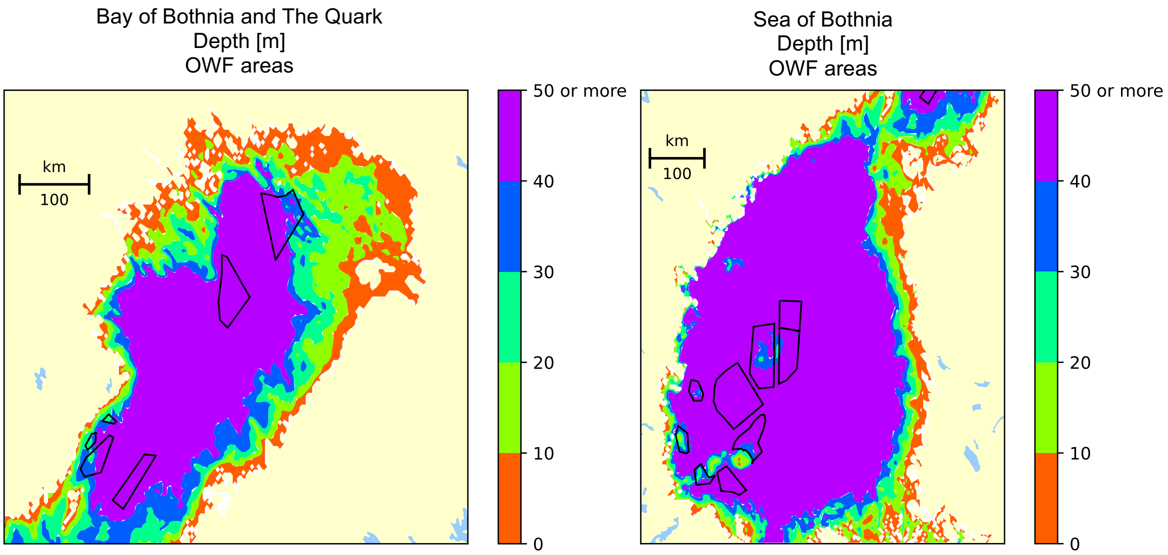

Figure 16: Bathymetry data for Bay of Bothnia and the Quark (left) and Sea of Bothnia (right).

5.2. Case study A results – the Bay of Bothnia

The figures and results from Case study A of the Bay of Bothnia area are presented below. Figure 17 (left) represents typical summer shipping tracks (routes) and indicates that B111 and B113, the two northernmost areas, are overlapping today's (historical) tracks. However, to navigate around them would not change the ship traffic too much. It would mostly restrict and make the routes narrower. Figure 17 (right) and Figure 18 presents different examples of winter traffic. The winter traffic changes from week to week, and even between days, due to the dynamics of the ice. These examples indicate that B111 often has ship traffic crossing it connecting the ports in the northern part of the Bay of Bothnia. Meanwhile, the lower area (B113) is largely unaffected by the ship traffic in Figure 17 (right) and Figure 18 (right). However there are situations when the ship traffic is routed into that area as well.

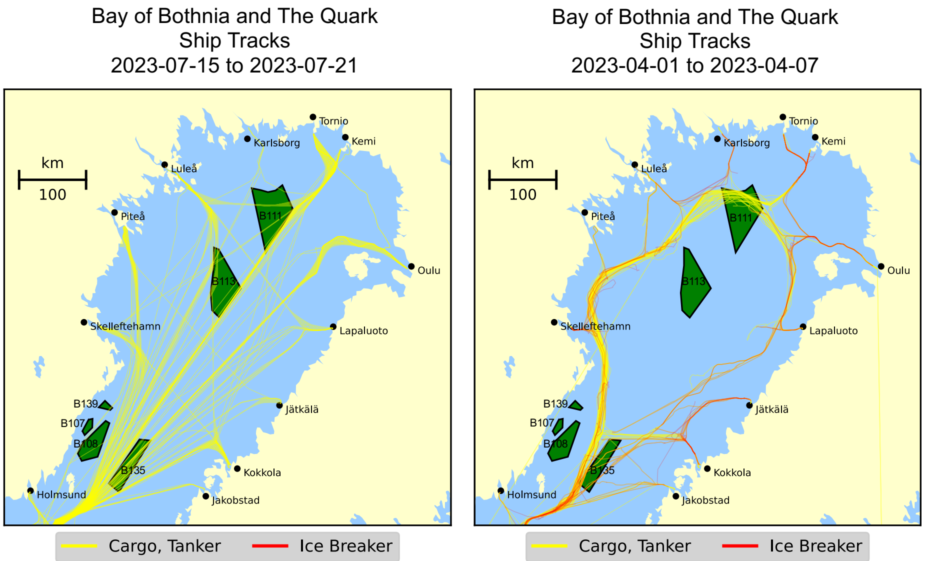

Figure 17: Ship tracks in summer (left) and ship tracks in winter, here, early April (right).

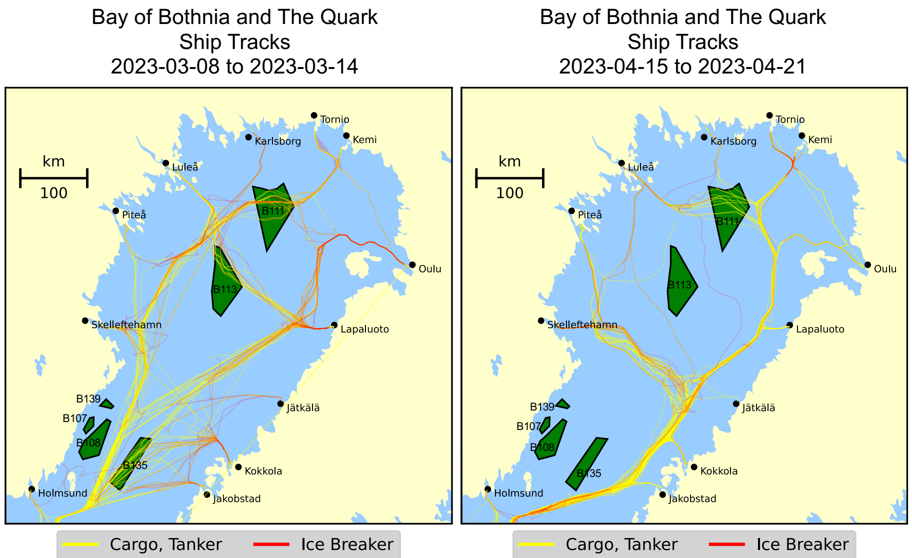

Figure 18: Winter navigation tracks.

The intersection statistics obtained for the considered weeks are presented in the Figures 19 and 20. The traffic remains similar to the AIS tracks in Figure 17 (left), throughout the summer and the trend is observed in the intersection plots as well. 10 to 30% of the vessels passing through the reference area crosses the OWF areas B111 and B113. The fraction of ships crossing the two areas are roughly the same in ice-free waters. However, for the winter traffic, the distribution of the vessels varies quite a lot and depends on the ice conditions in the area. For instance, in the first week of April, 60.0% of the vessels passing through the reference area intersected with the OWF area B111 and only 2% crossed B113; see Figure 19 (right). In the third week of April, the statistics change drastically according to Figure 20 (right). Only 17.1% of the ship traffic crossed the area B111 while the ship traffic crossing area B113 remained relatively unchanged at 1.4%. In the second week of March, see Figure 20 (left), 29.1% of the traffic crossed area B111 while it was 7.3% for area B113. Even though, the fraction of vessels crossing area B113 is low, it is extremely dependent on the prevailing ice condition.

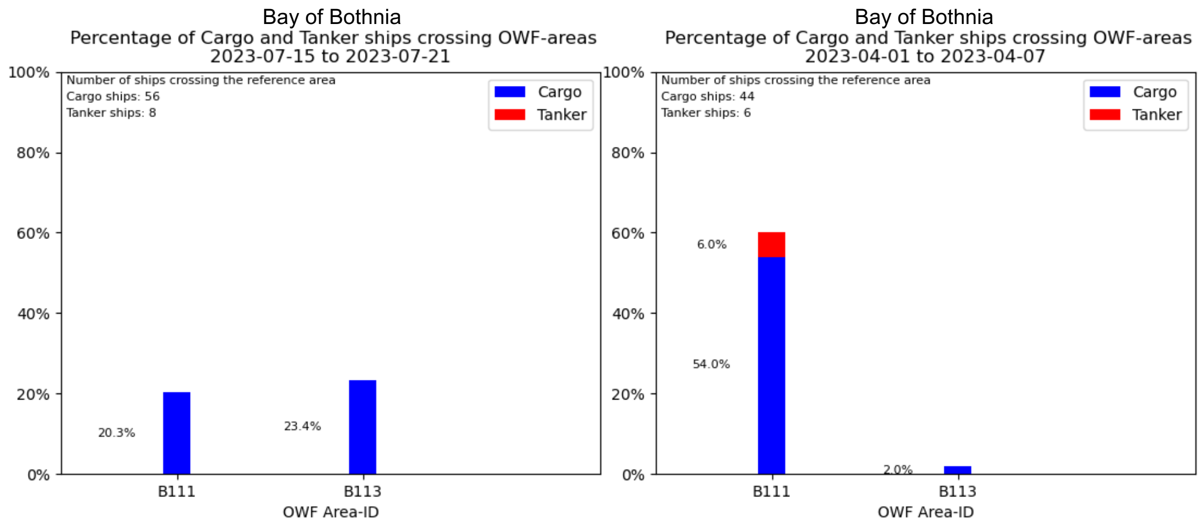

Figure 19: Intersection statistics for summer (left) and winter, here, early April (right).

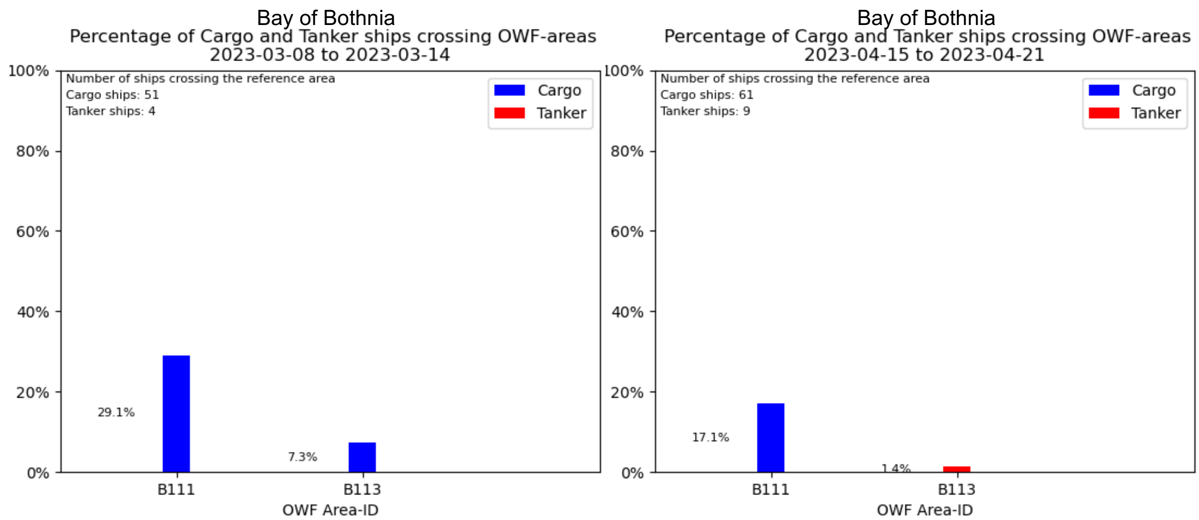

Figure 20: Intersection statistics for mid-March (left) and mid-April (right)

The ice charts are a tool to understand the reason behind the different and varying routes. The midweek ice charts in Figure 21 shows the thinner ice layer north of the large thicker area which matches the traffic routes in the same week as presented in Figure 17 (right).

