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COEXISTENCE OF OFFSHORE WIND FARMS AND WINTER NAVIGATION

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FOREWORD

In this report no 134, the Winter Navigation Research Board presents the results of Wind-Trapped - Coexistence of offshore wind farms and winter navigation. The project goal was to gain insights on the effects of planned offshore wind farms to the winter navigation system.

The Winter Navigation Research Board warmly thanks the authors for this report.

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Coexistence of offshore wind farms and winter navigation

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1. Introduction

A large number of offshore wind power plants are planned to be installed in the Gulf of Bothnia. These will be organized in offshore wind farms that span several nautical miles. Navigation through such OWFs is typically forbidden for large vessels also during ice-free seasons, and a certain safe distance must also be maintained. However, the situation becomes much more problematic in the presence of sea-ice.

First, there are potential glaciological effects. A wind turbine attached to the seabed (either via a solid foundation or anchoring) binds the surrounding ice sheet, thereby affecting ice motion. This is likely to increase ice ridging both in quantity and thickness, which can be difficult and even dangerous for vessels to pass without ice-breaking assistance. Fast ice could also inhibit the formation of ice-free regions (shore leads) along the coast, thereby limiting the options for ice-free routing.

Second, there are navigational aspects. Safety margins around OWFs may lengthen the shortest route by tens of nautical miles. Gaps between farms, intended to allow ship passage, may become clogged by deformed ice. Vessels need to double check that they will not get stuck in ice if there is a chance of drifting close to an OWF. The need for ice-breaking assistance will be increased, while the routing options for ice breakers will be more limited.

Third, there is navigational safety. Ships may become beset in a compressive ice cover drifting with speeds up to 1 kn. In the proximity of OWFs this requires immediate action from the icebreakers. In extreme conditions, most recently during the winters 2009-2010 and 2010-2011, large numbers of ships became beset at the same time for extended periods. In the presence of OWFs it is uncertain how such situations can be managed except by precautionary closure of all traffic.

Finally, climate change causes additional uncertainty. Although the area of ice-covered regions might decrease, ridging of ice especially near shoreline will likely increase. Future ships will likely be less powerful, their hulls less resistant to ice, and their crews less experienced in winter navigation.

This project analyses historical shipping routes in Gulf of Bothnia during winters, using for example high-resolution Automatic Identification System (AIS) data, available ice charts and ice radar images, and compares these with positions of the planned OWFs. This gives more insight into assessments on OWFs, and highlight recurring costly, problematic or otherwise dangerous sea areas.

2. Currently recognized impacts of OWFs on navigation and maritime transport

2.1 OWFs in ice-free sea areas

Considering the coexistence of maritime transport and OWFs, most reports containing applicable findings and analyses appear to be for ice-free conditions. All risks identified for ice-free conditions are also present in ice infested waters and are possibly aggravated by the ice conditions. This applies e.g. for collision risks where decreased maneuverability, besetting and drifting with the moving ice cover must be added to the analysis. On the other hand, impacts and risks related to the winter navigation system cannot simply be extrapolated or amended by adding local ice conditions to open water analyses, as the optimization of icebreaker assistance configurations and the constant rerouting of traffic in search of easiest routes through the ice cover are specific to winter navigation.

The far-reaching maritime effects of OWFs include the impact of OWFs on the navigation infrastructure and on the functioning of the maritime traffic system, and, on the other hand, new types of risks due to proximity of ships and farms. Navigational primary risks that are introduced or altered by the establishment of OWFs include ship-turbine collisions, ship-ship collisions due to maneuvers seeking to avoid the OWF, and grounding risks. Grounding risks may also become reduced as shallower waters are screened off by the OWFs. Secondary risks include reduced detectability of navigational marks and other ships in the radar, especially service vessels operating withing the OWF grid, disturbances in radio communications, e.g. AIS, limited possibilities of emergency routing and anchoring, and the limiting of helicopter operations during search & rescue and emergency transport operations. Comprehensive reports on all aspects of risks and impacts are especially [21] and also [4] [15] [16] [17]

In ice-free sea areas the impact of OWFs on the marine infrastructure and traffic system is usually considered a problem for planning and impact assessment preparation. The fairways may become rerouted and travel times to ports may increase. Some areas assigned for anchorage may be lost, and narrower space for maneuverability may require new vessel traffic management practices [10]. National decision processes and detailed guidelines on how navigational issues should be taken into account are reviewed in [20] and [21]. National guidelines [18] for UK waters require evaluations covering all phases of planning, construction, operation and decommissioning, and a comprehensive traffic survey of the planning area prior to submission of impact assessment reports. Safety domain theory [19] is recommended as a tool for statistical risk assessments, and AIS data is widely used in theoretical studies related to ship-OWF proximity, e.g. [22]. From the wind farm viewpoint there is the task of optimizing the maintenance vessel activities [8]. The wind farm site selection could be approached similarly as an optimization problem for all actors and parameters [9] but such approach appears to have little relevance in national development strategies and decision making.

The possibility of collisions, or allisions in formal marine accident terminology, between offshore wind turbines and ships has been acknowledged, although the risks have not been considered to be high in comparison to navigational risks in general [6]. Allision is often defined to include cases where a ship enters, without making contact with the turbines, a farm area accidentally due to navigation errors or avoidance measures (powered allision) or due to drifting (powered allision). Collisions and allisions with severe consequences between passing ships and other structures are not very common overall, e.g. in the case of bridges there is on the average two incidents in three years worldwide [11] and for the North Sea drilling platforms less than 10 incidents during 50 years [12]. However, the increasing number of offshore wind farms is likely to increase the probability of incidents, and the growing size of the turbines may increase the cost of incidents. The number of numeric collision simulations, analytic treatments of collision mechanics and statistical studies of event return periods has been steadily increasing; a review is found in [14]. Also, the risks to the power cable damage due to anchors gets attention as the economic losses may greatly exceed those from single damaged turbine [7]. The cables can therefore also prevent or delay emergency anchoring.

The potential collision incidents fall into two main categories, ships assigned to the servicing and installation of the wind farm, and ships passing the farm. Known incidents for passing ships include three severe cases during 2021-2023: capsizing of an offshore wind installer vessel, a collision by a bulk carrier after it had lost rudder in a collision with another vessel, and extensive damage suffered by a cargo ship strayed off course [5]. For servicing ships there appears to be only one severe incident with three injured persons [13]. The fact that for North Sea drilling platforms the number of incidents is ten times higher for servicing ships than for passing ships [12] might be explained by the exigencies to keep schedules in any weather. The incidents have been mainly considered from the ship's point of view. However, also collisions with low speeds typical to service operations may induce structural damage to the turbines [2]. Also for the ships there are new types of hazards from the potential collapsing of the turbine or turbine parts on the ship, especially the toppling of turbine nacelle on ship superstructure. The outcome of a collision incident depends strongly on the height of the impact location and the flexibility of the turbine and is basically different for the three main foundation types (gravity base, monopile, jacket) from which the monopile appears to be least hazardous from the ship point of view [1].

2.2. OWFs in ice-infested waters

Seasonally ice-covered waters with existing offshore wind farms include Baltic Sea, Bohai Sea [23] and Vänern [24]. Installations are being planned for Great Lakes and Gulf of St Lawrence while the plans have been cancelled for the White Sea [28]. Most Baltic offshore farms are located in the southern parts of the sea where ice conditions, whenever they occur, are at most moderate. For such areas the required environmental assessments report the statistics of ice conditions, principally ice thickness, ice drift speed, and ice drift direction. This data is used in structural planning, especially for calculating ice-induced vibrations of turbines.

The only installation in the northern Baltic is the small nearshore Tahkoluoto pilot wind farm within the fast ice zone and can provide insight neither on the phenomena in the pack ice zone nor on navigation issues. The ice conditions have mostly been considered from the ice-structure interaction viewpoint only and assumed to have no greater impact on the regular interaction between OWFs and navigation and on the associated risks. The first larger Baltic OWF in more difficult ice conditions will be the Gulf of Riga WF installed across an area of 183 sq.km and scheduled to enter construction phase in

2025. The need to analyze the joint effect of the farm and ice conditions on navigation is recognized in the EIA of the said project but not considered problematic [25].

On the other hand, concerns have been raised about the potentially complicated coexistence of navigation and OWFs in the Northern Baltic, especially in the Bay of Bothnia. However, apart from media the only references addressing this appear to be [26] that lists conceived risks and problematic issues without deeper analyses, and a more comprehensive report [27] combining ice conditions data with AIS-retrieved traffic data and planned OWF areas in the Bay of Bothnia and Sea of Bothnia. This reference presents a number of case studies for different midwinter ship track patterns that are principally determined by the prevailing ice conditions and are changed whenever the ice conditions change. The main phenomenon here is the opening and closing of easily navigable coastal leads and the consequent alternation of traffic patterns. The case studies exemplify that in the long run for any OWF location the preferred routes intersect the OWF for a certain fraction of time. Especially in the Bay of Bothnia any OWF will thus reduce the efficiency of the winter navigation system in some way that in principle could be quantified in more detailed analyses.

To summarize, the following topics related to the co-existence of wintertime ship traffic and OWFs can be conceived. The topic list extends the issues gleaned from the references with themes related to the winter navigation system and expected OWF-induced changes in ice conditions. Most issues are also considered in the impact assessments prepared for the Northern Baltic OWFs (Section 3.2).

Primary risks for ships and OWFs

- Generally aggravating the risks pertaining to open water navigation and OWFs.
- Space sufficient for avoidance maneuvers in open water is not sufficient when ice is present or the maneuvers cannot be made, for example when the ships cannot exit ice channel. Maneuverability may be reduced by sudden changes in ice conditions.
- Allisions due to complicated traffic situations more likely, especially during convoy operations.
- Drifting allisions with OWF by beset ships drifting with ice, especially by OWF servicing vessels
- Aggravating primary risks involved to convoy operations and to events obstructing their progress
- Basinwide compressive situation involving many ships beset for longer periods cannot be handled or can be avoided only by the closure of all traffic.
- Recovery of spilled oil within the ice covered OWF and oil combatting logistics more difficult or impossible.

Possible risk aggravating changes in ice conditions and navigational practices:

- By obstructing ice movements and by increasing deformation the OWFs may change ice conditions in a way that the risks and impacts assessed without considering this possibility must be reassessed.
- OWFs may obstruct ice movements and prevent formation of coastal leads between the OWF and fast ice. Instead, the lead may form on the opposite side of the OWF in which case the reduced wind fetch may reduce the frequency of occurrence of the leads.
- The fragmentation of ice when drifting through OWF creates ice that deforms easily, enhancing drift and ridging. Ice may accumulate inside the OWF grid and prevent access by servicing vessels. Ice may accumulate to the coastward side of the OWF and remain static until the end of the ice season.
- New channels must be opened if existing channels drift close to OWF, reducing the possibilities for commercial vessels to navigate independently to icebreaker meeting points along the existing channels.
- Increasingly narrow areas with multiple channels reduce the strength of the ice cover and generate excessive deformation.
- The shipmasters may lack experience in ice navigation, especially for the severe ice winters and conditions.
- Due to energy efficiency directives, ship sizes tend to increase while relative engine powers decrease, reducing ice-worthiness and maneuverability in ice.

Expected and conceived impacts on winter navigation system:

- The extent of navigable waters is reduced even to 50%
- The possibilities to take straight or optimal course to next waypoint reduced. Travel times and fuel consumption increase as OWFs are avoided by navigationally suboptimal routes.
- Possibilities to make route planning according to known ice navigability conditions reduced (strategic navigation). Possibilities to select locally easier ice types reduced (tactical navigation).
- Obstructing the possibilities of rerouting traffic to coastal leads. Access to or exit from coastal lead ends blocked by OWFs. Emergency exit from a coastal lead blocked. Coastal leads may not form anymore on the coastward side of an OWF.
- Possibilities of independent navigation are reduced, increasing the need for icebreaker assistance. Icebreaker travel times to meeting points increase.
- Access of servicing vessels to OWF turbines may be prevented by ice or the vessels may be beset inside the turbine grid, requiring assistance or even rescue.
- Increased need of escorting all traffic through narrow areas created between adjacent OWFs (as presently done in Northern Quark)

- Certain ports temporarily inaccessible due to combined obstruction by OWF and ice. Current icebreaker fleet insufficient to assist ships to all ports throughout the whole ice season.
- Certain extreme ice compression phases or other extremal situations cannot be handled otherwise than by allowing only escorted ships to the basin or closing down traffic partially or completely.

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3. Planned offshore wind farms in the Northern Baltic

3.1 The farms

The coordinates for the bounding polygons for the planned Northern Baltic OWFs were obtained from Finnish Transport Infrastructure Agency (Väylävirasto). The project plans and, when completed, EIAs are found from Finnish Environment Institute (Suomen Ympäristökeskus, www.ymparisto.fi).

There are 52 OWFs taking into account that there were two different names for one and the same farm in two cases. The farms are listed in alphabetical order in Table 1. The ordering was changed to sea area oriented order as in Table 2. This numbering is used to identify the farms in charts and other graphics. In Figure 1 and in later traffic density analyses, the farm areas were expressed as cell polygons of a 1 NM grid.

Table 1. Northern Baltic planned offshore wind farms, alphabetical.

Short name	Väylä database name	Short name	Väylä database name
aurum_1	Aurum 1	krist_east	Kristinestad East
aurum_2	Aurum 2	krist_west	Kristinestad West
baltic_alpha	Baltic Offshore Alpha	kristiina	Kristiinankaupunki
baltic_beta	Baltic Offshore Beta	laine	Laine
baltic_eps	Baltic Offshore Epsilon	langgrund_1	Långgrund 1
bores_A	Bores Krona A	langgrund_2	Långgrund 2
bores_B	Bores Krona B	maanahk_A	Maanahkiainen A
bores_C	Bores Krona C	maanahk_B	Maanahkiainen B
bothnia	Bothnia Offshore Kappa	najaderna	Najaderna
bothnia_kappa	Bothnia Offshore Lambda	navakka	Navakka
bothnia_lambda	Bothnia Offshore Omega	noatun_north	Noatun North=Stormskär
bothnia_omega	Bothnia Offshore Sigma	noatun_south	Noatun South= Väderskär
bothnia_sigma	Bothnia West	norrskar	Norrskär
bothnia_west	Bothnia	olof_konung	Olof Skötkonung
dyning	Dyning	polargrund	Polargrund
ebba	Ebba	reimari	Reimari
edith	Edith	skridblander	Skridblander
erikseger	Erik Segersäll	storgrundet	Storgrundet
eystrasalt	Eystrasalt	sylen	Sylen
fyrskeppet	Fyrskeppet	tahkoluoto	Tahkoluoto
gavle_ost	Gretas Klackar 1	tyrsky	Tyrsky
gretas_1	Gretas Klackar 2	utposten	Utposten

gretas_2	Gävle Öst	vagskar_A	Vågskär A
halla	Halla	vagskar_B	Vågskär B
hauki	Hauki	voima	Voima
korsnas	Korsnäs	wellamo	Wellamo

Table 2. The basin oriented ordering and grouping of the wind farms.