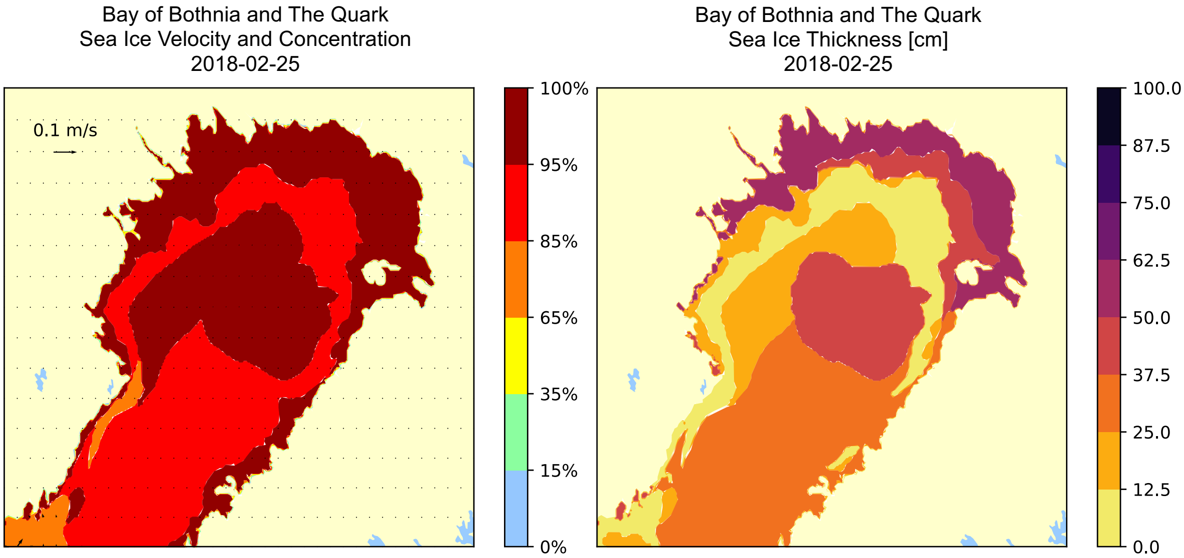

Figure 21: Sea ice concentration (left) and thickness (right) (date: 2018-02-25).

The ice charts in Figure 22 indicate a lower ice concentration and thickness close to the Swedish coast. This explains the traffic pattern in Figure 18 (left). The ice condition resulted in vessels taking routes more central in the Bay of Bothnia and avoiding routes in the north-eastern part of the Bay as compared to the first week of April, where the central location of the thicker and concentrated ice resulted in vessels to route around it closer to the coast; see Figure 17 (right). This resulted in more vessels crossing the area B113.

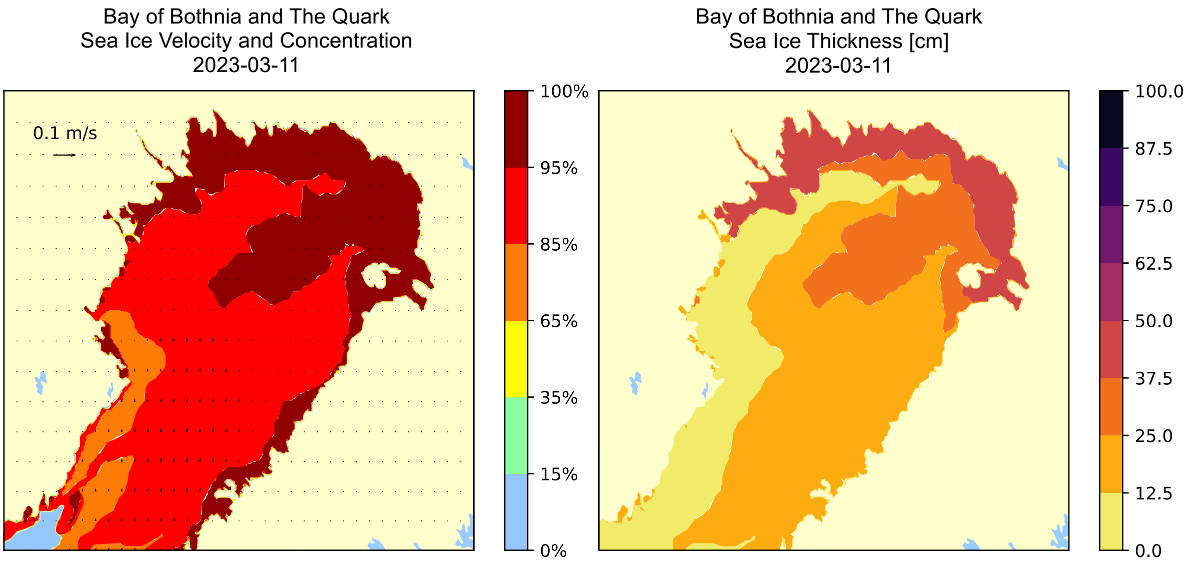

Figure 22: Sea ice concentration (left) and thickness (right) (date: 2023-03-11).

The majority of the ship traffic during winter in Figure 18 (right) take a southern route. Considering the ports involved, it can be concluded that much of the traffic in the reference region is through an area outside the OWF areas and this is not a direct impact of the ice condition, see Figure 23. However, the thicker ice in the centre keeps vessels off the area B113. The ships that are crossing the area B111 are doing so due to the negligible ice concentration in the area allowing easier passage since it does not require assistance from an icebreaker.

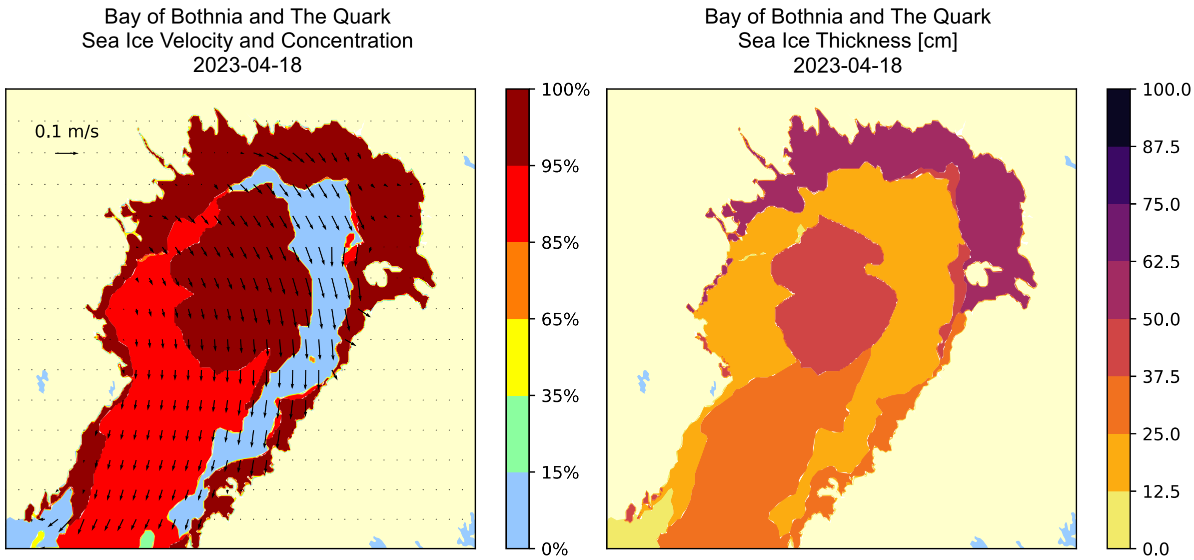

Figure 23: Sea ice concentration (left) and thickness (right) (date: 2023-04-18).

5.3 Case study B results – The Quark

Results from the case study for The Quark region is discussed in this chapter. For the summer traffic, the first week of July is analysed. The highest percentage of ships crossing the OWF areas in summer was found in this period. The third week of April has the most traffic during winter (82 vessels) in the reference area. The third and fourth weeks of March experienced the highest fraction of ships crossing the OWF areas. The summer traffic in Figure 24 (left) shows that once the ships exit the narrow and restricted passage in the south of The Quark they follow a straight line to the different ports in the Bay of Bothnia. Most ships cross the OWF area B135 while the other OWF areas have little to no ship traffic that cross them. The traffic in the third week of April, see Figure 24 (right) had 82 cargo and tanker ships passing through the region during the week, while none of them passed through any of the OWF areas. The third and fourth weeks of March, see Figure 25, had the highest fraction of ships passing through the reference area crossing an OWF area. In both of these weeks, area B135 received most ship traffic crossings.

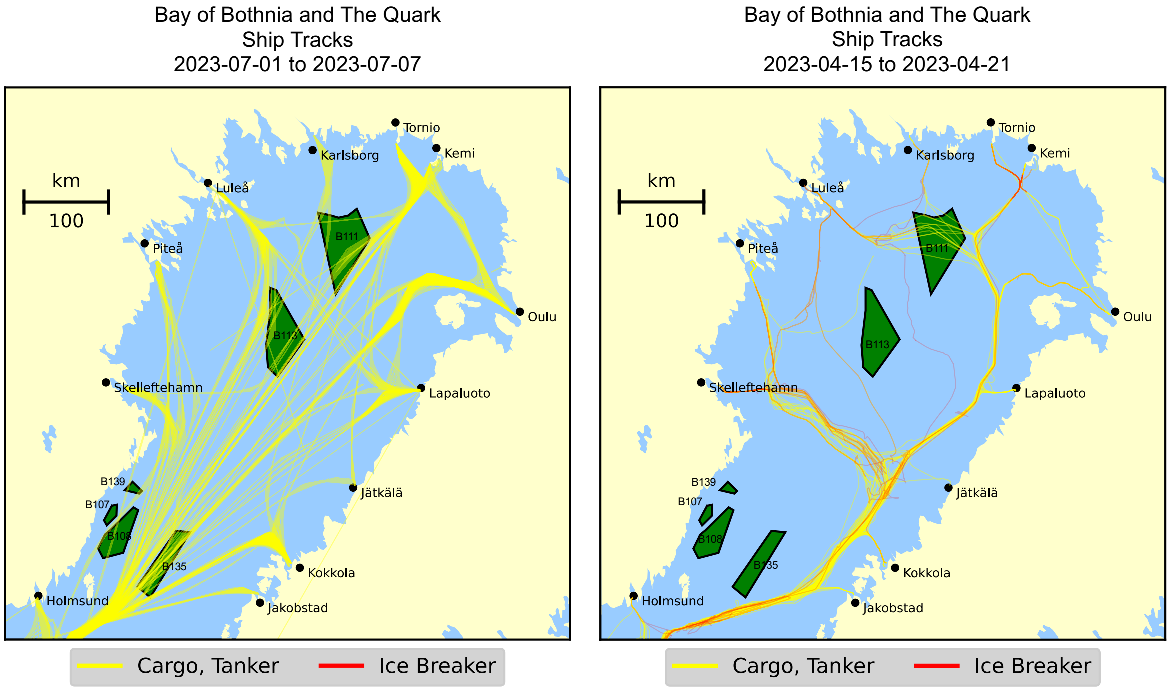

Figure 24: Ship tracks in summer (left) and ship tracks in winter, mid-April (right).