	Group name	Short name
1	Bay of Bothnia northwest	bores_B
2	”	bores_C
3	”	bores_A
4	Bay of Bothnia north mid basin	polargrund
5	”	bothnia_omega
6	”	halla
7	Bay of Bothnia middle east coast	ebba
8	”	maanahk_B
9	”	maanahk_A
10	Bay of Bothnia south west coast	aurum_1
11	”	aurum_2
12	Bay of Bothnia south mid basin	bothnia_kappa
13	”	laine
14	”	voima
15	”	reimari
16	Bothnian Sea north east coast	tyrsky
17	”	norrskar
18	”	korsnas
19	”	edith
20	Bothnian Sea middle east coast	navakka
21	”	krist_east
22	”	kristiina
23	”	hauki
24	”	tahkoluoto
25	Bothnian Sea middle mid basin	eystrasalt
26	”	bothnia_sigma
27	”	krist_west
28	”	bothnia_west
29	Bothnian Sea south mid basin	bothnia
30	”	wellamo
31	Bothnian Sea southwest	bothnia_lambda
32	”	sylen
33	”	gavle_ost
34	”	fyrskeppet
35	”	olof_konung
36	”	najaderna
37	Bothnian Sea south west coast	gretas_1
38	”	gretas_2
39	”	storgrundet
40	”	utposten
41	Bothnian Sea south coast	vagskar_A

42	”	vagskar_B
43	”	noatun_north
44	”	noatun_south
45	Northern Baltic Proper mid basin	baltic_beta
46	”	erikseger
47	”	skridblander
48	”	baltic_eps
49	Northern Baltic Proper west coast	langgrund_1
50	”	langgrund_2
51	”	dyning
52	”	baltic_alpha

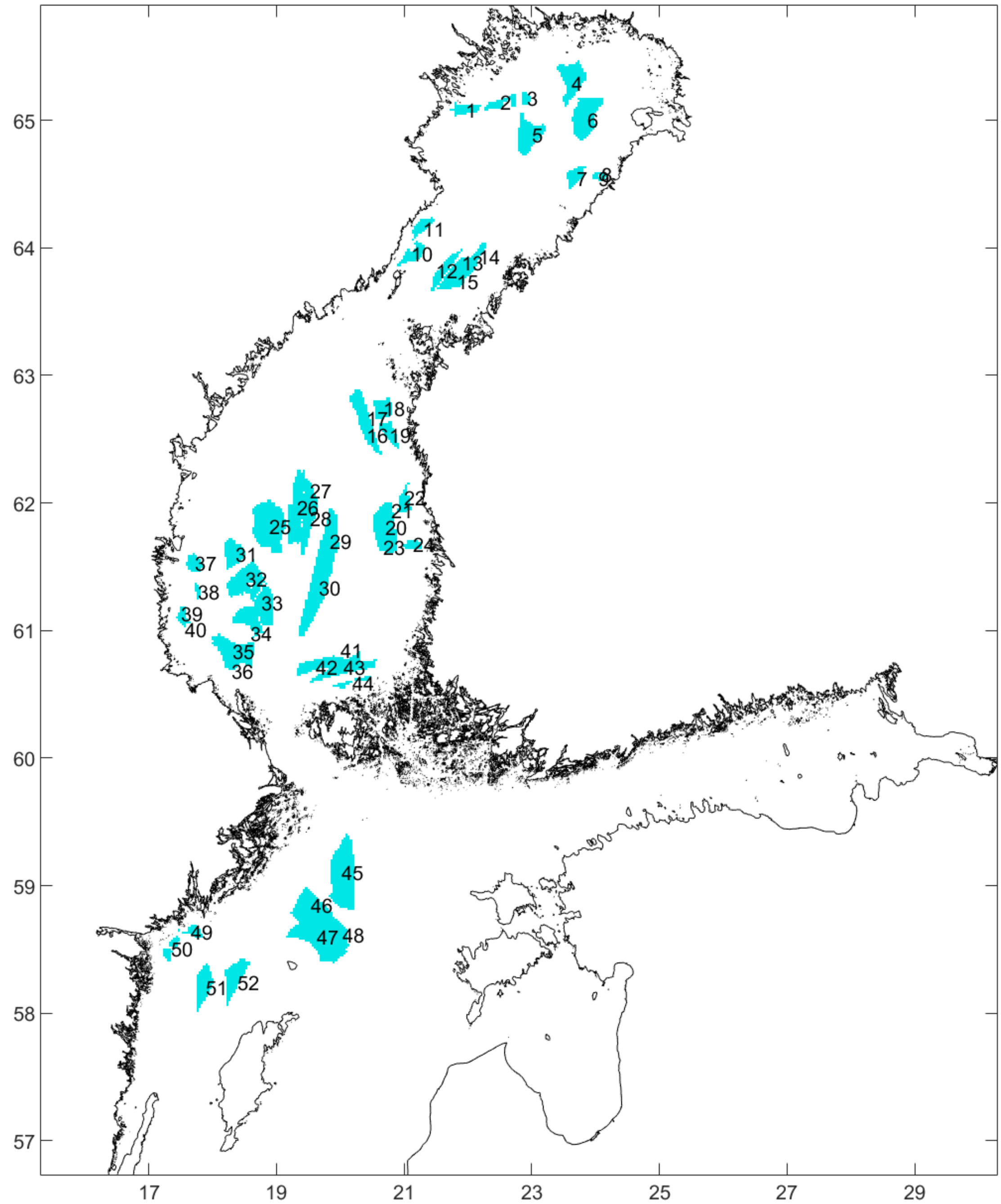


Figure 1: The envisioned wind farms in the Northern Baltic with numbering from Table 2.

3.2 Winter navigation in impact assessments

The impact assessments for the Northern Baltic OWFs include also the assessment of the impacts on the ship traffic as a part of the general assessment report and often also as specific reports. The assessment is presently under way for a considerable number of farms and also completed for several cases. All documents for both Finnish and Swedish farms are easily found from the website of the Finnish Environment Institute (www.ymparisto.fi) with the name of the farm. Three completed assessments from the Bay of Bothnia were inspected for their coverage of marine traffic issues in general and specifically of winter navigation. Polargrund (number 4) and Halla (number 6) are located adjacently to each other in the northern midbasin in Swedish and Finnish waters, respectively. Halla is located in the middle of an area with high wintertime traffic density and complicated icebreaker operations, while Polargrund is expected to have less impact on winter navigation. However, taken together the two farms create a large OW development area separated by a traffic corridor. Laine (number 13) locates in southern midbasin, north of Quark. It belongs to a group of four planned farms in the same area that is one of the areas with higher traffic density in the basin. Also wintertime traffic reroutings are typical for the area.

All assessments address the commonly recognized risks summarized in Section 2.1. and generate the risk matrices and other quantifications following internationally accepted methodologies. Different types of collisions, allisions and groundings and associated chains of events are considered. The basic traffic statistics for different ship types and sizes are presented, and the ice winters and ice conditions are characterized. A considerable part of the assessments is description of methods, concepts, shipping statistics, environmental conditions, and expected future changes in conditions and traffic, which is common background for all wind farms in the Bay of Bothnia. Such material could have been collected into a report made available for assessment preparation purposes. This would have also improved the intercomparability of the results as now they each follow their own methodologies with respect to conditions, traffic patterns, and their interaction. The ice condition data in the reports is mainly descriptive and the climatological ice data is missing or, when available from other sources, not used, that is, statistics of ice concentration, thickness, deformation degree etc. with descriptors like maximum and minimum values, average, variance, etc. The impacts of wave conditions are not discussed, although the ice edge zone under wave action is one of the more risky combinations of conditions. A common result of wind and wave action and a difficult obstacle of navigation, the brash barrier (windrow), is not considered.

The same applies to traffic analyses from low-frequency AIS data covering typically one year only. The traffic intensity maps are shown and certain quantitative descriptors calculated like traffic flow through selected control surfaces. This backs semiquantitative discussions on how the OWFs impact the wintertime navigation when the ships and convoys are not free to select the easiest route to destination. The possible changes in ice conditions following the interaction between OWFs and the moving ice cover are also discussed. The result is usually the recognition of different scenarios serving as bases for further discussions. The Polargrund assessment includes some more informative scenarios that describe the route patterns for a single ship on regular route during a year, and the opening of leads with wind blowing from four cardinal directions. In the Laine assessment the icebreaker and commercial vessels are described separately. However, the approaches of the assessments do not allow quantitative analyses on the impact of winter navigation and this is not attempted either. It is also stated that the results from risk modelling tools (IWRAP) do not apply for ice season. In the Halla assessment it is stated that cost-benefit analysis does not belong to the scope, but this should not prevent analyses in terms of increased travel time, for example.

Some risks are not considered. The risks for the servicing vessel are not included, as these are considered internal for the OW companies. However, a servicing vessel beset within a turbine grid may need icebreaker assistance, or it may drift from the grid to a shipping lane. How the OWFs would increase oil accident risks and hamper oil combatting is also outside the scope. Although icebreaker assisting occurs mostly in convoys, known to be prone to collisions and other risks, these are not mentioned in the assessment reports. This somewhat undermines the collision and allision risk analyses.

4. Ice conditions and coastal leads

4.1 Charted ice thickness and coastal leads

Climatological ice data characterizes the ice conditions and their variation for an extended number of years. Climatological charts were calculated from daily ice charts and from satellite data. The ice charts covered 26 winters 1980-2005 and were digitized from original graphic charts into gridded format in 1 NM resolution. The average conditions calculated from the chart series can be interpreted also in terms of probability or expectation. The average duration of the ice season (Figure 2a) is the expected duration of ice season at a location, and the average thickness (Figure 2b) is the expected thickness at a location on the condition that ice is found.

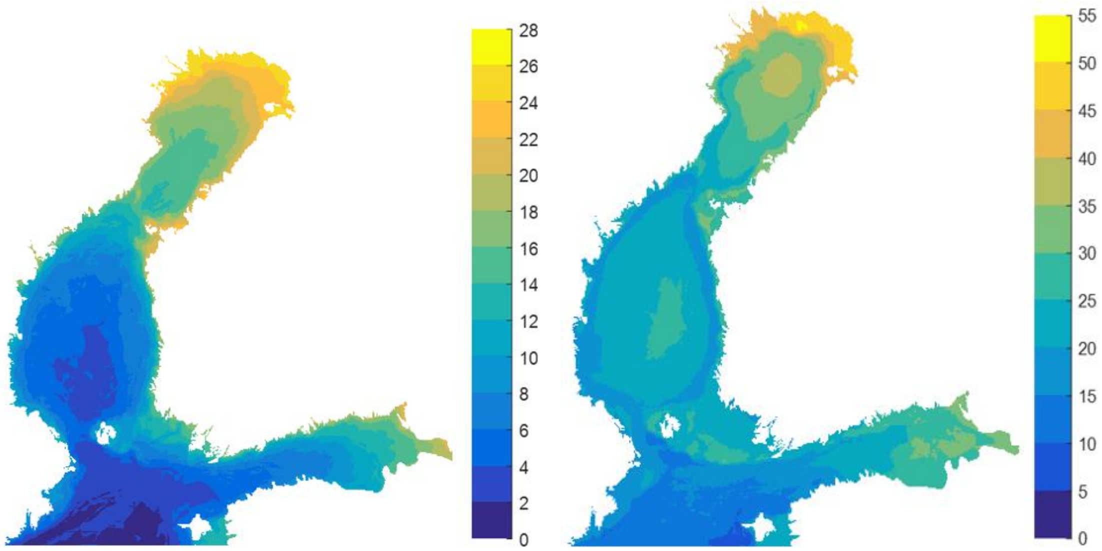


Figure 2. a) Average duration of ice season (weeks). b) Average ice thickness.

Coastal leads are of principal importance for the winter navigation system and for the OWF coexistence problem. In a very concrete manner the ships and OWFs compete for ownership of the leads. The presence of coastal leads is seen in Figure 2b where the opening of the leads and the thinner ice of refrozen leads reduce the average thickness along the coasts. In the Sea of Bothnia this feature is quite similar on both sides of the basin while in the Bay of Bothnia it is more pronounced on the Swedish side. This is due to the prevailing SW direction of stronger winds during mild winters when the Sea of Bothnia does not freeze over.

A better quantification of coastal leads is obtained by persistence measures. Ice cover persistence is defined as the number of ice days at a location divided by the length of ice season at the location (days from first to last day when ice is found), Figure 3a. Thus in the Sea of Bothnia the recurring coastal leads are ice covered only half of the total time when ice is found in the area. In the Bay of Bothnia a better description is obtained by considering the persistence of thicker ice types. The costal zone need not be ice free or have low concentration to provide the best routing option, it is sufficient that the ice is thinner than for the other route options. This applies especially to refrozen coastal leads. In Figure 3b the case for ice exceeding 30 cm in thickness is shown, that is, the number of days when ice at least 30 cm thick is found divided by the period from first to last instance of at least 30 cm thick ice. As a summarizing conclusion, coastal leads that are either ice free or covered by thinner ice types are found about 50% of the time at most coastal locations.