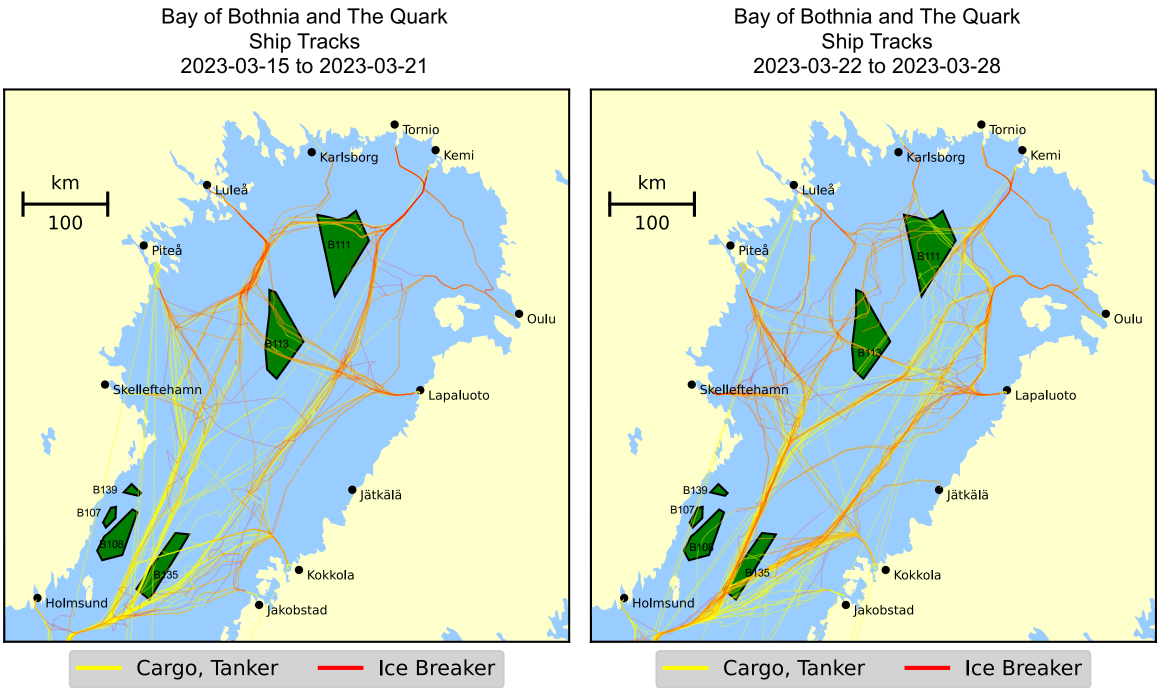

Figure 25: Winter navigation tracks.

The intersection plots confirm the visual inferences, see Figures 26 and 27. In the summer traffic 42% of the ships passing through the reference area crosses the OWF area B135 while the fraction reduces to 4.5% and 3.0% in B108 and B139, respectively. Area B107 saw no traffic neither in the summer period nor in any of the cases discussed. Amongst the generated statistics for 2023, it was found that a small fraction of vessels crossed area B107 only in mid-November. In the third week of April no ships were found to be crossing the OWF areas as inferred in the visual analysis.

In the last two weeks of March, it was found that more than 50% of the commercial shipping through the reference area passed through the OWF area B135. The value peaked at 82% of total cargo and tanker ships, intersecting with B135. The intersection statistics also show that the other regions, B108, B107 and B139, had very little to no ship traffic.

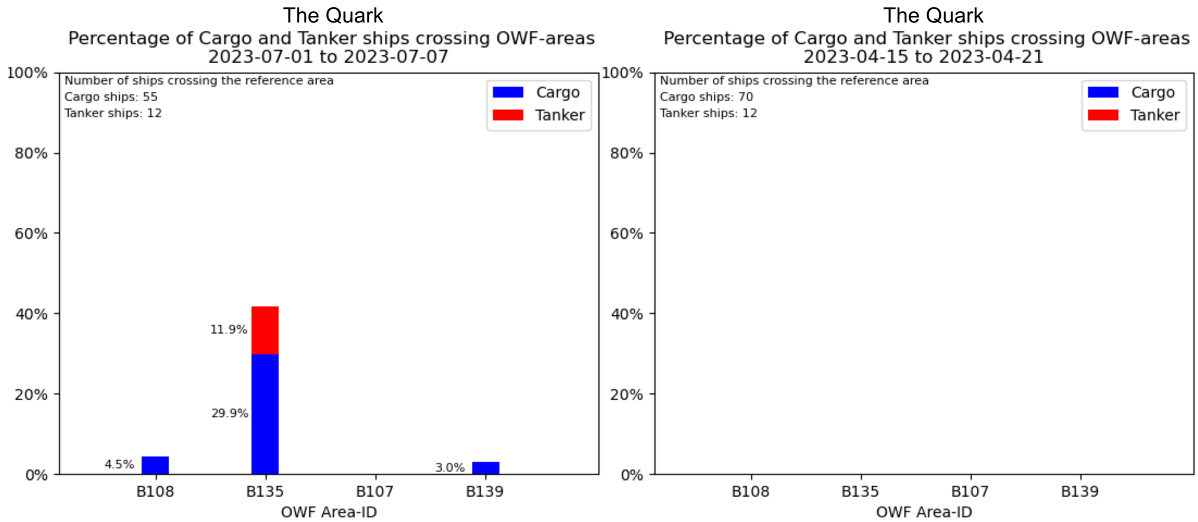

Figure 26: Intersection statistics in summer (left) and ship tracks in winter, mid-April (right).

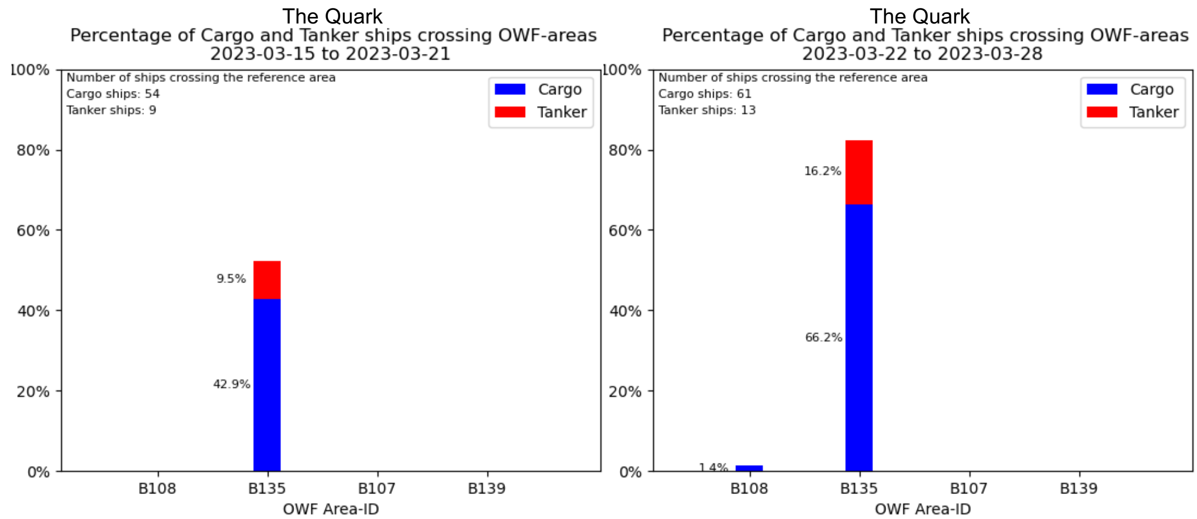

Figure 27: Intersection statistics mid and late March.

The ice charts presented in Figure 28 give a good understanding behind the AIS plots presented in the former figures. The ship traffic seems to align with the route and region with the least ice concentration with marginal ice thickness. The ice charts from the third week of April shows that ice concentrations were low close to the Finnish coast and thus provided a route far from the OWF areas in The Quark.

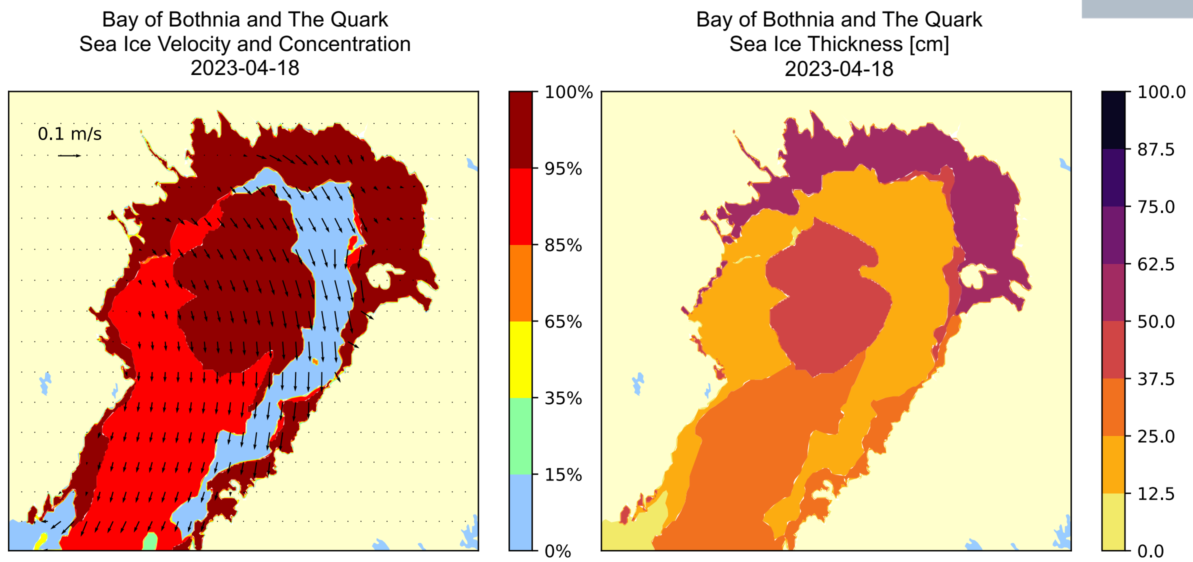

Figure 28: Sea ice concentration and thickness (date: 2023-04-18).

The ice charts for the third week of March in Figure 29 show higher ice concentrations compared to the charts from April for most of the areas. The ice concentration along the Finnish coast is still lower compared to the central and western The Quark region. The spread in the AIS tracks in Figure 25 (left) can be attributed to the even thickness of the ice in the region.

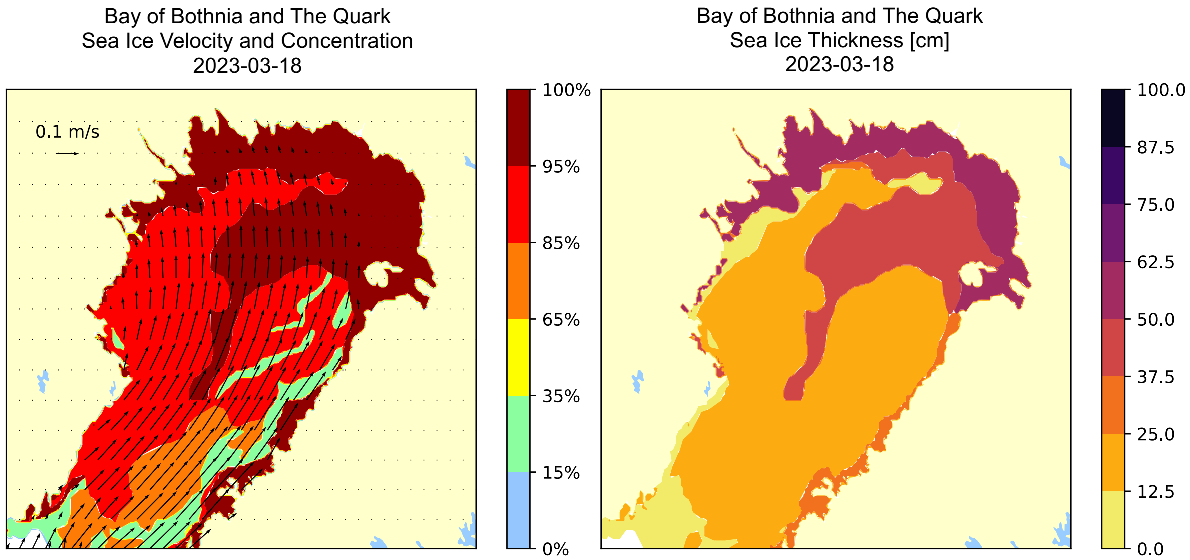

Figure 29: Sea ice concentration and thickness (date: 2023-03-18).