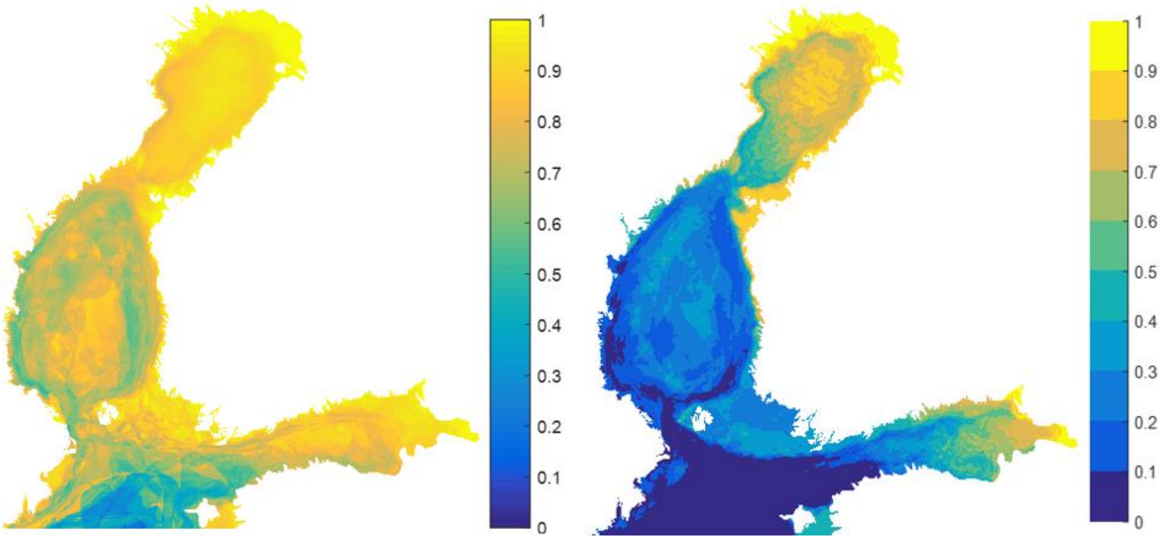


Figure 3. a) Ice cover persistence during ice season; the number of ice days at a location divided by the length of ice season at the location (days from first to last day when ice is found). b) Persistence of ice exceeding 30 cm in thickness.

4.2 Coastal leads from ice models

The occurrence of leads is investigated using Copernicus Marine Services (CMS) Baltic Sea physics reanalysis product (BALTICSEA_MULTIYEAR_PHY_003_011). This product provides a reanalysis for the physical conditions for the whole Baltic Sea area, including the Transition Area to the North Sea, from January 1993 and up to about 1-1.5 years behind present. The product is produced by using the ice-ocean model system Nemo; the Nemo version 4.0 is used in combination with the sea ice and thermodynamic model SI3. The used dataset here includes one daily sea ice parameter: sea ice concentration (SIC). The spatial resolution is 1 nautical mile (delta latitude is 1' and delta longitude is 1'40''). The temporal range of the data is from January to April in 1993-2021, i.e. 29 years time span (1993 earliest data available and 2021 latest data).

Using the reanalysis product leads are identified with SIC dropping below 80%, and closing of leads happening when SIC raises again to over 80%. This way low concentrations in the beginning and late ice season are not counted as leads. The shape of a lead is not mapped, it can be from narrow curvilinear feature to circular opening in the ice pack. Leads can be between ice pack and fast ice or ice-free coast, or within pack ice only. Lead statistics, i.e. climatology, are investigated in the following way. For each pixel daily presence of leads is determined which results in number of lead days in an ice season (2D matrix). Next, seasonal matrices (29 in total) are averaged to give mean fraction for lead occurrence in a pixel. Multiplying the lead fraction with a time span, e.g. number of days in Jan-Apr, gives the average number of days a lead is present.

Figure 4 shows lead fraction climatology for the Bay of Bothnia and northern part of the Sea of Bothnia together with areas of planned off-shore wind farms north of 62.3N. The highest lead fractions are concentrated in the coastal areas and in the Quark area. In the middle of the basins, lower fractions are present. The lowest fractions are found within land fast ice. Only few wind farms are located in areas of high lead fraction. Next, lead fractions are calculated for three different Baltic Sea ice seasons: severe (one ice season, 2011), normal (13 seasons) and mild winters (15 seasons), see Figure 5. During the severe ice season there is noticeable average lead fraction in the Bay of Bothnia only along narrow stripes on the east and west coasts. Within the wind farms the mean lead fraction is up to 0.15, but there are wind farms with zero lead fraction, see Figure 5a. The lead fraction for the normal ice season shows frequent lead occurrence along coastal areas of the Bay of Bothnia and northern part of the Sea of Bothnia. This is the case also for the mild ice season, but with wider areas of large lead fraction in the Bay of Bothnia. The lead fraction in the Quark is high both in the normal and mild seasons. For the wind farms during normal season the mean lead fraction is typically small, below 0.10. The maximum lead fraction is around 0.14. During the mild season the maximum lead fraction is 0.17 for the wind farms. The lead fraction for the wind farms is typically slightly larger for the mild season than for the normal season, see Figures 5b and 5c.

Finally, lead fractions are presented as monthly figures, see Figure 6. In January the lead fraction is quite high along the west coast of the Bay of Bothnia. February and March show high lead fractions along the east and west coast of the Bay of Bothnia and in the Quark. In Jan-Mar there are high lead fractions along the east coast of the Sea of Bothnia. In April the lead fraction has slightly elevated values over wide areas of the Bay of Bothnia.

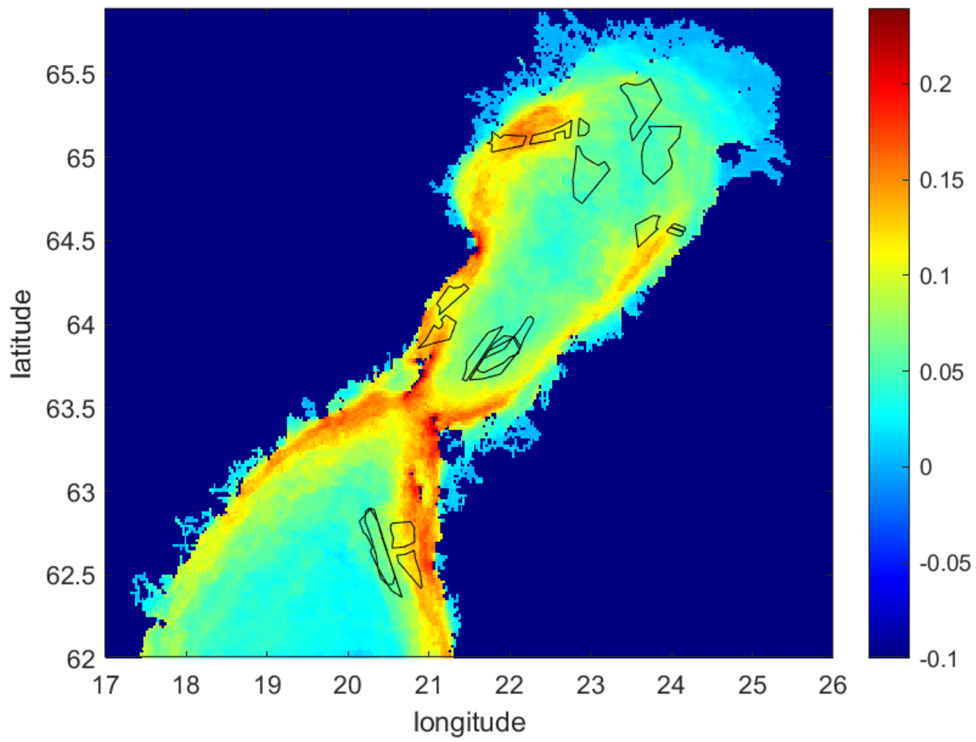
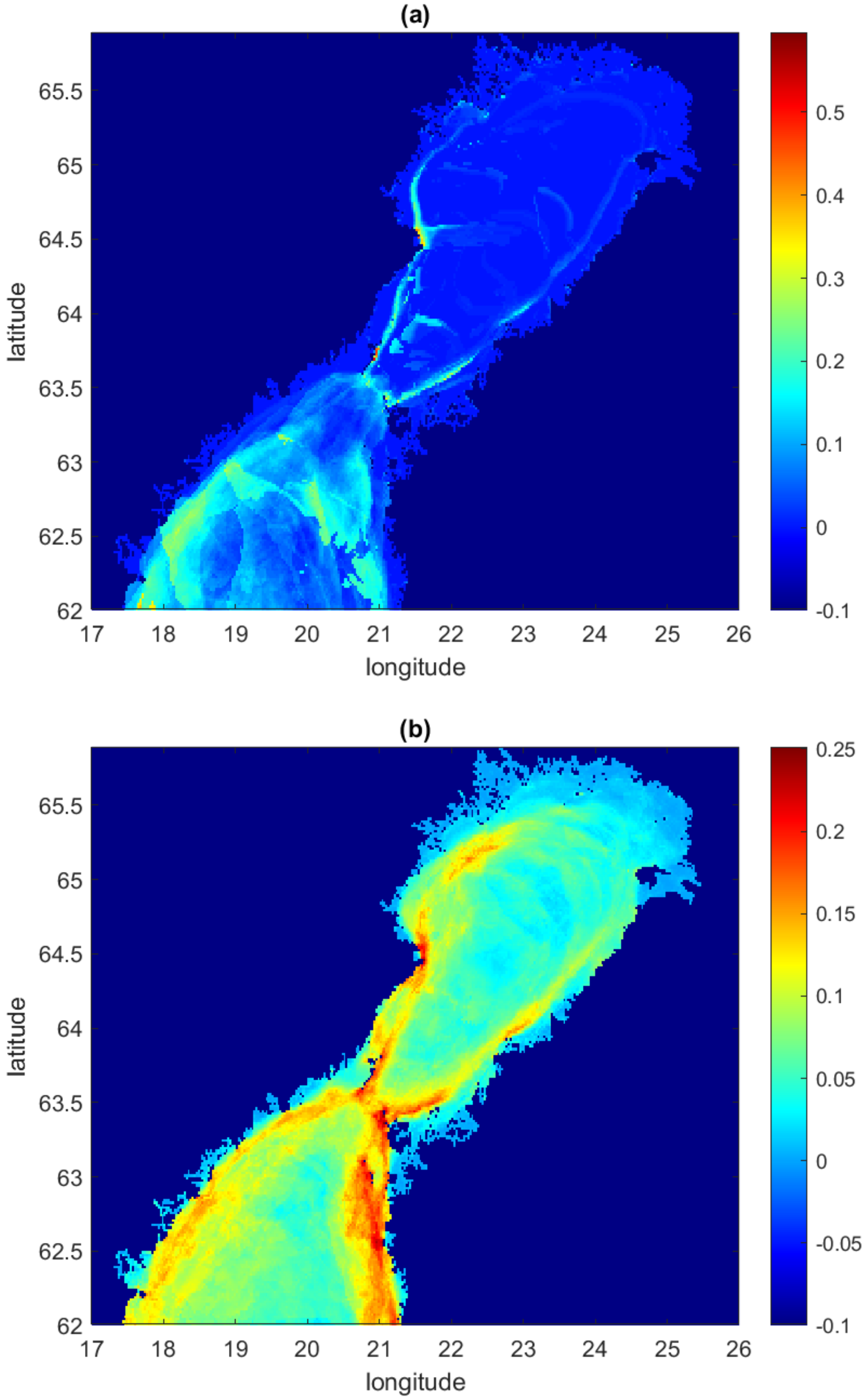


Figure 4. Mean lead occurrence fraction in Jan-May 1993-2021 using the CMS reanalysis product. Planned off-shore wind farms north of 62.3N are also shown. Land mask has value of –0.1.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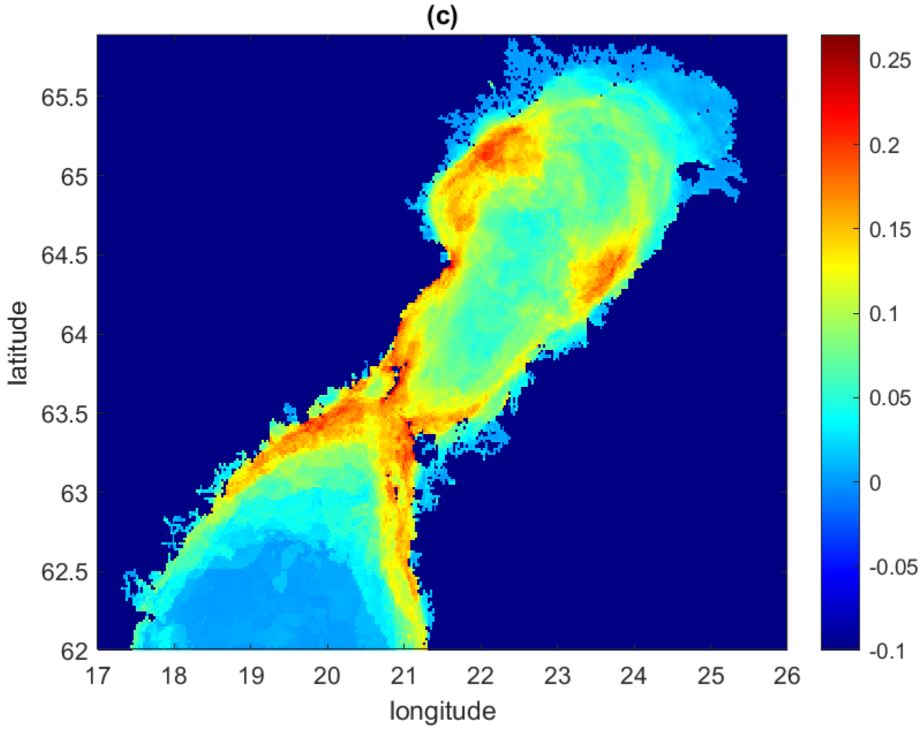

Figure 5. Mean lead occurrence fraction for (a) severe ice season, (b) normal ice season, and (c) mild ice seasons. Calculated using the CMS reanalysis product for Jan-May 1993-2021.