In the last week of March 2023, the ice charts in Figure 30 show that there is an increase both in the concentration and thickness of ice in The Quark region. The increased thickness of ice is most visible in the eastern part of The Quark. Thus, the ships are forced to take a route through central The Quark which results in the peak of intersections with area B135.

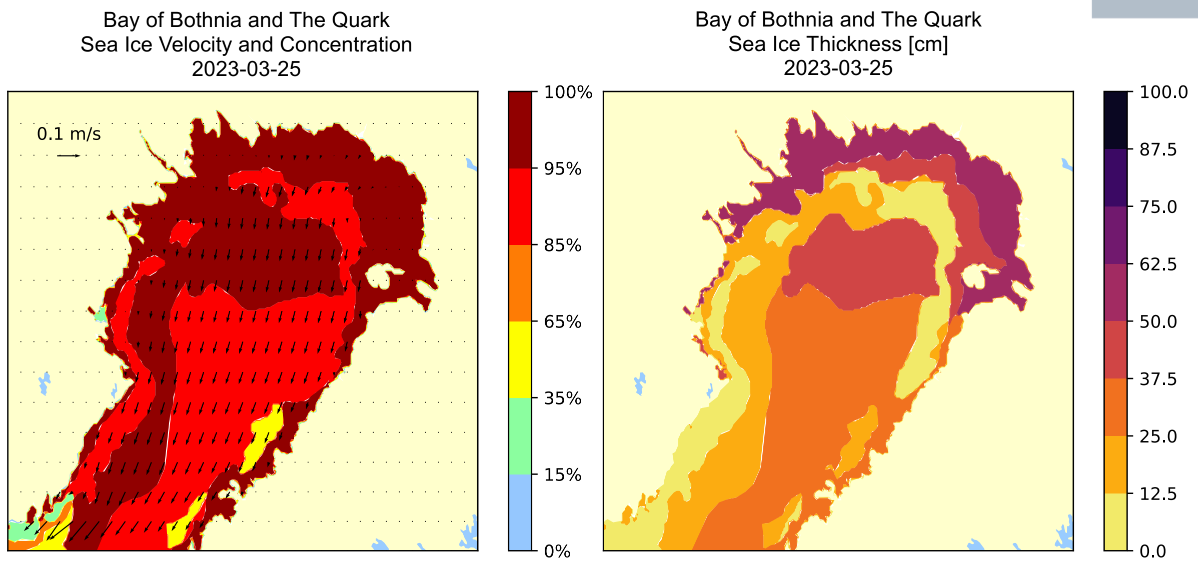

Figure 30: Sea ice concentration and thickness (date: 2023-03-25).

5.4. Case study C results – the Sea of Bothnia

In this chapter, the AIS tracks and statistics results for the Sea of Bothnia reference area are presented and discussed. The AIS tracks for typical summer trading patterns in Figure 31 (left) shows that the ships follow almost straight lines to or from different ports. The ship tracks intersect the OWF areas quite often especially in the central OWF areas. The area with least interaction is B142. The winter routes are rather similar to the summer routes for the studied years, which can be related to mild ice winters with low or non-existing ice coverage in the shipping lanes. Just as in summer navigation, the ships seem to cross the central OWF areas the most. Figure 31 (right) and Figure 32 show that icebreaker activity, indicated by the red lines, is minimal in the region and much less intertwined with the traffic in the central regions of the Sea of Bothnia.

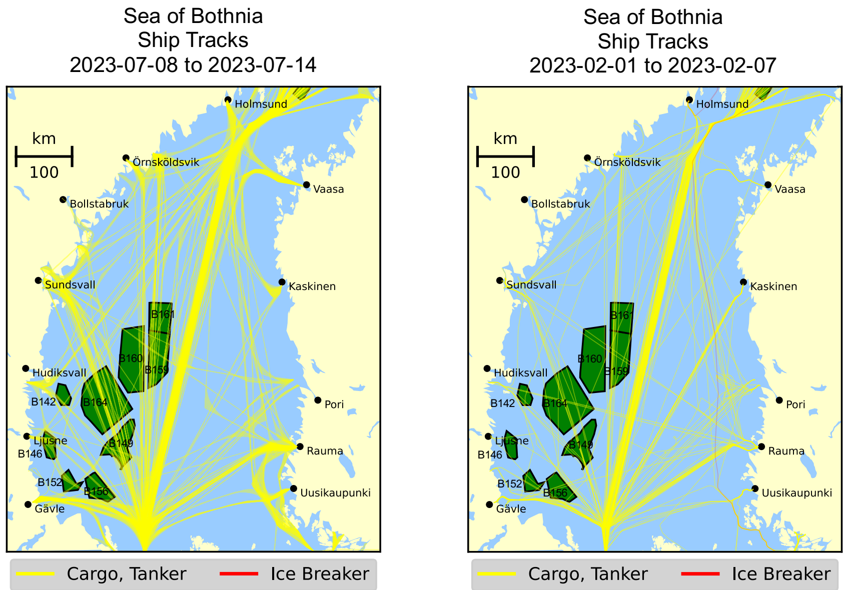

Figure 31: Ship tracks in summer(left) and ship tracks in winter, early February (right).

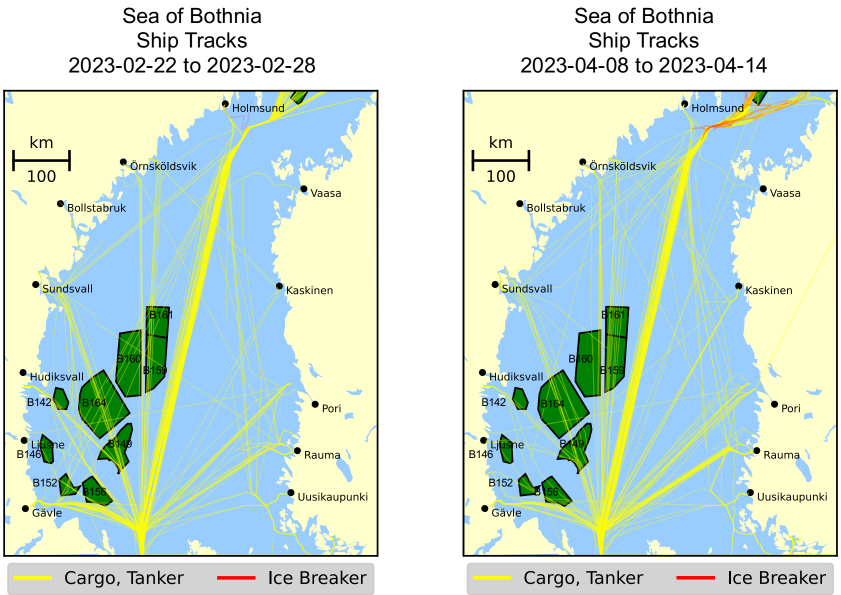

Figure 32: Winter navigation tracks late February (left) and mid-April (right).

The intersection statistics presented in Figures 33 and 34 support the inferences made from the visual analysis of the AIS tracks. The least affected OWF areas in the Sea of Bothnia are the ones near the coast, i.e., areas B142, B146, B152 and B156 with percentage of ships in the reference area crossing them ranging from 1% up to 24%. The central OWF areas, especially B149, B164, B160 and B161, receive significantly more ship traffic compared to the other OWF areas in the region. The large amount of ship traffic originates from ships that are heading to or from the ports near the other OWF areas, but also those to or from Swedish ports in the northern part of the Sea of Bothnia. The OWF areas B149 and B164 have up to 40% intersections of ship traffic in 2023, while the areas B160 and B161 had up to 28% of the weekly traffic in the region. It is also indicated that the number of vessels passing through the reference area stays relatively similar regardless of season.

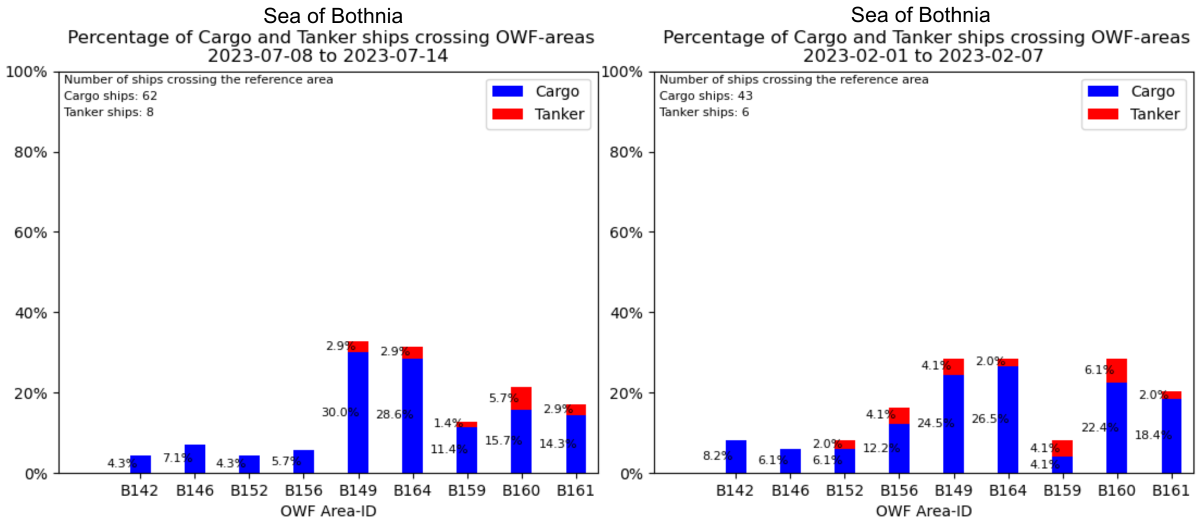

Figure 33: Intersection statistics in summer (left) and ship tracks in winter, early February (right).

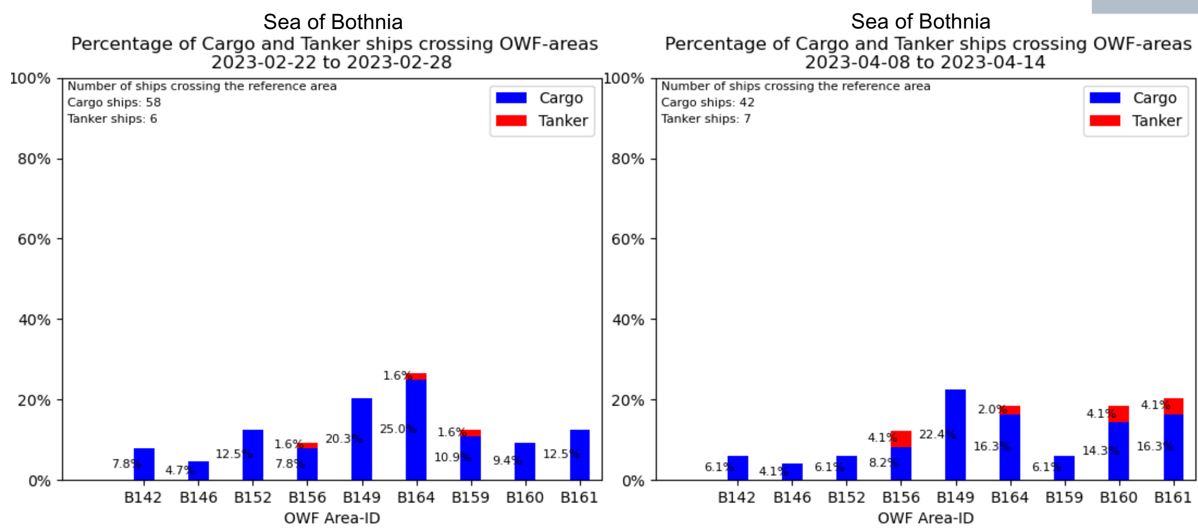

Figure 34: Intersection statistics late February (left) and mid-April (right).

Figures 35 to 37 present the ice coverage in the dates selected for this case study. These were some of the dates with the most ice in 2023. The figures show that the ice does not extend far south into the Sea of Bothnia. This means that the ice will not affect the ship traffic in the Sea of Bothnia. Some ports are infested with ice, but ports are generally supported by their own tugs to break ice.

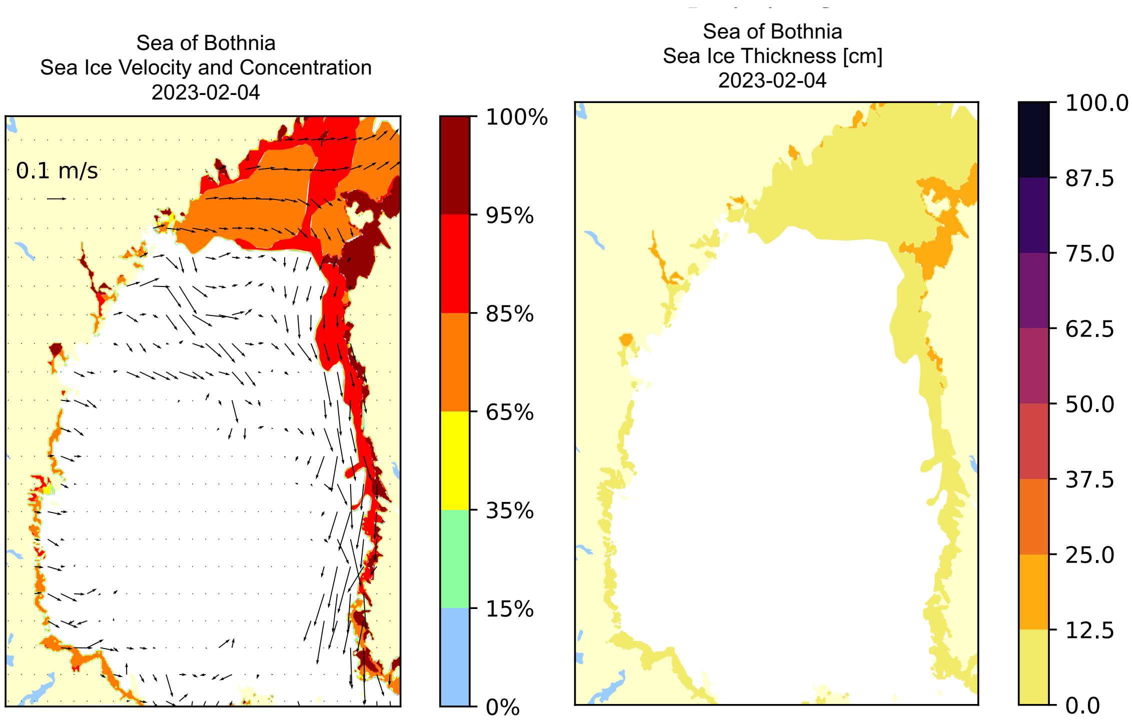

Figure 35: Sea ice concentration and thickness (date: 2023-02-04).

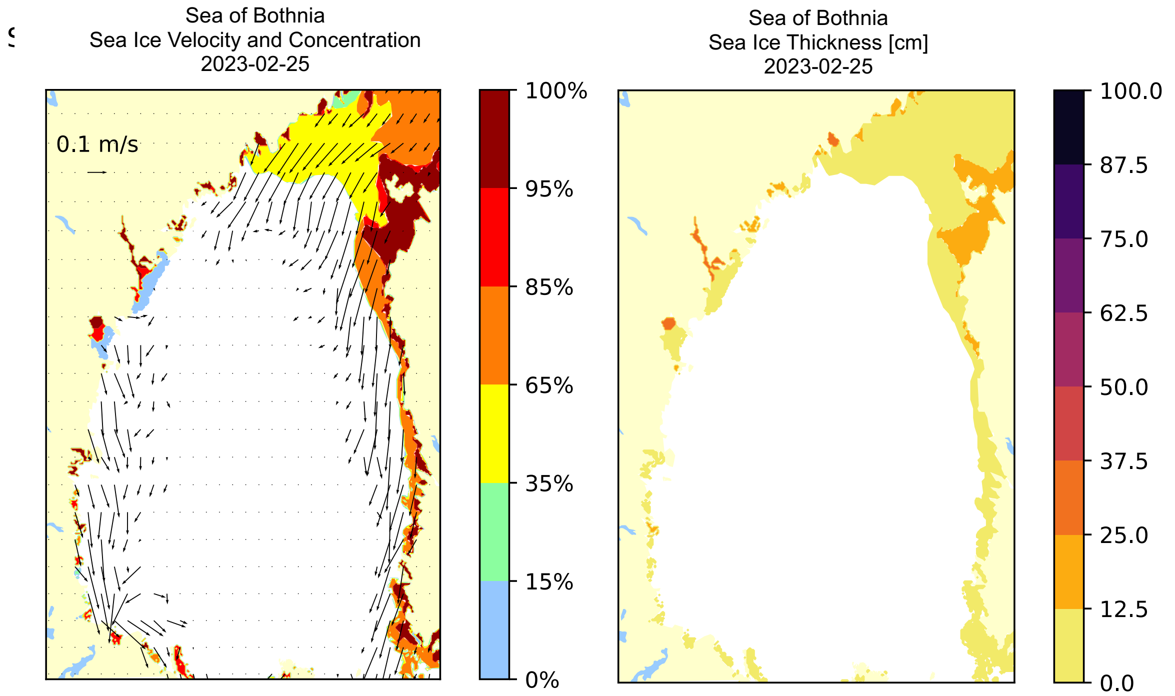

Figure 36: Sea ice concentration and thickness (date: 2023-02-25).

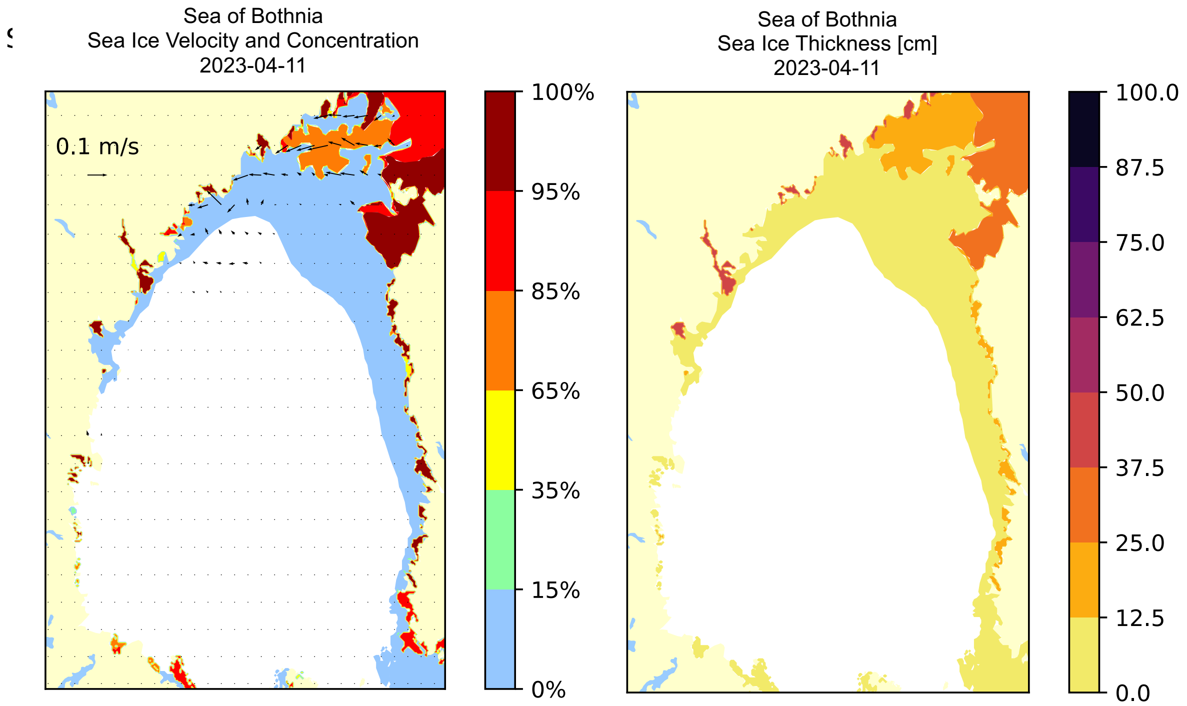

Figure 37: Sea ice concentration and thickness (date: 2023-04-11).

5.6. Case study D results – re-routing a ship crossing the OWF area B111

From the simulations and analyses of the three different routes and two ship speeds during winter, presented in Chapter 4.4, different voyage duration and corresponding fuel consumptions were obtained. For reference, the three different winter routes simulated included (see Figure 11): the route passing through the designated OWF area (reference case), the alternative route passing north of the area, and the more direct route passing south of the area (summer route).

- Compared to the reference case, a re-routing along the northern path resulted in a 3 hour longer voyage to reach the destination when the target speed was 5 knots, and it consumed 25% more fuel. With the same route but with a target speed of 10 knots, the voyage took only 1 hour longer time to complete with an additional 11% fuel consumption.
- When the route south of the OWF area was simulated, the voyage took 3 hours less time to reach the destination with 12.5% fuel savings at a 5 knots ship speed. When the ship speed was increased to 10 knots, the time saving was 2 hours, and the fuel savings was around 17%. It should be noted that the southern route is not a realistic route since the sea ice thickness is much larger than the northern route. If this would be the only available route, costs due to icebreaking would increase dramatically. The summer route does not connect other ports in the northern part of the bay which also makes it unrealistic.

5.7. Summary of results sorted by OWF area ID

The chapter presents a summary of results for each OWF area ID, based on the simulations and analyses carried out for the ship traffic, metocean and ice data years 2018, 2022 and 2023. It is important to highlight the results are based on historical data. More research is needed to include, e.g., yearly ice forecast, icebreaker planning and the effect of the windfarm structures on ice formation, if the results should be able to be used for decision-making purposes.

Bay of Bothnia

Area B111

The number of vessels crossing the areas B111 and B113 in winter is influenced significantly by the prevailing ice conditions. Due to the presence of thicker ice in the central reaches of the reference area, during March and April, area B111 was found to have more traffic. However, for the rest of the year, area B113 accommodates a higher volume of ship traffic compared to B111.

Figure 38 presents the weekly rate of intersection throughout the different years (hereafter referred to as the annual statistics). It indicates a relatively stable rate of intersection during summer months around 5 to 25% for all years. For winter traffic, however, the intersection rate fluctuates a lot. Year 2023 showed high peaks around 60% while both the years 2022 and 2018 had lower rates in early winter than in summer. However, in late winter, around April and May, a peak can be seen up to 40% before the ice melts and ship traffic pattern goes back to summer traffic.

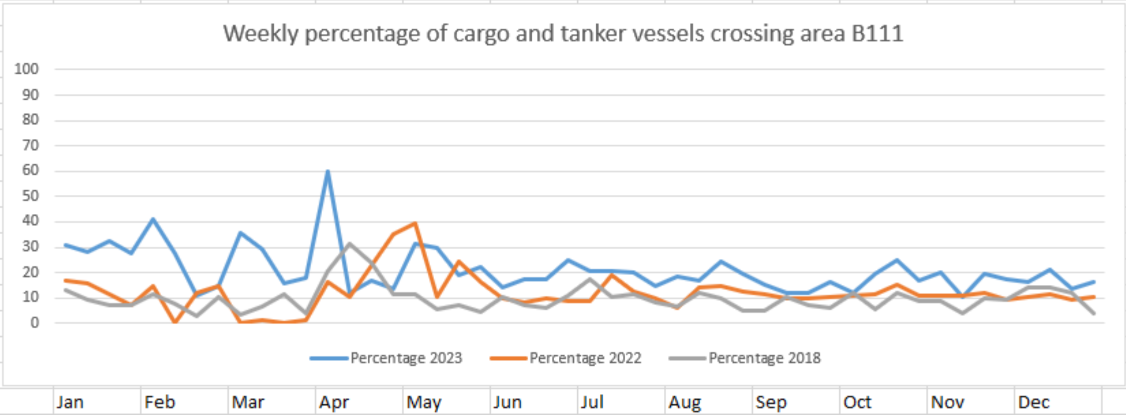

Figure 38: Annual statistics for the OWF area B111 for 2018, 2022 and 2023.