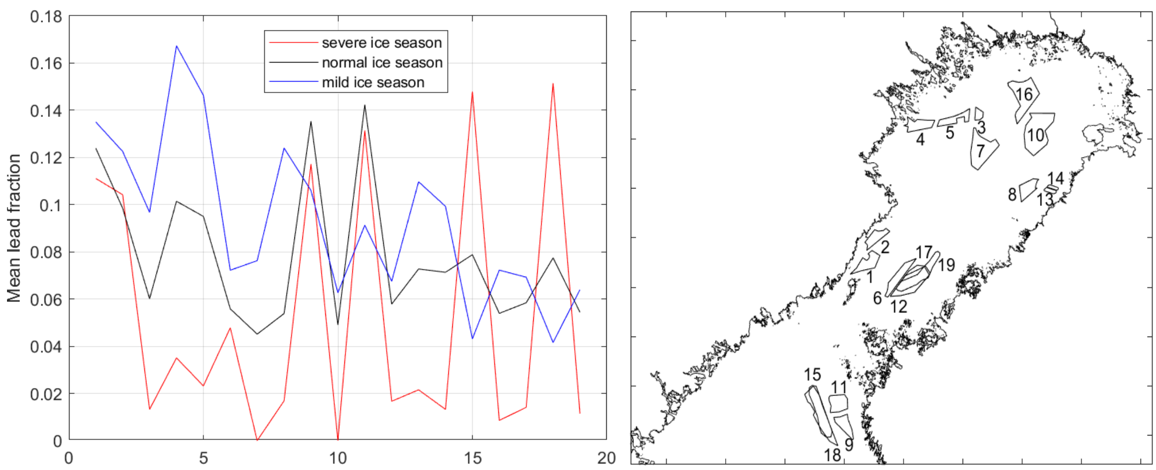

Figure 6. Mean lead occurrence fraction for the wind farms during severe, normal and mild ice seasons. Calculated using the CMS reanalysis product for Jan-May 1993-2021.

4.3 Modeled sea ice thickness

The thickness values in ice charts refer to level ice and slightly deformed ice like rafted ice. Most midbasin thickness data is from icebreaker observations from upturning ice blocks and occasional thickness drillings. Ice ridges are not quantified in the charts by their size or by the average thickness of ridged ice but only by semi-qualitative numerals combining the frequency of occurrence and size of the ridges. More realistic thickness data is obtained from ice models that can describe, due to mass conservation, how thinner ice types are deformed into thicker ones.

Sea ice thickness (SIT) statistics within the wind farms is first investigated using daily ice thickness field from the CMS Baltic Sea physics reanalysis product. Using the SIT data for 29 ice seasons daily mean SIT for 1 Jan to 31 May was calculated, see example in Figure 7. Next, daily mean SIT was calculated for each wind farm, see Figure 8. There is large variation of the mean SIT for the wind farms, some have mean SIT at maximum only 25 cm (farms at northern part of the Sea of Bothnia) whereas others (farms at northern part of the Bay of Bothnia) have mean SIT values close to 1 m.

Next, SIT statistics within the wind farms is investigated using manual ice chart which shows level ice thickness for polygonal areas. The temporal range of the ice charts was chosen to be Jan – May 2015-2024, i.e. ten ice seasons. The resolution of rasterized ice charts is around 1 km. Using the charts ten year daily mean SIT was calculated, see example in Figure 9. SIT values here are much smaller than in Figure 7 because the ice chart shows level ice thickness whereas the reanalysis product has level + deformed ice thickness. Daily mean SIT was calculated for each wind farm, see Figure 10. During Jan the mean level SIT is small for all wind farms, below 15 cm. The maximum SIT occurring in Mar-Apr is below 35 cm. For the wind farms in northern part of Sea of Bothnia the mean SIT is at maximum only 6 cm.

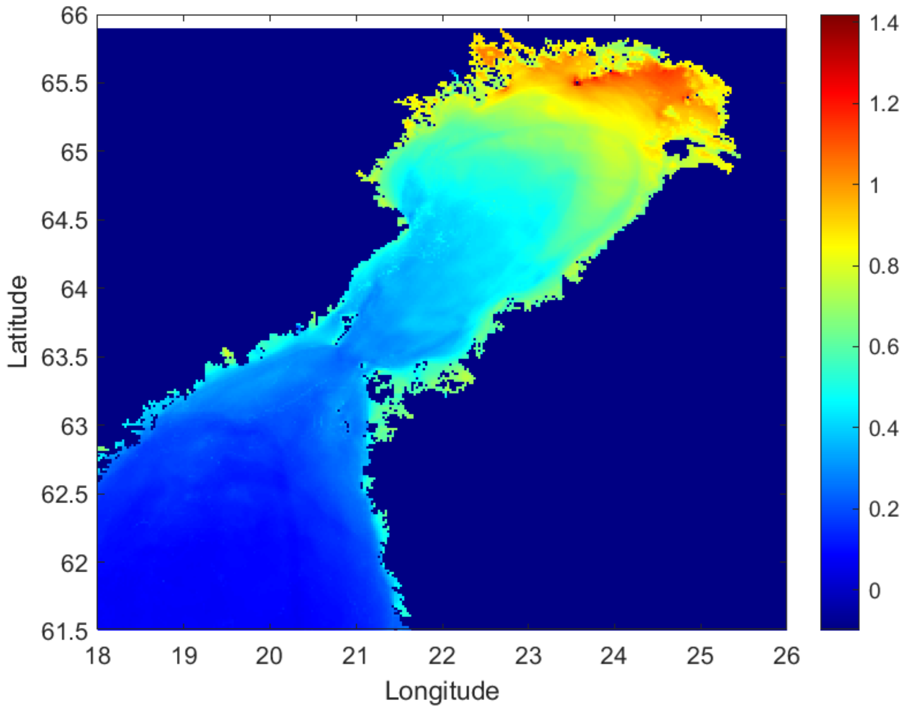

Figure 7. Daily mean sea ice thickness on 1 March calculated using the CMS reanalysis product for Jan-May 1993-2021.

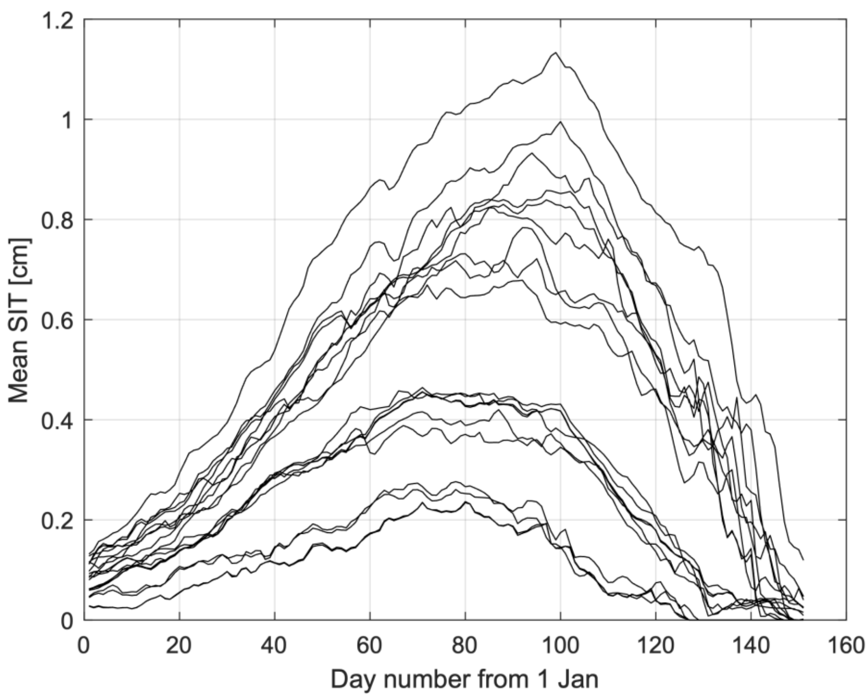

Figure 8. Daily mean sea ice thickness from 1 Jan to 31 May for the wind farms. Calculated using the CMS reanalysis product for Jan-May 1993-2021.

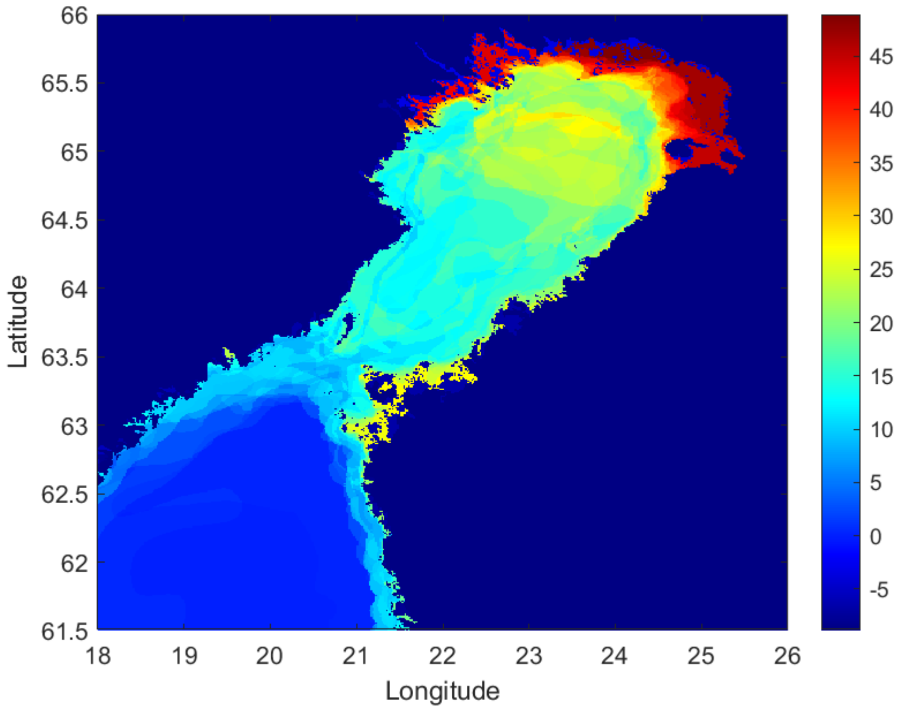

Figure 9. Daily mean sea ice thickness on 1 March calculated using the ice chart thickness data for ten ice seasons in 2015-2024.

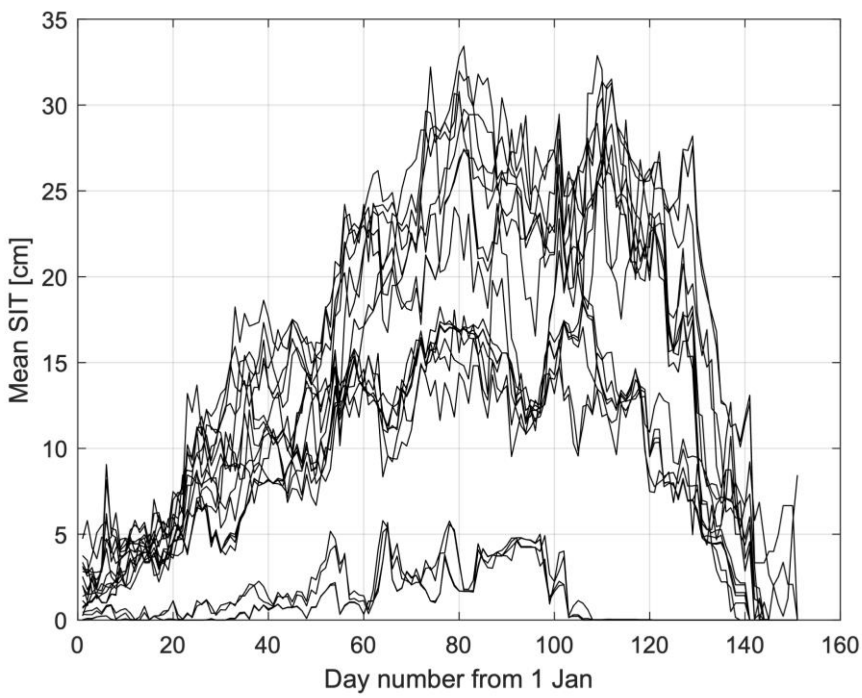

Figure 10. Daily mean sea ice thickness from 1 Jan to 31 May for the wind farms. Calculated using ice chart thickness data for ten ice seasons in 2015-2024.

4.4 Ice drift statistics from SAR images

Ice drift in the Bay of Bothnia is investigated using synthetic aperture radar (SAR) based drift product (SEAICE_BAL_SEAICE_L4_NRT_OBSERVATIONS_011_011/ FMI-BAL-SEAICE_DRIFT-SAR-NRT-OBS). An ice drift chart is produced after receiving two SAR images over the same area in the Baltic Sea with a time gap of less than three days between the SAR images. Each received SAR image is studied after it has been received, and if it has common areas with an earlier SAR image less than three days older, an ice drift chart is computed. The images can currently be either from Sentinel-1 (EW mode), Radarsat-2 or RCM (SCW mode). The drift estimates between pairs of images from different instruments (mixed pairs) are also computed. The product is based on computing the phase correlation of pairwise data windows sampled from two images in two resolutions. In the coarse resolution the large-scale motion is located and in the fine resolution these motions are refined. In the SAR areas without features suitable for computation of correlation the drift is not computed. Such featureless areas include level ice areas and open water. The product gives estimates of the ice drift between the images, these are naturally just estimates of the integrated ice trajectories between the time instants corresponding to SAR acquisition times. The results are given in 800 m resolution, which is half of the window size (16x16 pixels for a SAR image with a pixel size of 100 m). The ice drift displacement can be converted to average ice drift speed between acquisition of the SAR image pairs. Drift data were collected for six ice seasons, Jan-Apr 2019 to 2024. The drift data were rectified to a fixed lat-lon grid with 0.5 minutes pixel size, and average drift speed (m/s) was calculated (from six ice seasons of data), see Figure 11. The drift speeds in the Bay of Bothnia are small, typically below 0.1 m/s, whereas in the Quark there are speeds over 1 m/s. The average drift speed on the wind farms is only from 0.04 to 0.14 m/s. The 95 percentile drift speeds are somewhat higher, from 0.09 to 0.38 m/s. The average drift speed in Figure 11 shows spatial artefacts due to spatial variation of SAR swath based drift speeds.

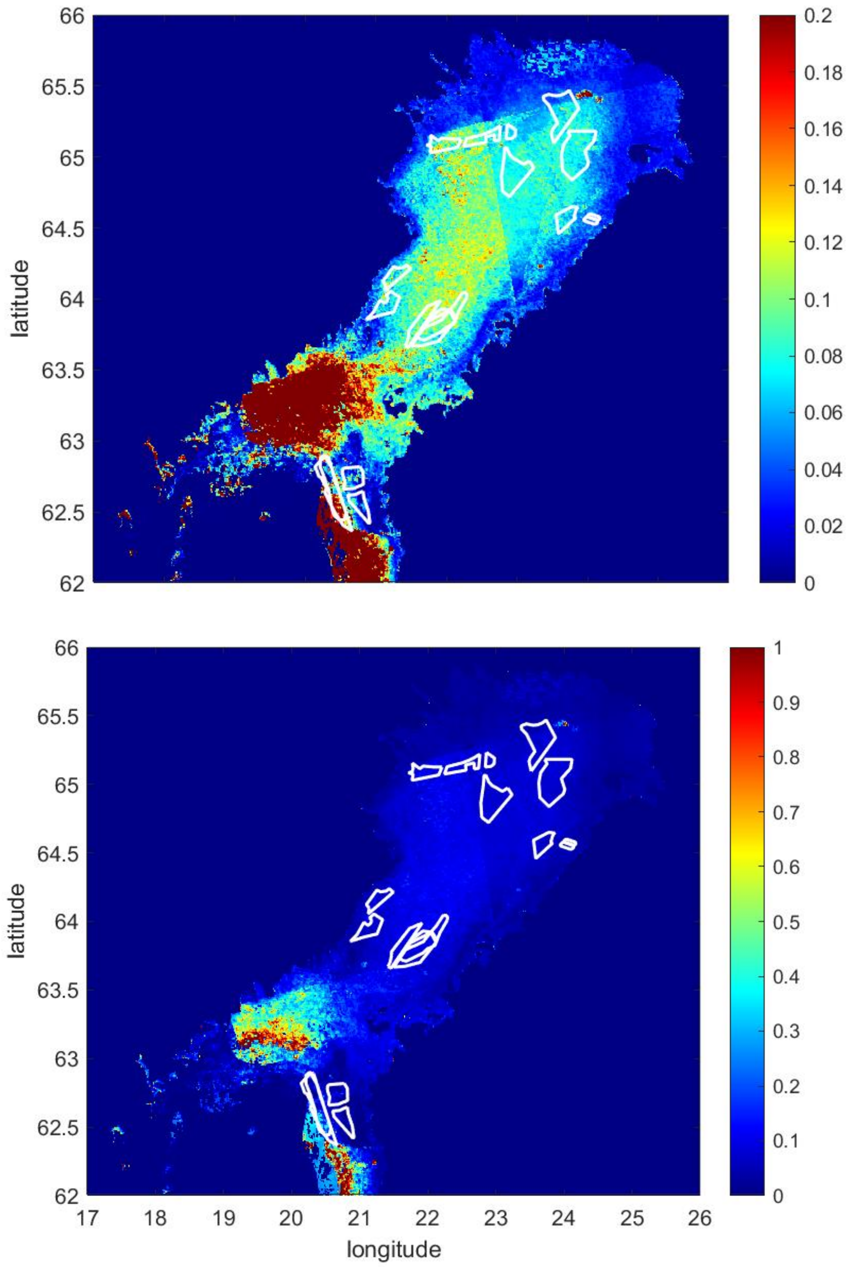

Figure 11. a) Average pixel-wise ice drift speed (m/s) calculated from SAR drift data for six ice seasons, from Jan-Apr 2019 to 2024. Pixel size is 0.5 minutes. b) Double scale used to differentiate speed variation in the southern part of the chart.

4.5 Lead formation and deformation in the coastal zone

Ice cover stresses increase with wind speed and wind fetch. When the stresses exceed ice cover compressive strength, the ice fails and deforms, usually by ridging. If the wind direction is offshore then in small basins like the Bay of Bothnia the ice typically compresses close to the opposite, onshore wind side of the basin. As the tensile strength of ice cover is low, a lead may open up on the offshore side although the wind fetch is short and stresses thereby low. This may happen along the fast ice edge or somewhat further away if ice ridge keels anchor the pack ice to the bottom.

A common cycle is that a coastal lead is created and then frozen over during a colder and less windy period. This is followed by stronger wind from the opposite direction that deforms level ice cover of the lead, opening up a new lead at the opposite side of the basin. The cycle may repeat several times during the ice season and results in typical bandlike zones of thick deformed ice aligned with the fast ice edge.

The thickness of such coastal deformation zones is not reported in ice charts and is not well captured by ice models either but have been measured by electromagnetic (EM) thickness sounding flights and field measurements. In Figure 12a the dense pattern of EM flights starting from Kokkola reveal the extent of the deformation zone with thicknesses exceeding 2 m. In Figure 13 the ice thickness exceeds 4 meters over 5 km distance. This is not a result from the closing of a lead but from an extreme deformation event in the Sea of Bothnia. The 12 m deep coastal ridge in Figure 12b was compressed from 2600 meters of uniform level ice, and the deepest ridge measured in the Baltic (28 m) was reported to be a result of closing coastal lead.

The interaction of OWFs with the coastal opening/deformation processes is yet to be modelled. However, the following alternatives to the usual course of events can be conceived.

- The wind fetch from fast ice to an OWF may not be sufficient for the offshore wind to drive the coastal ice cover through the turbine grid. The lead does not form on the shore side of the OWF.
- In the preceding case, the lead may open up on the far side of the OWF. However, as the wind fetch to the opposite side of the basin is shorter, the frequency of such events is smaller.
- In the case of onshore wind and coastal lead opening on the opposite side of the basin, the ice may be driven through the turbine grid and a deformation zone forms between the OWF and fast ice. On the other hand, the thick deformed ice

type is then more difficult to drive back when the wind turns offshore which may prevent further lead formation.

- The ice may also deform and accumulate inside the turbine grid and, after consolidating, prevent the opening of a coastal lead.

Palosuo, E. (1975). Formation and Structure of Ice Ridges in the Baltic (Winter Navigation Research Board, Rep. No. 12). *Board of Navigation, Helsinki*.

Nyman, T., Riska, K., Soininen, H., Lensu, M., Jalonen, R., Lohi, P., & Harjula, A. (1999). The ice capability of the multipurpose icebreaker Botnica-full scale results. In *15th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'99* (pp. 631-643). Helsinki University of Technology.

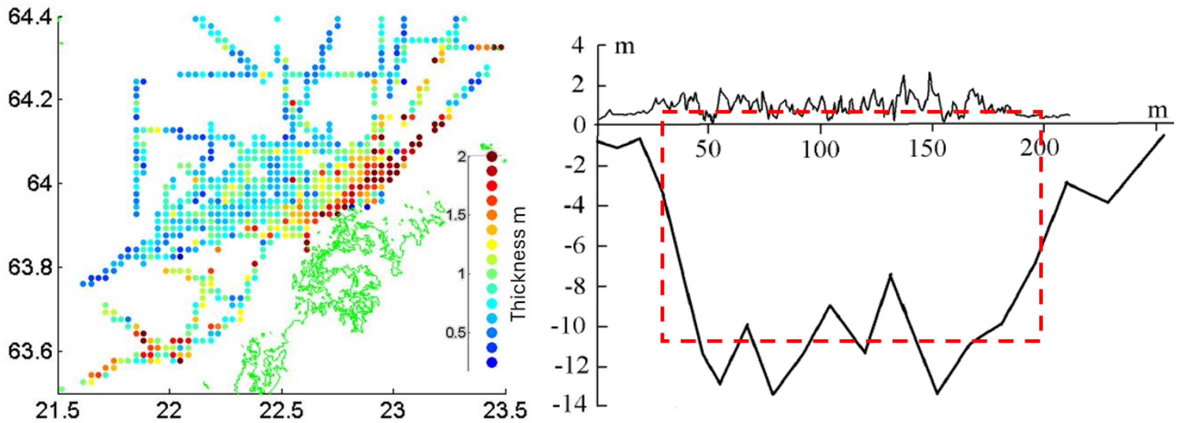

Figure 12: a) Thickness of coastal deformation zone as measured by electromagnetic sounding. The thickest ice area is located by the Kokkola lighthouse. b) Large ridge formation in the coastal deformation zone.

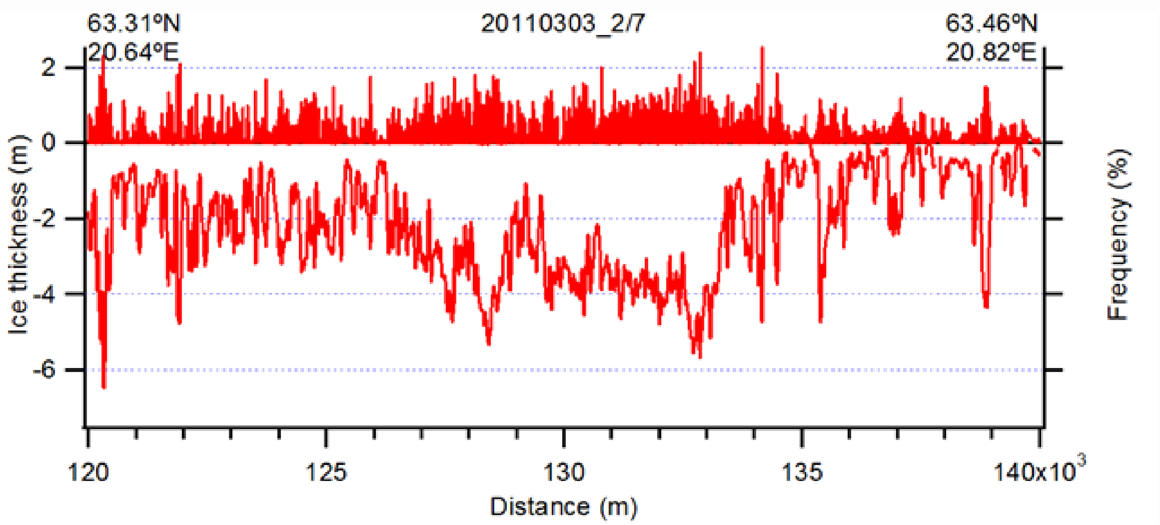

Figure 13. Thickness profile from electrogmagnetic sounding (Southern Quark).

5. Traffic analysis

5.1 Data sources

The ship traffic density data was obtained from a database combining AIS-retrieved ship navigation data and ship particulars data with environmental parameters (Lensu and Goerlandt 2019). From the database subsets can be extracted by conditions set in terms of AIS data (ship identity, location, speed,...), ship parameters (type, iceclass, length,...) and environmental parameters. The AIS data are full update rate (~ 10 second interval) messages from Finnish terrestrial stations. The AIS data covers completely the Bay of Bothnia, Gulf of Finland and Northern Baltic Proper. On the other hand, Gulf of Bothnia close to the Swedish coast, the Baltic Sea south of Nothern Baltic Proper, and Gulf of Riga have intermittent AIS data coverage due to variations in VHF transmission conditions.

Since a major purpose of the database has been winter navigation system analysis, the main environmental data sets consist of daily ice charts and 6-hour HELMI ice model forecasts. To capture the ice seasons, the navigation year extends from the beginning of July to the end of June next year. The database has been completed for nine navigation years as in **Table 3** while later data has been only partially processed. The average ice conditions and cumulated ship traffic over the 9-year period are in **Figure 14**. Ship particulars data are obtained from listing that contains 96111 ships, i.e. rows in the list.

Table 3. Temporal coverage and the number of AIS position reports (millions of reports, Lensu and Goerlandt 2019)

Navigation year	Data coverage %	Reports, navigation year	Reports, ice season	Max ice extent 1000 km^2	Ice winter characterization
2007-2008	62	477	211	49	Extremely mild
2008-2009	81	663	274	110	Mild
2009-2010	81	637	262	244	Average - severe
2010-2011	79	722	385	309	Severe
2011-2012	75	706	262	179	Average

2012-2013	76	718	376	177	Average
2013-2014	78	797	350	100	Mild
2014-2015	66	629	267	51	Extremely mild
2015-2016	45	413	147	110	Mild
Overall	73	5,762	2,534		

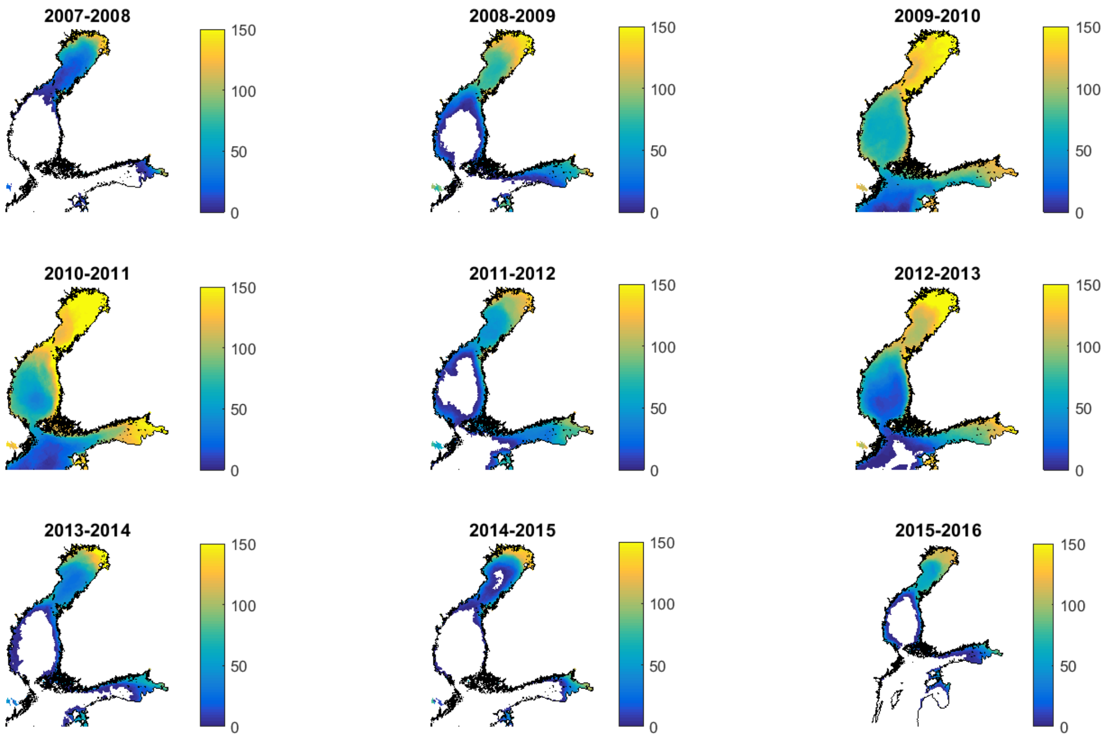

Figure 14. The durations of the ice seasons in the database (Lensu and Goerlandt 2019).