Area B113

During months other than March and April, B113 consistently interferes with 10 to 40% of the traffic with very few exceptions. The central positioning of ice in the Bay of Bothnia during these two months moves the traffic to the north and south of the area. Re-routing ships passing the region in winter will again depend on the effective management of ice. Here it can be seen to be relatively stable during summertime, though varying slightly between the years with 2023 giving slightly higher values. While the winter months have higher fluctuations and are much more unpredictable. This confirms the dynamics of winter navigation routes, with some periods resulting in favourable routes for area B113 with less intersections, and vice versa.

The seasonal variation in the annual statistics found for area B111 is reflected in the annual statistics for area B113 (see Figure 39). In contrast to the upward shift in intersection rates in April for area B111, the rates drop for area B113 in 2022 and 2023. This is due to the northward movement of ship traffic due to the thick ice formation in the central area of the Bay of Bothnia, as shown and concluded in previous presentations of the ice and AIS plots. The summer intersection rates remain stable between 10 and 30%. The seasonal fluctuation is indicative of the shifting ice moving the routes and forcing ships to follow alternative routes, and emphasises the need for effective ice management if the OWFs are to be set up in the Bay of Bothnia region.

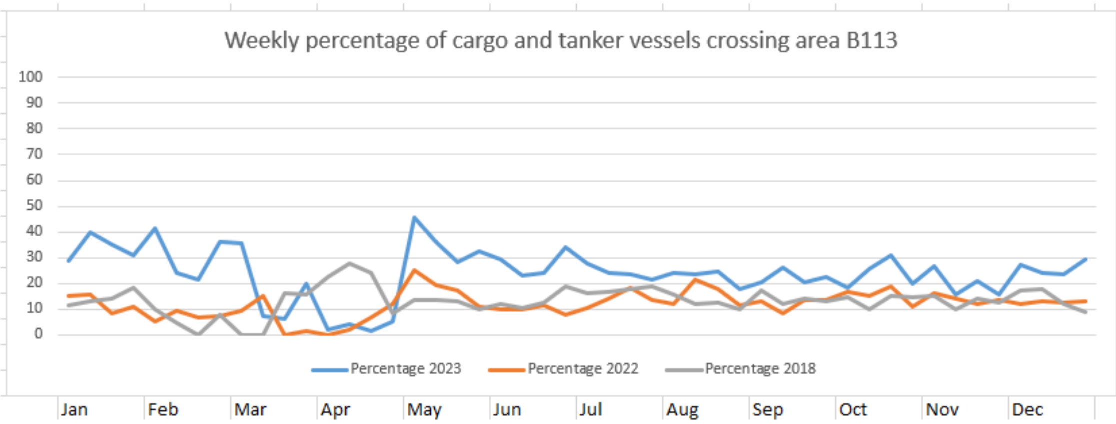

Figure 39: Annual statistics for OWF area B113 for 2018, 2022 and 2023.

The Quark

Area B107

Area B107 does not receive any ship traffic from the cargo and tanker ships in the region in the winter. It rarely receives ship traffic in the rest of the year as well.

Area B108

Less than 3% of the ship traffic passing through The Quark region in winter intersects with area B108. The fraction only extends to up to 6% even during the rest of the season. Also, the ships tend to only graze this area, which, for the studied winters, suggests they can be re-routed into the "channel" in between the areas B108 and B135.

Area B135

Due to the central location of area B135, it receives substantial ship traffic as discussed in the previous chapters. However, for the studied winters, re-routing is straightforward and does not involve a significant detour. Analysis of the AIS plots and intersection statistics indicates that there exist periods when no ships (cargo or tanker) cross the area B135. This was attributed to the extensive icebreaker activity in the region east of B135 providing ships with an ice channel. As indicated in Figure 40, the summer traffic intersects this area with levels around 15 to 35 %. During the winter months, the range is between 0 and 80% for the 2023 season, which is the season with the highest ice coverage.

The seasonal variation of the intersection rates are even more prominent in the annual statistics for area B135, see Figure 40. The intersection rate peaks at 82% in March but drops to 0% in April for the year 2023. For 2018 and 2022, the intersection rates drop in mid-February and March but becomes more stable from April.

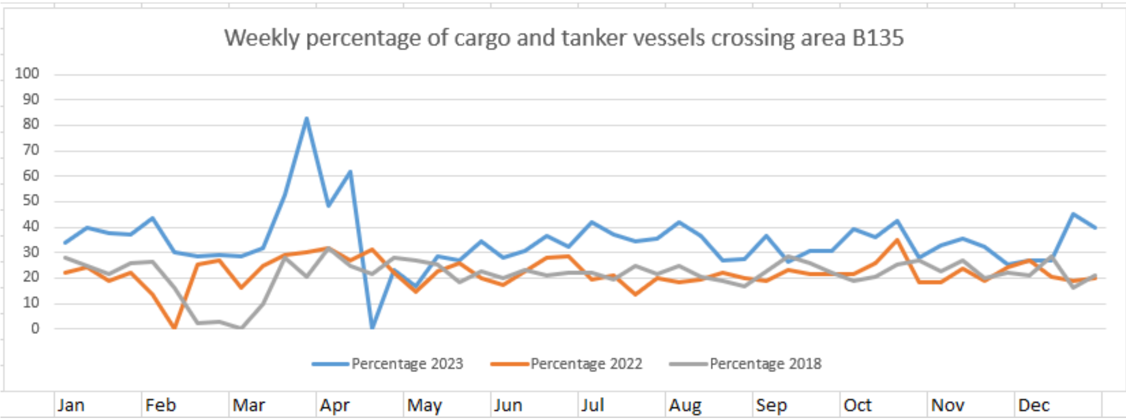

Figure 40: Annual statistics for the OWF area B135 for 2018, 2022 and 2023.

Area B139

Area B139, like B108, receives minimal traffic especially in winter for the three studied winters. Consequently, establishing an OWF in the area will not be a direct threat to winter navigation. However, further studies need to be done on the impact of establishing an OWF in the area on the ice dynamics in the region. This applies to other areas in The Quark as well due to the proximity of the OWF areas and the constrained passages between them.

Sea of Bothnia

Area B142

Area B142 receives ship traffic from the ships heading to and from the ports along the lower eastern coast of Sweden in the Sea of Bothnia. In 2023, it accounted for 2% to 17% of the weekly traffic in the reference area. AIS plots show that the ships navigate these waters without icebreaker assistance. Therefore, re-routing plans developed for ice-free periods should suffice for winter traffic as well during winters with mild or normal ice conditions. However, it is not possible to judge the situation for winters with severe ice conditions.

Area B146

Area B146 receives ship traffic from the ships heading to and from the port of Ljusne. It accounted for 4% to 19% of the weekly traffic in the reference area in 2023. Re-routing of ships crossing the area B146 follows the reasoning presented for the area B142.

Area B149

As discussed in the former results chapters, the OWF areas in the central region of the reference area receive substantial traffic. Area B149 is one of those areas and it receives a significant fraction of the traffic in the region accounting for up to 40% of the ships traversing the reference area weekly. As for the other OWF areas in the region, re-routing of ships follows the reasoning presented for the area B142.

Figure 41 presents the annual statistics. There is no trend between seasons, most probably due to the low ice coverage in this region for all the assessed years.

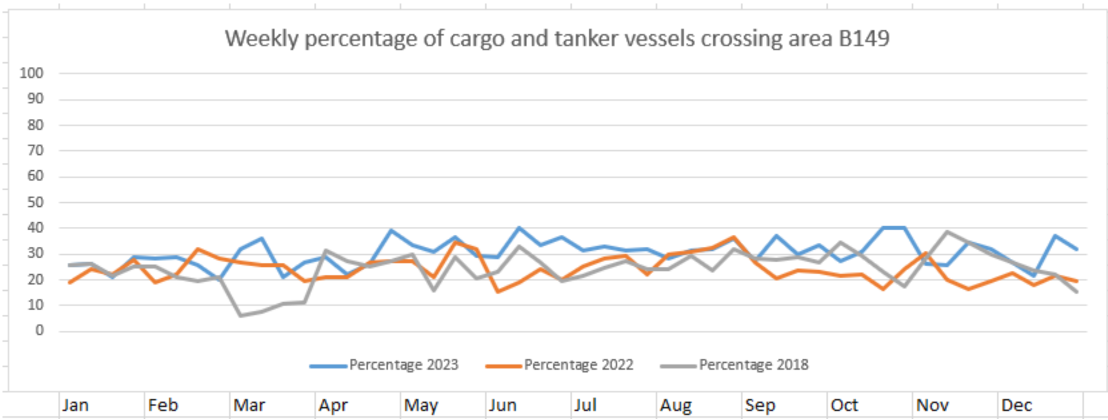

Figure 41: Annual statistics for the OWF area B149 for 2018, 2022 and 2023.

Area B152

Area B152 shares similar characteristics with area B142. The area receives up to 16% of the weekly traffic in the region, primarily from shipping to and from the ports along the lower eastern coast of Sweden bordering the Sea of Bothnia. The AIS plots indicate navigation without icebreaker assistance, consequently, re-routing may be one recommendation for winters with mild or normal ice conditions. Note that it is not possible to judge what is the situation for a winter with severe ice conditions. Furthermore, the effect of ice drift on the ships may cause problems in shallow water regions since it will affect the ships' manoeuvrability and expose them to an unnecessary safety risk.

Area B156

Area B156, despite not being in the central region, receives higher traffic compared to the areas B152, B142 and B146. This is due to its positioning right near the entrance to the Sea of Bothnia from the Baltic Sea. The area receives up to 24.6% of the weekly traffic passing through this region. Similar to area B149, there is no clear difference between summer and winter, see Figure 42, due to the low ice coverage. Values are varying between 5 and 20%.

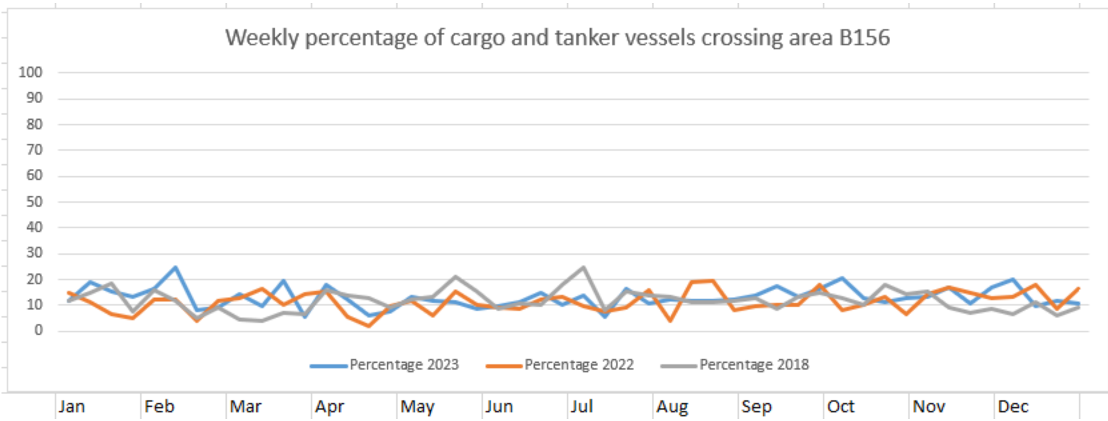

Figure 42: Annual statistics for the OWF area B156 for 2018, 2022 and 2023.

Area B159

In 2023, area B159 received up to 20% of the weekly ship traffic in the region. A re-routing of the ships passing through area B159 could be possible for mild and normal ice conditions, but the proximity to the areas B160, B161 and B164 must be considered. Therefore, re-routing of ships to avoid area B159 as well as the nearby areas would require establishment of new defined routes, but scenarios for ice conditions during severe winters must be further assessed. The summer routes could work for winter navigation as well since the area showed little to no coverage of ice for the years 2018, 2022 and 2023. As in the case for other OWF areas in Sea of Bothnia studied, the annual statistics, shown in Figure 43, indicate no seasonal variation of the intersection statistics.

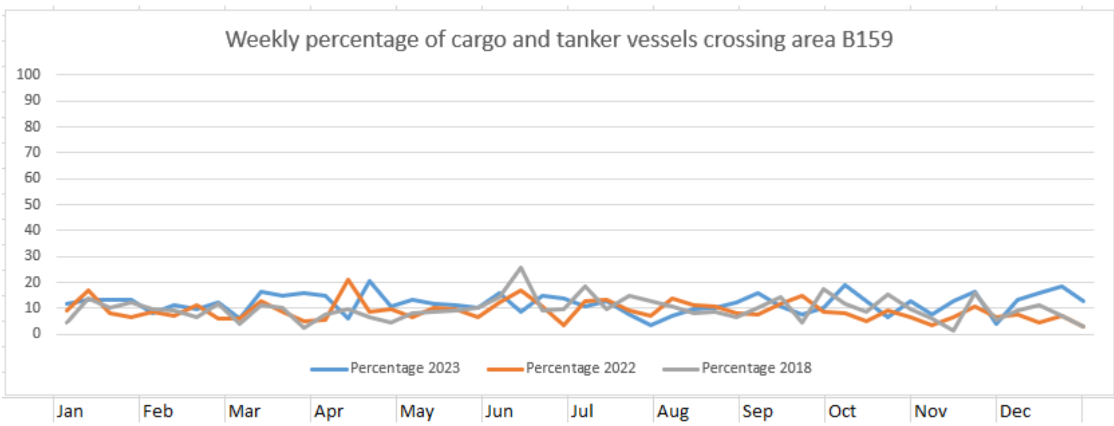

Figure 43: Annual statistics for the OWF area B159 for 2018, 2022 and 2023.

Areas B160 and B161

The areas B160 and B161 received up to 28.5% and 27% of the weekly ship traffic in the region, respectively. As for the area B159, re-routing plans need to be further investigated to include ice conditions for mild to severe winters, and the ice's movements. The annual statistics presented in Figure 44 indicate that the intersection rates remain relatively unaffected by seasonal changes and remains between 2 and 30% for the years observed for area B160.

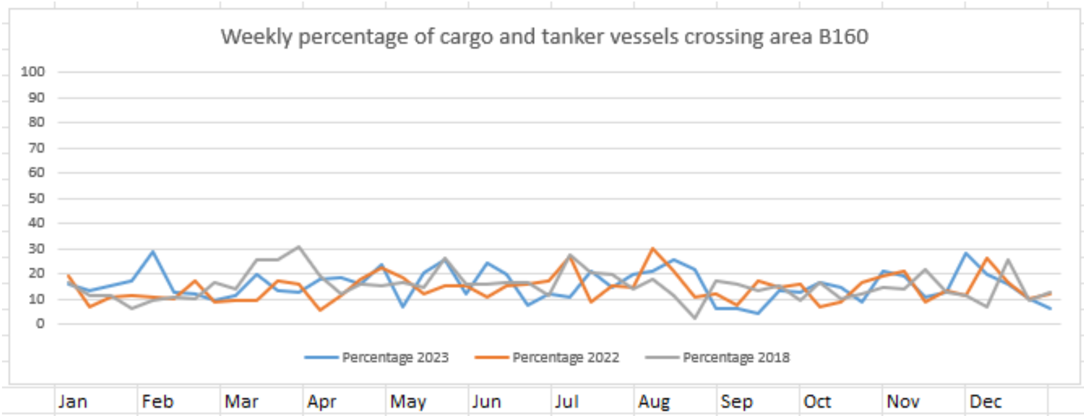

Figure 44: Annual statistics for the OWF area B160 for 2018, 2022 and 2023.

Area B164

Area B164 received up to 40% of the weekly ship traffic in the region on the account of its size and central location. See the area B160 and B161 for a discussion regarding re-routing of ship traffic. The seasonal independence of routes is reflected in the annual statistics generated for the years 2018, 2022 and 2023; see Figure 45.

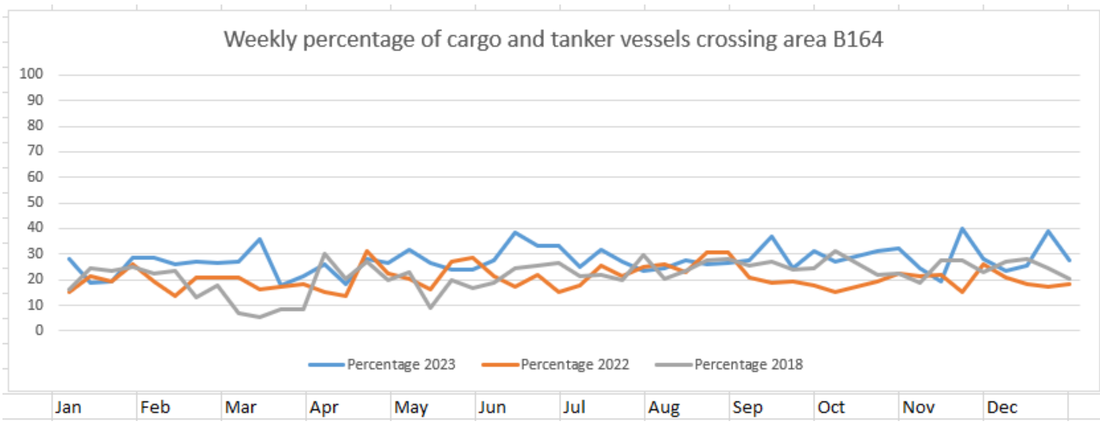

Figure 45: Annual statistics for the OWF area B164 for 2018, 2022 and 2023.

5.8. Need for more research

This project identified several areas of knowledge gaps where little or no prior research has been made. Some areas that need more research to be able to support in the decision-making process are discussed below.

Ice formation

From the different case studies, it has become clear that efficient winter navigation depends on finding the shortest common routes with the minimum ice concentration and thickness. This is, however, heavily dependent on the characteristics of the season, which include, e.g. the ice thickness distribution, ice drift (which is also dependent on the surface currents and surface winds), and ice concentration (which is correlated with the ice formation and breaking and drift). With ever increasing uncertainties in global climate, it is difficult to forecast even the seasons of the present year. However, it would be advantageous to predict future ice conditions so that alternative routes and conditions can be studied before detailed planning of the OWFs is made.

Even though some research has been presented on how ice sheets break around a single vertical cylindrical structure, there is a research gap on how an array of offshore wind turbine monopiles in the winter can affect ice formation, drift and ridge formation in the area in proximity to the wind farm and in downstream region. Does the ice break up and leave heavily ridged ice structures in the path of ships and icebreakers? Or, will the structures act as an anchor and form uniformly thick ice sheets in the region? Will the array or wind turbines act as an archipelago and accelerate formation of ice? These are just examples of questions that can be answered through further research on how the system of offshore wind turbines can alter the ice formation around it. These questions can in turn validate the considerations of suggesting alternative routes and assessing hazards in winter navigation around the OWFs.

Icebreaker operation in proximity to wind farms

Studies need to be conducted to study how icebreaking activity in proximity to an offshore wind turbine structure affects the structure. This will help to determine how close to a wind farm an icebreaker should be allowed to operate, which in turn will determine the shipping routes.

6. Conclusions

The project has developed a simulation and analysis methodology that can be applied to the assessment of marine installations' spatial planning how these affect the established ship traffic patterns, or how the ship traffic patterns may have to be adjusted. It was applied to areas of the Gulf of Bothnia defined by SwAM. Emphasis was on winter navigation; however, the analyses have included summer shipping for comparison purposes. The conclusions from the project are presented with reference to the three questions raised by SwAM in Chapter 1.1.

How are the shipping lanes affected by offshore wind farms?

The studied OWF areas are primarily placed such that the most heavily trafficked shipping lanes are unaffected when following the yearly regular trading patterns, i.e. summer and winter ship traffic. However, exceptions were identified such as the areas B149 and B164 in the southwest Sea of Bothnia. These areas will require a re-routing of the current statistical ship traffic based on AIS data. The new routes will be longer and pass over shallower waters which can increase the risk during winter conditions. The area B135 in The Quark poses a threat to the ship traffic towards Finnish ports during some periods of the year. However, re-routing is possible without large consequences in neighbouring areas.

How will the extension of offshore wind farms in ice covered seas change the conditions for winter navigation with regards to: (a) available routes, (b) icebreaker operations and the demand for icebreakers, and (c) optimized planning of traffic and icebreaking?

With a few exceptions it is concluded that the areas proposed by SwAM have been planned with only summer traffic taken into consideration. The dynamics of ice (ice movements) and tactic icebreaker assistance have not been considered. The results from the three studied years show that winter conditions and winter navigation between the years can vary significantly with respect to ice thickness and concentration. Hence, icebreaking tactics must be allowed to be dynamic to offer safe shipping conditions during winter.

It is found that installations of OWFs in ice infested waters will likely make ice management more difficult as it will limit the options for ship route planning. The need for re-routing of ships around the areas will not only increase the voyage time for the commercial traffic but also increase the demand of icebreaking capacity. In one study case the fuel consumption was also predicted to increase dramatically for a case study ship. This will increase the operational cost, and capital cost in the form of additional icebreakers for the Finnish and Swedish maritime organisation.

Looking at a seasonal average would give acceptable rate of intersections, the same level as for summer. However, it is the maximum instant demand for icebreakers that defines the capacity needed. OWFs could therefore result in a more unstable, intermittent icebreaker demand than before.

How will the formation of ice (with regards to, e.g., thickness, hardness, movement, and growth of ice ridges) be changed if offshore wind farms are installed?

The dynamics of ice in the Baltic Sea will locally be altered by the introduction of OWFs. What the effect will be is not known since published research is scarce on this topic. Studies are ongoing and have been presented for cylindrical-shaped structures in other regions of the world with ice wintertime. However, ice formation, mechanics and characteristics depends on many variables so the results from those studies cannot be applied to the conditions in the Gulf of Bothnia. It is clear though that an OWF poses the risk of acting as an archipelago, accelerating the growth of ice or increase the ridging of ice in the region due to the wind turbines breaking up the ice. How this will affect winter navigation or the long-term conditions and safety of the OW towers remain to be studied.

7. Recommendations for future work

Due to the nature of the project with its limitations, not all areas of scientific interest were covered. A continuation of the project can take different directions depending on the funding agency's and different stakeholder's interests. Some suggestions are presented below in addition to the topics mentioned in Chapter 5.8.

- *True cost analysis*
    - If the shipping routes become longer as a consequence of the new OWFs, and the icebreaking activities must increase, an accurate analysis of fuel consumptions and monetary costs must be made. These should be discussed in relation to the life cycle costs associated with the wind farm and its energy production.
    - The study has not discussed if Finland and Sweden have sufficient icebreaker capacity if OWFs are installed. It is plausible that extra icebreaker resources may be needed in both countries.

- *Systematic variation and definition of reference areas for intersection statistics*
    - Depending on how the reference areas are defined, different rate of intersections can be calculated. In this sense all the areas are compared on unequal terms. An area with 10% rate of intersection might in fact have higher impact on shipping than an area with 50% since the reference area might be larger for the prior. It is therefore recommended to continue to make a sensitivity study by defining the areas even more carefully and compare results for different reference areas. It is also recommended to include an assessment of safe distances to shipping lanes and traffic separation schemes if larger safe margins are required compared to the boundaries considered in this study.