Reference:

Lensu, M., & Goerlandt, F. (2019). Big maritime data for the Baltic Sea with a focus on the winter navigation system. *Marine Policy*, *104*, 53-65.

5.2 Types of traffic analyses

The database can be used for different types of analyses related to the navigation system. For the ship traffic and offshore wind farm coexistence the principal ones are trajectory analysis and density analysis. The density analysis considers the ship occurrence in the planned OWF areas and can be used for basic estimates of the areal impact of the OWF to the navigation system. Trajectory analysis can be used to study the impact of the farms on routing of individual ships and ship classes.

The main auxiliary functionality is ship-ship proximity detection. In a simple version this is binary, that is, ships that are proximate/not to some other ship (known or unknown) are identified. Figure 15 illustrates the different characteristics of ice transit and open water transit in terms of the proximity relation. In open water transit the proximity is forced by overall traffic density, while for ice transit ships prefer to proceed in groups. These are not only in convoys led by an icebreaker but often as groups where weaker ships follow more ice-worthy ships, usually those belonging to ice class 1A Super.

In full version of the proximity all ship traffic is partitioned into groups where all ships are connected by chained proximity relation (e.g. an icebreaker convoy) or are singletons (group of one ship). This is done for all time instances so that for any group it can be followed how it combines with other groups or is split into smaller groups. This provides a complete breakdown of the winter navigation system events but is a too advanced tool for the purposes of general characterization in this report.

On the general level, outside the ice navigation season the trajectory analysis provides little additional information to gridded analyses as the future traffic will bypass the OWFs along evident routes. This will change the traffic densities and increase travel times in an unproblematically foreseeable manner. During the ice navigation season, in a simplistic picture, ships seek to find the best route to the destination across variable ice conditions. This involves the minimization, typically manifesting only as an expert's estimation, of a cost function defined in terms of travel time, fuel consumption, besetting risk etc.

However, during ice navigation season it is rather the Northern Baltic traffic system that constantly adjusts itself to the ice conditions and seeks to not only locate the best routes to the destination for each ship but find the optimal solutions for the whole system. This involves also anticipating changes in ice conditions in the near future. The systemic features are dominated by icebreaker assistance configurations as only a fraction of the ships can proceed to the final destination without assistance, and the icebreakers seek to maintain a network of meeting points and ice channels for the purpose. It is clear that any OWF in navigable waters will in some situation obstruct the optimal arrangement of this network.

This first part of the traffic analyses considers the long term traffic density statistics both for the open water and ice transit. The second part will study specific problems of winter navigation, basing on case studies and selected periods with difficult ice conditions.

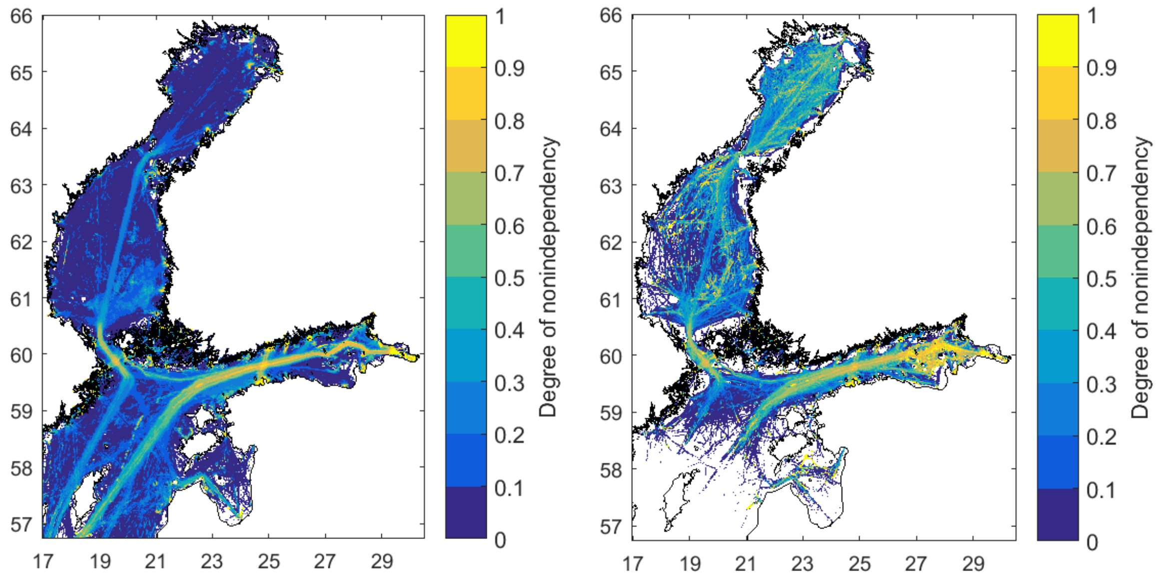

Figure 15. The degree of nonindependency (fraction of ships proximate to some other ship) for a) open water transit and b) ice transit.

5.3 Traffic density

Gridded analyses and presenting of data utilizes the grid of the HELMI ice model. Its grid has 415 nodes in the *x* or from west to east direction, and 556 nodes in *y* or from south to north direction, in total 230704 nodes. The south/west lower corner coordinates are 16.7168 E 56.7416 N, north/east corner coordinates 30.4835 E 65.9916 N and the increment is 1/30 degrees eastwards and 1/60 degrees northwards. This is approximately 1 NM in both directions at 60N latitude, while the eastward increment decreases from 1.10 NM to 0.82 NM between the southern and northern bounds of the grid. However, in this report the grid cell area is assumed to be 1 square NM. The database is arranged by navigation days. The basic gridded data generated from the database is typically *(i,j,k)* where the *(i,j)* are grid cells and *k* relates to navigational and environmental data for a certain time period.

For the present analysis we use principally the *ship presence matrix* datatype that was generated for each navigation day present in the database. This is essentially a daily binary 3D matrix of size 556 x 415 x 96111 where *(i,j,k)*=1 if the ship with the row *k* in the ship listing has visited at least once in the grid cell *(i,j)* during the navigation day and 0 otherwise. The presence matrix datatype simplifies the description but still retains essential features of the traffic variation.

- For a single ship *k* the grid cells *(i,j)* with *(i,j,k)*=1 maps the ship's daily track in 1NM resolution, and restricting *(i,j)* to some region *R* (like an OWF) maps the track through the region.
- Summing further over ship list *k* gives the daily ship density in the cells of *R* (number of ships that have visited the cell).
- Summing instead over the *(i,j)* of the region *R*, the number of nonzero instances in the result gives the number of different ships that have visited the region.
- From the daily data, results for longer time periods up to the time span of the database (9 years) are obtained together with associated statistics (mean, variation).

The basic partition of the density matrix data was into the following three mutually exclusive classes:

- A Visits outside ice navigation season (no FMI ice chart for the day)
- B Visits during ice navigation season, but no ice transit
- C Visits with ice transit

The densities are defined as the average number of daily visits over a considered time period. For long term statistics the densities were summed over the nine years spanning the database. The densities can then be interpreted as the expected number of daily visits in a grid cell.

Outside the ice season (A) this expectation is very stable also for shorter periods (~month). For the ice transit data (C) the expectations depend on how the severity of the ice season has varied and how the ice conditions have varied in different regions of the Baltic basins. The 9 year period is not sufficient to generate proper climatological average of the ice conditions. The life span an OWF, about 30 years, might be sufficient if the effect of climate change is not accounted for.

However, unlike outside the ice season, the long term averages contain limited information on how the OWF would affect the winter navigation system. This is better studied by considering ice seasons categorized to different severity classes and considering how the traffic densities vary spatially during the winter. Combining this with the time series of ice season severity and the expected climatic changes the average expected effects can be estimated. This is done in the later sections of the report.

The presence of ice data affects also the open water transit during the ice season (B), for example in the typical situation when other half of a basin is ice covered while the opposite half is open water. Thus the B and C types of data must be used in the analysis when a basin is partially ice covered.

5.4 Observations of density variations

The overall average density (case A+B+C) is shown in Figure 16 and the same result for cases A, B and C are shown in Figures 17, 18 and 19. Certain patterns and hotspots are visible. The traffic congestion areas north of the Quark and after entering the Sea of Bothnia from the south are visible. Cases A and B are not much different but the ice transit case C already mirrors some typical patterns of the ice cover, for example the concentrating of traffic close to the coasts and avoiding the mid basin pack ice.

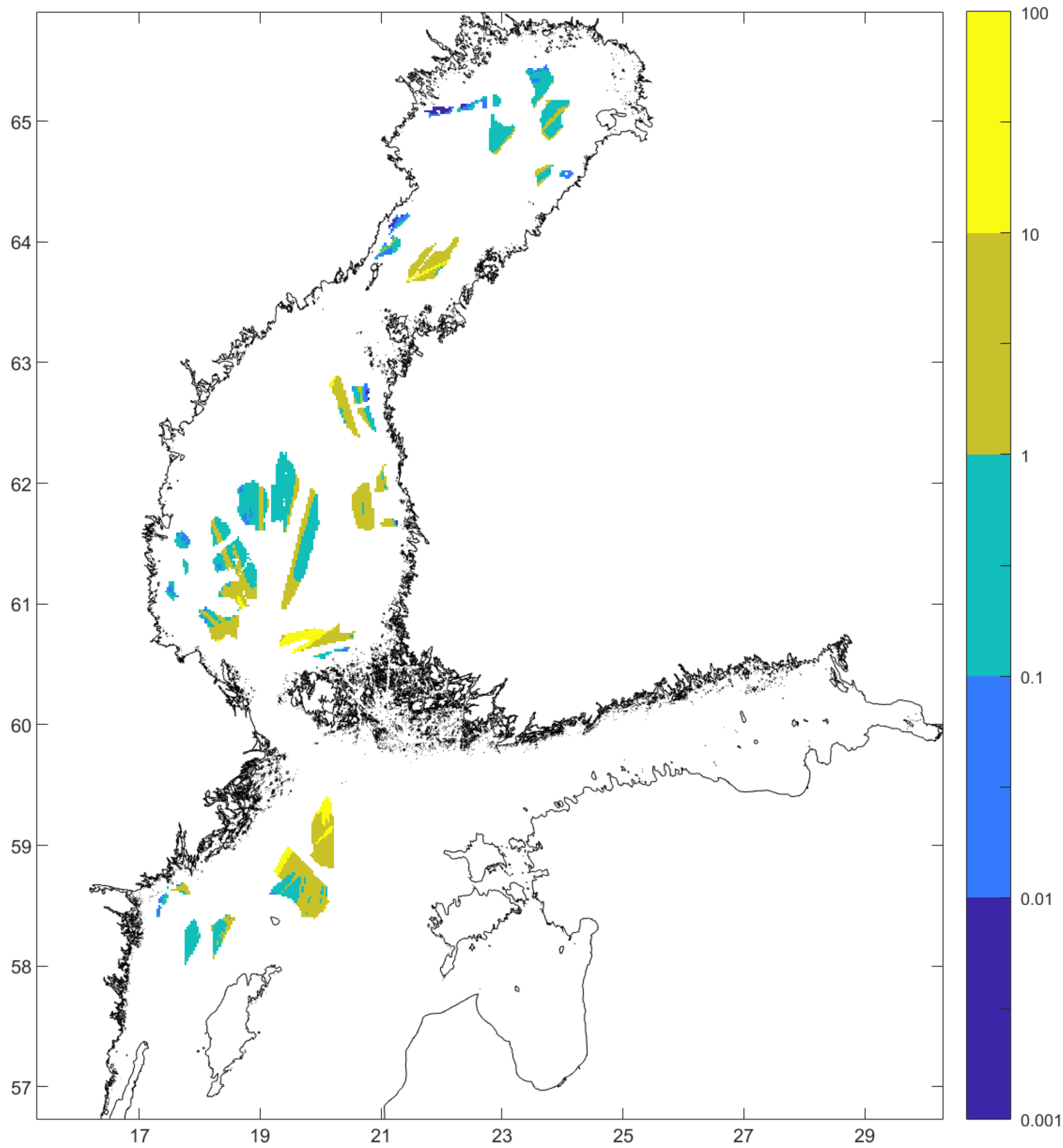

Figure 16: Expected daily number of different ships visiting a 1x1 NM cell (case A+B+C) average over 9 years).

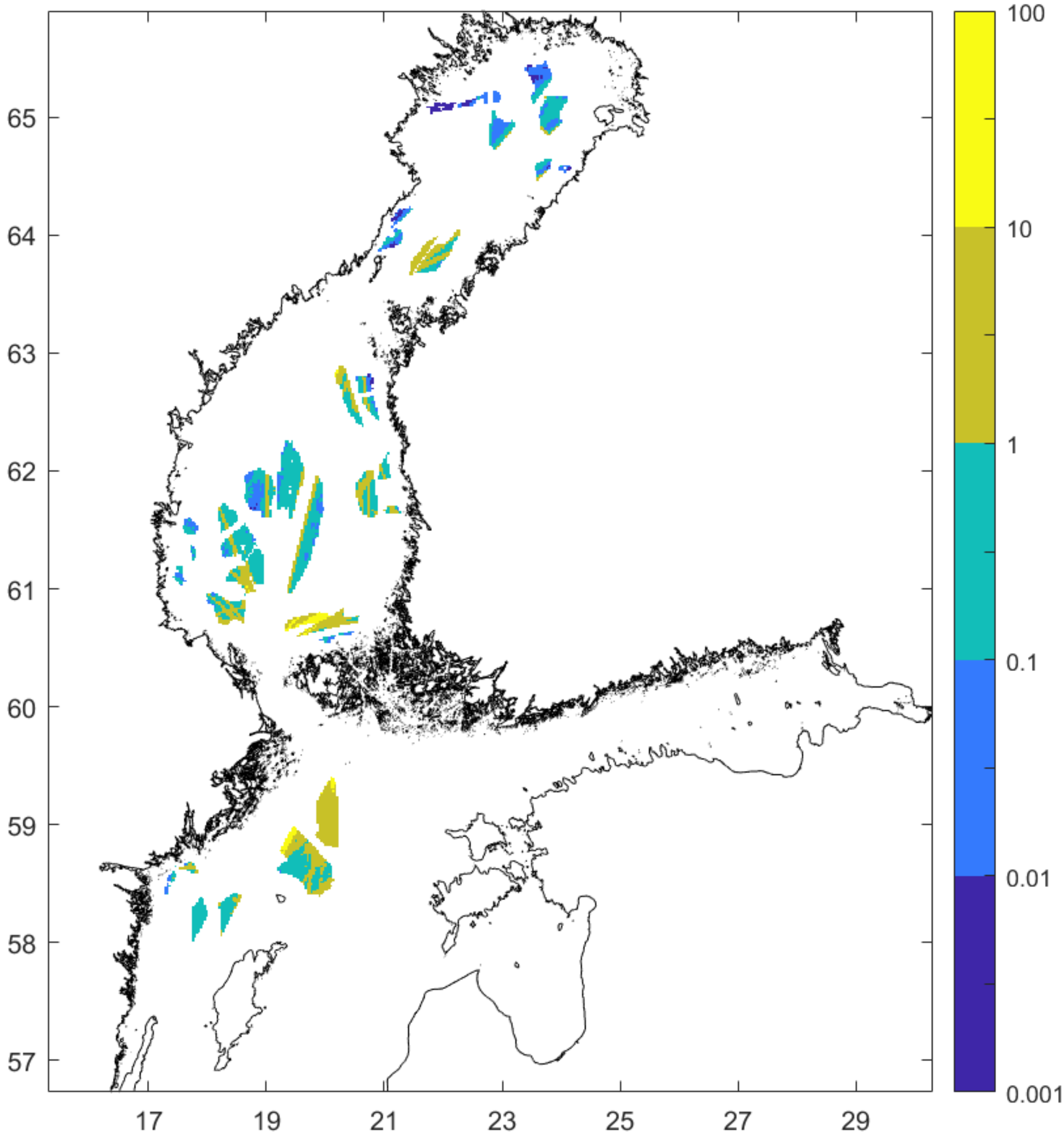

Figure 17: Expected daily number of different ships visiting a 1x1 NM cell outside ice navigation season (case A, average over 9 years).

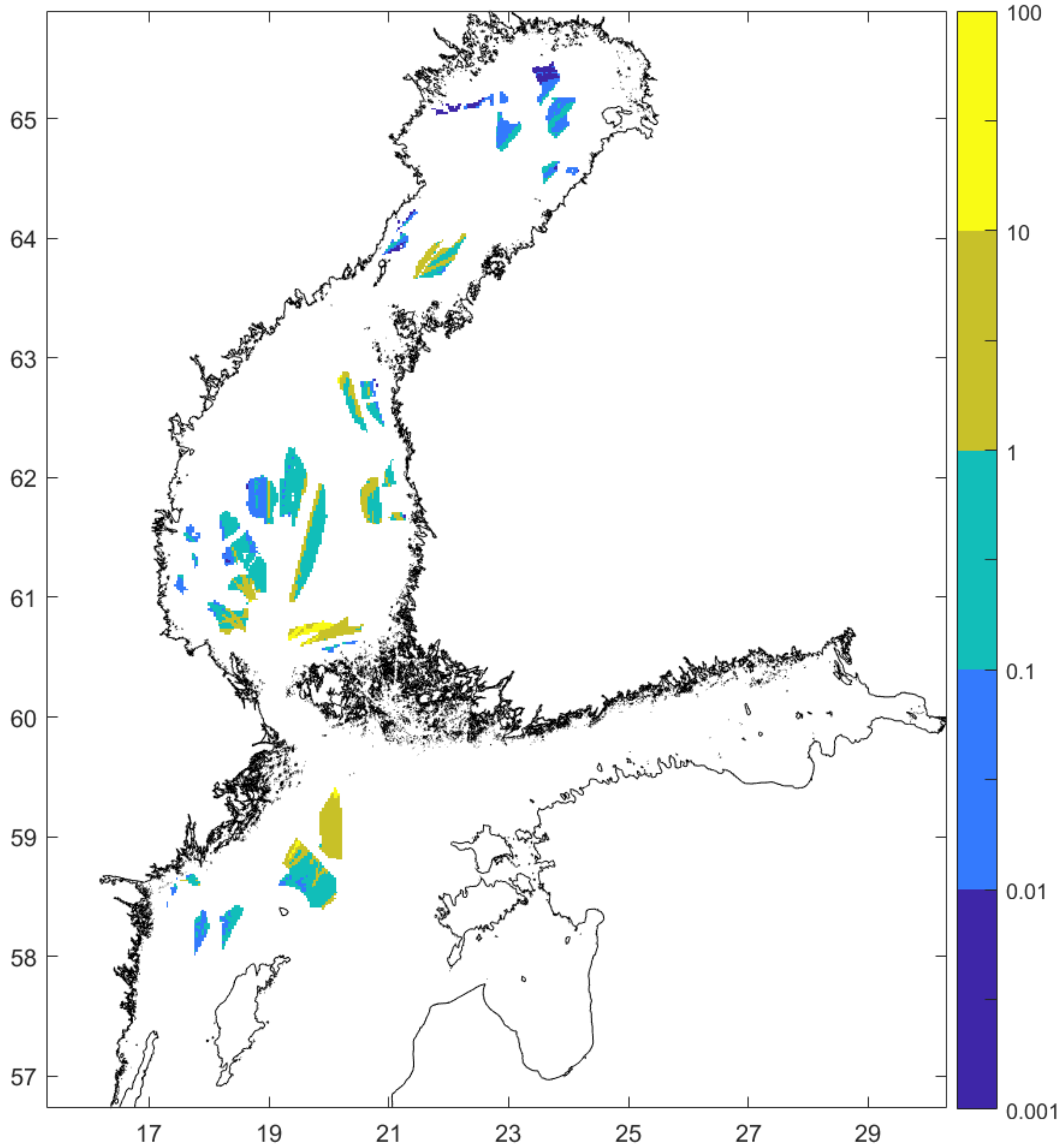

Figure 18: Expected daily number of different ships visiting a 1x1 NM cell in open water during the ice navigation season (case B, average over 9 years).

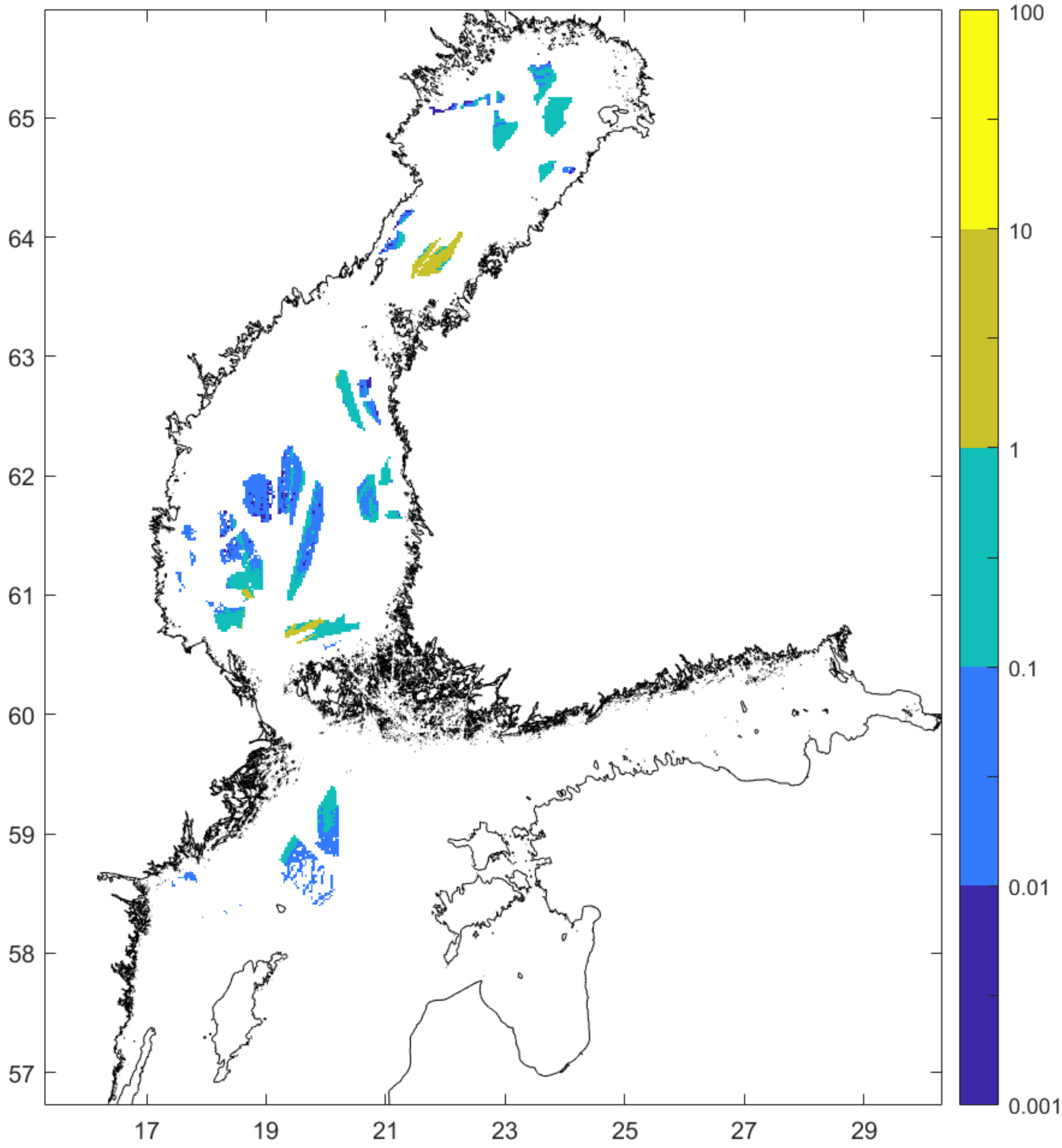

Figure 19: Expected daily number of different ships visiting a 1x1 NM cell within ice cover (average over 9 years).

The traffic densities for the invidivual farms are shown in Figures 20 and 21 where the stacked bars add into total densities. Figure 20 quantifies the actual traffic density within the OWF while the total numbers for the farms in Figure 21 is related to how much the farms affect the ship traffic, a quantity increasing both with the farm area and ship density.

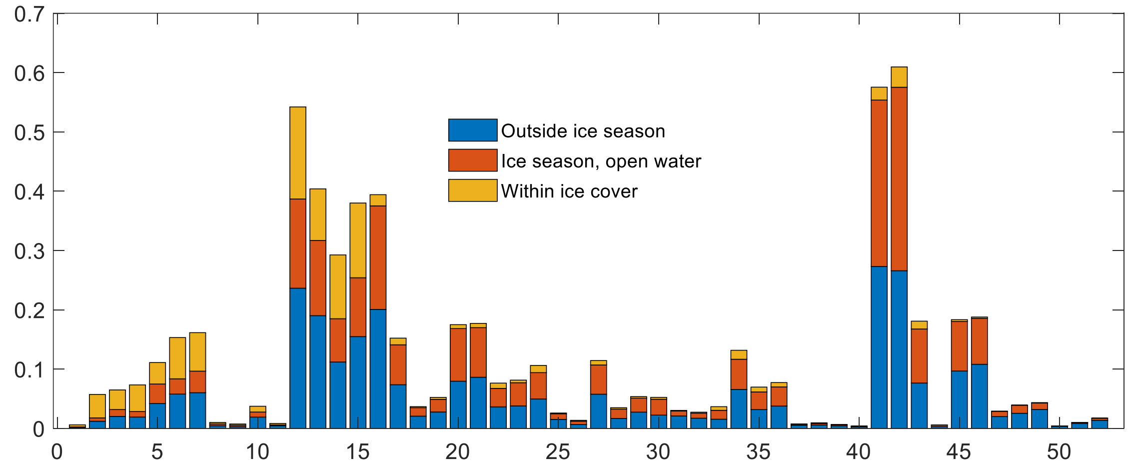

Figure 20: The expected daily number of ships to visit a randomly chosen 1x1 NM cell within the find farm.

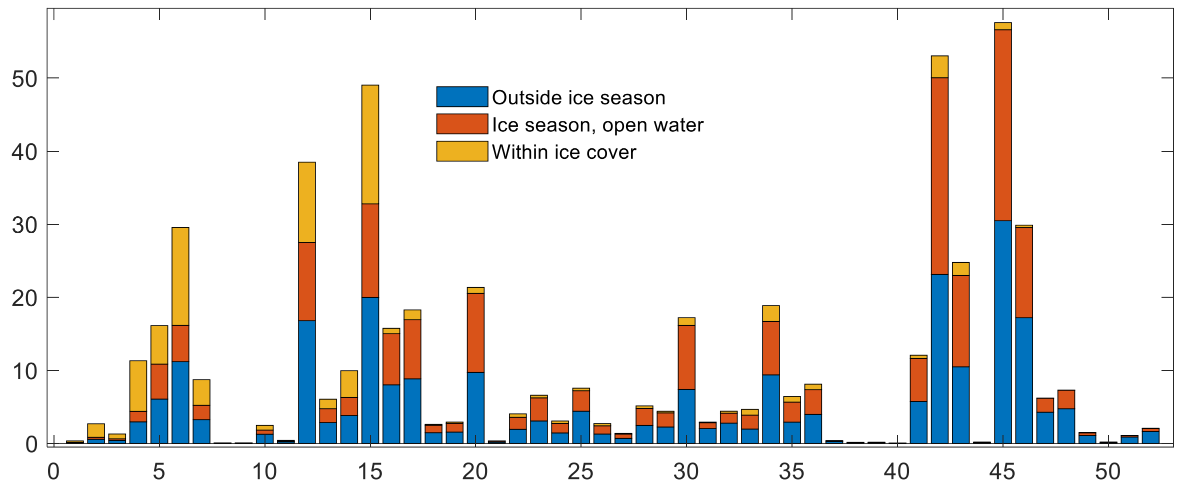

Figure 21: The expected daily number of ship visits in the within the wind farm.