- *Effect of wind farm structures on ice formation*
    - The effects of ice on monopile structures are well researched but how monopile structures affect the formation of ice and how the multiple structures in an OWF might interact together with the ice has not been studied thoroughly.

- *Perform analysis on additional years, with varying ice conditions*
    - The data provided for the years 2018, 2022 and 2023 were analysed in this study, however, those are years with mild and normal ice winters. Applying the methodology to years with more severe ice winters would be of interest both for assessing winter traffic in the Sea of Bothnia but also even more severe ice conditions in the Bay of Bothnia and The Quark. Larger data quantities categorized into mild, normal and severe ice winters could be analysed in a statistical manner. The methodology developed and presented in this report can be used for this purpose.

- *Energy consumption analysis including icebreaker assistance study*
    - A method has been developed to study the icebreaker assistance operations which can be used to identify convoy, escort or similar operations. The data can be used to estimate the vessel's resistance in such scenarios. Using the ShipCLEAN model, and the added information of the icebreaking assistance, more accurate ship performance and fuel consumption estimations can be obtained.

- *Revised icebreaking strategy*
    - Future and valuable work would be to simulate winter navigation with historical ice data and do a scenario-based assessment on icebreaker assistance where all areas have been implemented and closed off for traffic. In this simulation the demand of icebreaker capacity would be reported and compared to the current need and fleet size. The Swedish Maritime Administration has initiated a procurement process of one or two new icebreakers. Will these be enough, or will more icebreakers need to be ordered, and at what cost (see above)? How shall a new joint icebreaking strategy with Finland be developed?

- *Higher ice loads on vessels*
    - Not being able to sail in the most efficient route from a strategic perspective will most probably lead to ships being forced to operate in areas with higher ice thickness and concentration. It will result in an increased fuel consumption. It will also create a higher load and wear on the ships structure, and an increased maintenance. This could result in safety issues for ships that have insufficient ice class but have been ordered and built based on existing winter traffic conditions.

8. References

Akhtar N, Geyer B and Schrum C. (2022). Impacts of accelerating deployment of offshore windfarms on near-surface climate. *Scientific Reports* **12**(article no. 18307):1-16. https://doi.org/10.1038/s41598-022-22868-9.

Arabnejad MH, Thies F, Yao H-D and Ringsberg JW. (2024). Zero-emission propulsion system featuring, Flettner rotors, batteries and fuel cells, for a merchant ship. *Ocean Engineering* **310**(1):1-20. https://doi.org/10.1016/j.oceaneng.2024.118618.

Bodini N, Castagneri S and Optis M. (2023). Long-term uncertainty quantification in WRF-modeled offshore wind resource off the AS Atlantic coast. *Wind Energy Science* **8**(4):607-620. https://doi.org/10.5194/wes-8-607-2023.

Bodini N, Lundquist JK and Kirincich A. (2019). US east coast lidar measurements show offshore wind turbines will encounter very low atmospheric turbulence. *Geophysical Research Letters* **46**(10):5582-5591. https://doi.org/10.1029/2019GL082636.

Cañadillas B, Foreman R, Barth V, Siedersleben S, Lampert A, Platis A, Djath B, Schulz-Stellenfleth J, Bange J, Emeis S and Neumann T. (2020). Offshore wind farm wake recovery:airborne measurements and its representation in engineering models. *Wind Energy* **23**(5):1249-1265. https://doi.org/10.1002/we.2484.

Christiansen BM and Hasager BC. (2005). Wake effects of large offshore wind farms identified from satellite sar. *Remote Sensing of Environment* **98**(2-3):251-268. https://doi.org/10.1016/j.rse.2005.07.009

Goerlandt F, Goite H, Banda OAV, Höglund A, Ahonen-Rainio P and Lensu M. (2017). An analysis of wintertime navigational accidents in the northern Baltic Sea. *Safety Science* **92**(1):66-84. https://doi.org/10.1016/j.ssci.2016.09.011.

Fitch C, Joseph Olson AB and Lundquist KJ. (2013). Parameterization of wind farms in climate models. *Journal of Climate* **26**(17):6439-6458. https://doi.org/10.1175/JCLI-D-12-00376.1.

Hammer TC, Puolakka O and Hendrikse H. (2024). Scaling ice-induced vibrations by combining replica modeling and preservation of kinematics. *Cold Regions Science and Technology* **220**(1):1-15. https://doi.org/10.1016/j.coldregions.2024.104127.

Hendrikse H, Hammer TC, van den Berg M, Willems T, Owen CC, van Beek K, Ebben NJJ, Puolakka, O and Polojärvi A. (2022). Experimental data from ice basin tests with vertically sided cylindrical structures. *Data in Brief* **41**(1):1-18. https://doi.org/10.1016/j.dib.2022.107877.

Hüffmeier J, Sandkvist J and Forsman B. (2008). Ice management in Scandinavian ports. ASME 2008 27th International Conference on Offshore Mechanics and Arctic Engineering, Estoril, Portugal, 15-20 June 2008. Paper no. OMAE2008-58044. https://doi.org/10.1115/OMAE2008-58044.

Muchow M and Polojärvi A. (2024). Three-dimensional discrete element simulations on pressure ridge formation. *The Cryosphere* [preprint available]. https://doi.org/10.5194/egusphere-2024-831.

Platis A, Siedersleben KS, Bange J, Lampert A, Bärfuss K, Hankers R, Cañadillas B, Foreman R, Schulz-Stellenfleth J, Djath B, Neumann N and Emeis S. First in situ evidence of wakes in the far field behind offshore wind farms. (2018). *Scientific Reports* **8**(article no. 2163):1-10. https://www.nature.com/articles/s41598-018-20389-y.

Polojärvi A. (2022). Numerical model for a failure process of an ice sheet. *Computers and Structures* **269**(1):1-13. https://doi.org/10.1016/j.compstruc.2022.106828.

Prasanna M, Vuollekoski H, Polojärvi A, Haapala J, Lensu M and Åström J. (2024). Multi scale modelling of interaction between pack ice and offshore structures. The 27th IAHR International Symposium on Ice, Gdańsk, Poland, 9-13 June 2024. Paper no. 30404. https://www.iahr.org/library/infor?pid=30404.

Ronkainen L, Lehtiranta J, Lensu M, Rinne E, Haapala J and Haas C. (2018). Interannual sea ice thickness variability in the Bay of Bothnia. *The Cryosphere* **12**(1):3459-3476. https://doi.org/10.5194/tc-12-3459-2018.

Skamarock WC, Klemp J, Dudhia J, Gill D, Barker D, Wang W and Powers JG. (2005). A description of the advanced Research WRF version 2. *University Corporation for Atmospheric Research*. https://doi.org/10.5065/D6DZ069T.

Siedersleben KS, Lundquist KJ, Platis A, Bange J, Bärfuss K, Lampert A, Cañadillas B, Neumann T and Emeis S. (2018). Micrometeorological impacts of offshore wind farms as seen in observations and simulations. *Environmental Research Letters* **13**(12):1-12. https://doi.org/10.1088/1748-9326/aaea0b.

Sjöfartsverket. (2023). Isbrytarna håller hamnarna öppna. https://www.sjofartsverket.se/sv/tjanster/isbrytning/isbrytning/. (Accessed:2024-09-04).

Tillig F and Ringsberg JW. (2019). A 4 DOF simulation model developed for fuel consumption prediction of ships at sea. *Ships and Offshore Structures* **14**(S1):S112-S20. https://doi.org/10.1080/17445302.2018.1559912.

Vautard R, Thais F, Tobin I, Bréon F-M, De Lavergne JGD, Colette A, Yiou P and Ruti PM. (2014). Regional climate model simulations indicate limited climatic impacts by operational and planned European wind farms. *Nature Communications* **5**(1):1-9. https://doi.org/10.1038/ncomms4196.

Vihma T and Haapala J. (2009). Geophysics of sea ice in the Baltic Sea - a review. *Progress in Oceanography* **80**(3-4):129-148. https://doi.org/10.1016/j.pocean.2009.02.002.

Wang C and Prinn GR. (2011). Potential climatic impacts and reliability of large-scale offshore wind farms. *Environmental Research Letters* **6**(2):1-6. https://doi.org/10.1088/1748-9326/6/2/025101.

Yang B, Qian Y, Berg KL, Ma P-L, Wharton S, Bulaevskaya V, Yan H, Hou Z and Shaw JW. (2017). Sensitivity of turbine-height wind speeds to parameters in planetary boundary-layer and surface-layer schemes in the weather research and forecasting model. *Boundary-Layer Meteorology* **162**(1):117-142. https://doi.org/10.1007/s10546-016-0185-2.

Yu Q, Liu K, Teixeira AP and Guedes Soares C. (2020). Assessment of the influence of offshore wind farms on ship traffic flow based on AIS data. *Journal of Navigation* **73**(1):131-148. https://doi.org/10.1017/s0373463319000444.

Zhen R, Lv P, Shi Z and Chen G. (2022). A novel fuzzy multi-factor navigational risk assessment method for ship route optimization in costal offshore wind farm waters. *Ocean & Coastal Management* **232**(1):1-20. https://doi.org/10.1016/j.ocecoaman.2022.106428.

Zhou W, Tang J, Wang X, Wang S, Niu X and Wang Y. (2016). Evaluation of regional climate simulations over the CORDEX-EA-II domain using the COSMO-CLM model. *Asia-Pacific Journal of Atmospheric Sciences* **52**(2):107-127. https://doi.org/10.1007/s13143-016-0013-0.

Åström J and Polojärvi A. (2024). High-resolution fracture dynamics simulation of pack-ice and drift-ice formation during sea ice break up events using the HiDEM2.0 code. *Geophysical Research Letters*. (Under review).

Åström J, Robertsen F, Haapala J, Polojärvi A, Uiboupin R and Maljutenko I. (2024). A large-scale high-resolution numerical model for sea-ice fragmentation dynamics. *The Cryosphere* **18**(1):2429-2442. https://doi.org/10.5194/tc-18-2429-2024.

Appendix: data sources

Copernicus Marine Service is a public source for data. The data supplied by FMI, Sea Ice Thickness and Sea Ice concentration was in this project easy to work with but unfortunately, they did not contain the daily mean sea ice velocity. The sea ice velocity was supplied by Mercator Ocean through Copernicus Marine Service. However, this dataset was not as easy to work with. Two different datasets were needed. The Global Ocean Physics reanalysis contains historical data up to about 2 years before the report's date. The Global Ocean Physics Analysis and Forecast contains data rolling with two years historical data and 10 days forecast. Unfortunately, in the desired time period there was a gap in which the data had been removed from the Analysis and forecast dataset but not yet been reanalysed and put into the Reanalysis dataset.

Data	Dataset	Source	Origin	DOI
Sea Ice Thickness	Baltic Sea - Sea Ice Concentration and Thickness Charts	Copernicus Marine Service	FMI	https://doi.org/10.48670/moi-00132
Sea Ice Concentration	Baltic Sea - Sea Ice Concentration and Thickness Charts	Copernicus Marine Service	FMI	https://doi.org/10.48670/moi-00132
Sea Ice Velocity (1993-01-01 to 2021-06-01)	Global Ocean Physics Reanalysis	Copernicus Marine Service	Mercator Ocean	https://doi.org/10.48670/moi-00021
Sea Ice Velocity (2-year history – 10 day forecast)	Global Ocean Physics Analysis and Forecast	Copernicus Marine Service	Mercator Ocean	https://doi.org/10.48670/moi-00016

AIS data was supplied by the Swedish Maritime Administration and by Helcom. The data from Swedish Maritime Administration contained more information about the ships, and every possible data to be sent by AIS. Helcom had already filtered the data and it did not contain as much information. When using the data, care needed to be taken to ensure that the data was sorted in a chronological order.