5.5 Icebreaker operations

During the ice season commercial vessels navigate either independently or are assisted by icebreakers. Icebreakers that are not assisting are either idling and waiting for next action, or are proceeding to some waypoint. A commercial vessel may proceed independently to its destination if the ice conditions and traffic restrictions allow. Vessels with IA Super ice class are mostly capable to reach their final destination independently, and generally the ships are expected to navigate as far as they are capable, either to some waypoint set by icebreakers or to final destination. From the waypoint onward the ships are assisted by an icebreaker, preferably as convoys of several vessel. However, the progress to waypoint may be halted by ice conditions in which case they may get help from passing vessels (usually those with IA Super ice class) and be able to continue. If this continues to be unsuccessful, an icebreaker needs to arrive and escort the ship.

In the Northern Baltic the icebreakers coordinate the assisting together. This is based on a set of waypoints and interconnecting ice channels, or *dirways* (short for directed ways). The dirway network depends on the ice conditions and is adjusted or redrawn if the conditions change, although not without good reasons from the viewpoint of the whole navigation system. In an ideal case the icebreakers would be assisting most of the time and a lesser fraction of time would be spent idling or non-assisting transit.

The icebreaker density in Figure 22a can be assumed to be climatologically representative for the Bay of Bothnia. It shows the midbasin axis from which rather straight channels are diverted to fairway entrances. The Finnish waters north of Quark have high density. Concentric patterns duplicate the geometry of the fast ice edge within the pack ice. These mirror the dirway patters that seek to complete the midbasin channels to fairway entrances with coastal channels connecting adjacent fairway entrances. Such channels follow coastal leads if these are present. On the other hand, in the Sea of Bothnia the data is dominated by two severe winters with difficult ice conditions persisting on the Finnish side of the basin. The icebreaker tracks spread rather homogenously in the more difficult ice pack, also directionally. The approaches to fairway entrances create dispersed, fanlike patterns.

The Sea of Bothnia shows similar patterns in Figure 22b which can be loosely be interpreted to quantify the need of assistance. In the southern Bay of Bothnia the patterns are expectedly opposite to those in Figure 22a. On the Finnish side the larger proportion of non-icebreakers (3-10 commercial vessels per icebreaker) is likely to be due to higher traffic densities (more ships in a convoy) and independent IA Super traffic. On the Swedish side and in the northern basin there are on the average less than 3 commercial vessels per one icebreaker. Some areas with almost no other than icebreakers are also seen.

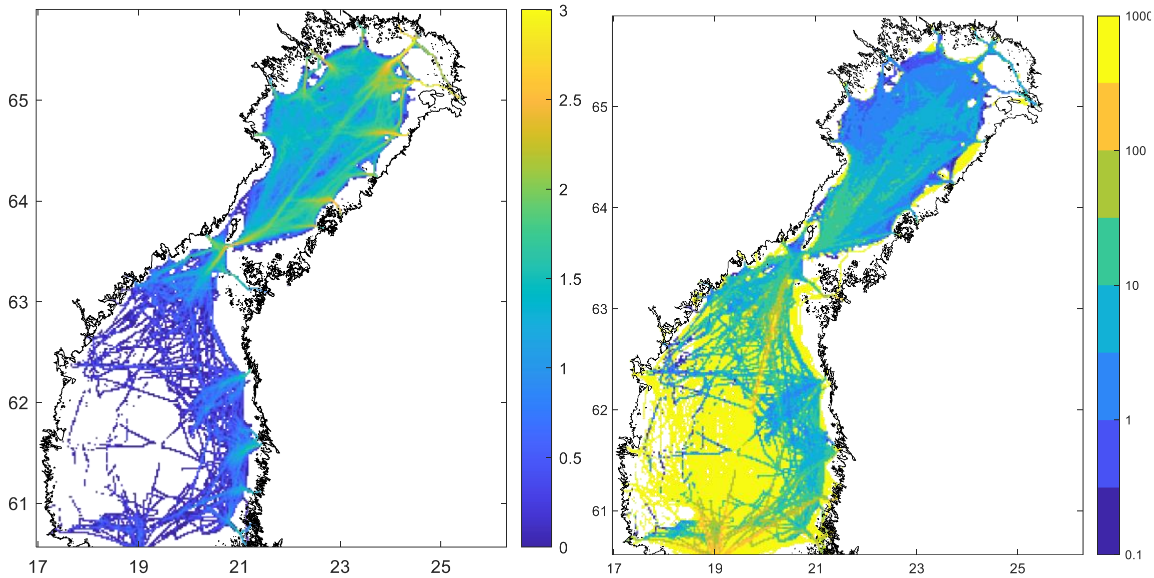

Figure 22. a) The icebreaker density average over the 9 years of the database. b) The ratio of non-icebreaker presence to icebreaker presence for the 9 years (ice transit only). If the ratio is *n* in a 1 NM cell it is on the average n times more likely to encounter non-icebreaker.

In Figures 23-30 the icebreaker visit densities are shown for ice seasons from 2007-2008 to 2014-2015 for both assisting and non-assisting transit. Season 2015-2016 is not included as the ice season was cut short in the data. It is assumed that when the icebreaker is proximate to some other ship, it is assisting, otherwise not. The densities for 1 NM cells are numbers of IB visits in the cell during the season. In the color code the main ice routes are discerned as having 10 visits or more during the season; however, the actual number of visits in a cell for this density class can be as high as 110 days per season for assisting transit and 60 days per season for non-assisting transit.

Mild winters have more or less similar traffic density pattern with longer non-assisting transits between the ice covered northern and southern parts of the basin. Close to fairway entrances the tracks disperse to all directions with no clearly preferred channels. This indicates opportunistic assisting where no dirways are followed and all operations take the shortest course between waypoints.

Each severe winter creates it own traffic patterns that are not well presented by compiled data for several such winters. Continued ice deformation creates heavily ridged areas that are difficult for the icebreakers also and are avoided. They usually retain their identity until the end of the season. During 2009-2010 the Bay of Bothnia mid basin is avoided and most traffic is channeled close to Finnish coast. In 2010-2011 the traffic Bay of Bothnia traffic follows the ’standard’ pattern as this was not hampered by the visible difficult areas. The season 2012-2013 had average-to-severe conditions and an atypical pattern for the main part of the traffic that otherwise spreads to all waters.

Difficult areas that are avoided by the traffic can be discerned also during mild and average winters, for example 2013-2014. Mild winters are often more stormy and the difficult deformed areas can be as difficult as during severe winters. From the 9-year data it appears clear that the formation of such areas is a random process that as a response generates a different traffic pattern for each winter. It is also to be noted that coastal leads do not have similar importance every season. This is particularly seen when comparing the two severe winters. One feature that appears more consistently is the opening of the lead north of Quark on the Finnish side.

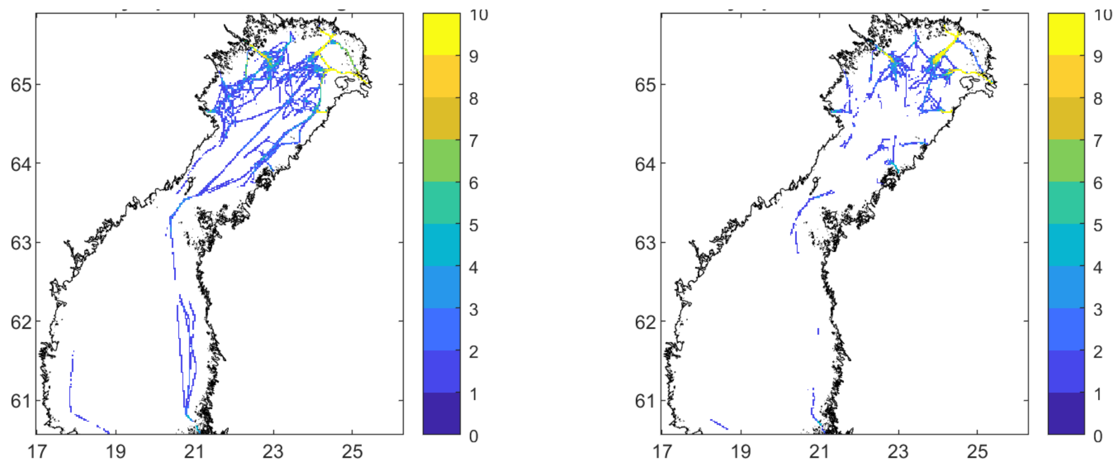

Figure 23. Non-assisting and assisting icebreaker traffic, season 2007-2008.

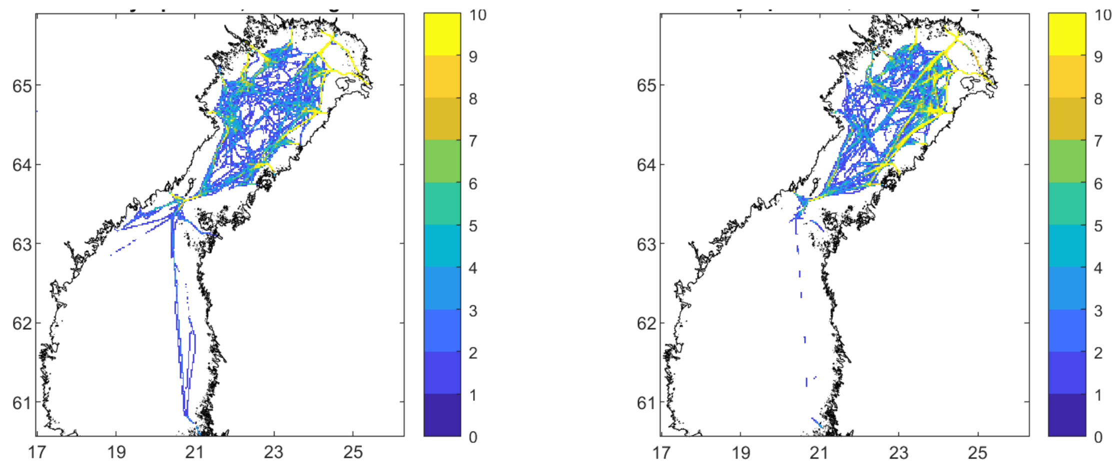

Figure 24. Non-assisting and assisting icebreaker traffic, season 2008-2009

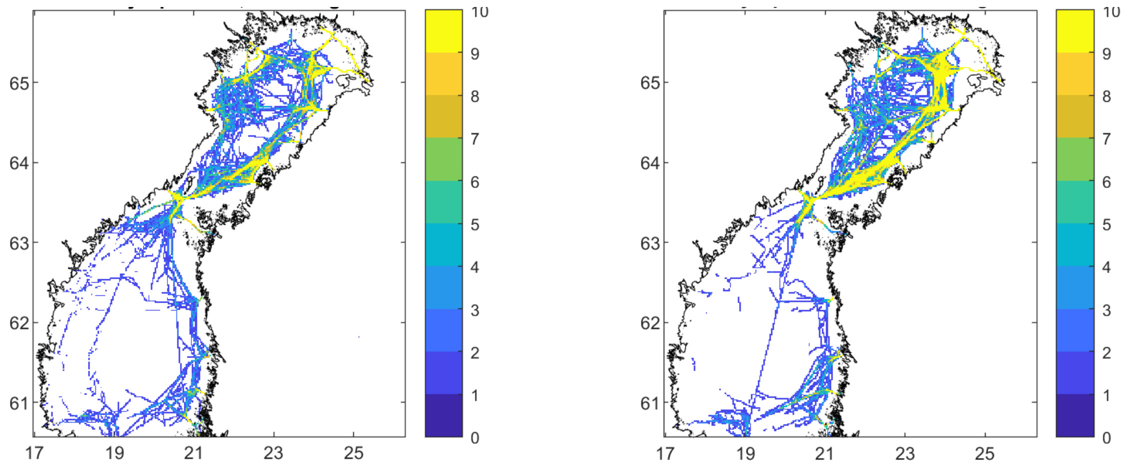

Figure 25. Non-assisting and assisting icebreaker traffic, season 2009-2010.

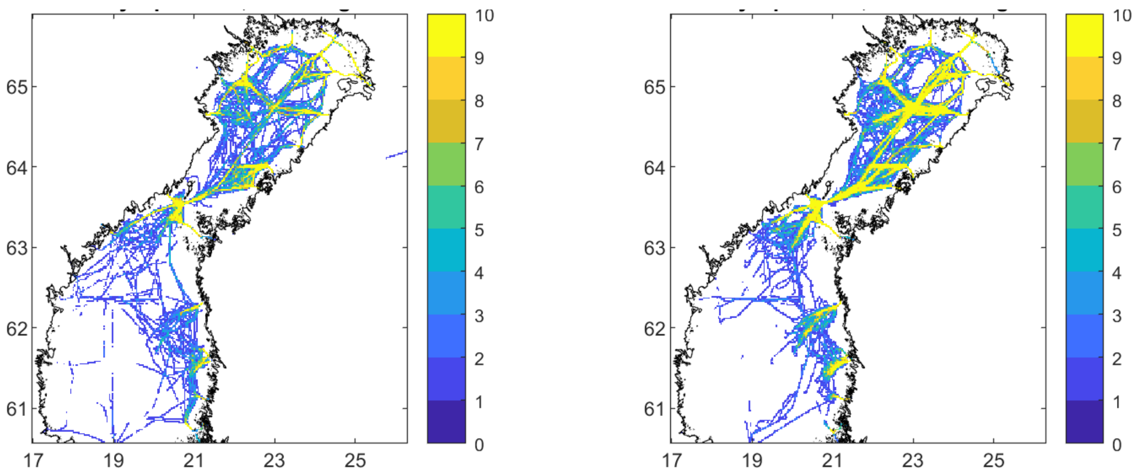

Figure 26. Non-assisting and assisting icebreaker traffic, season 2010-2011.

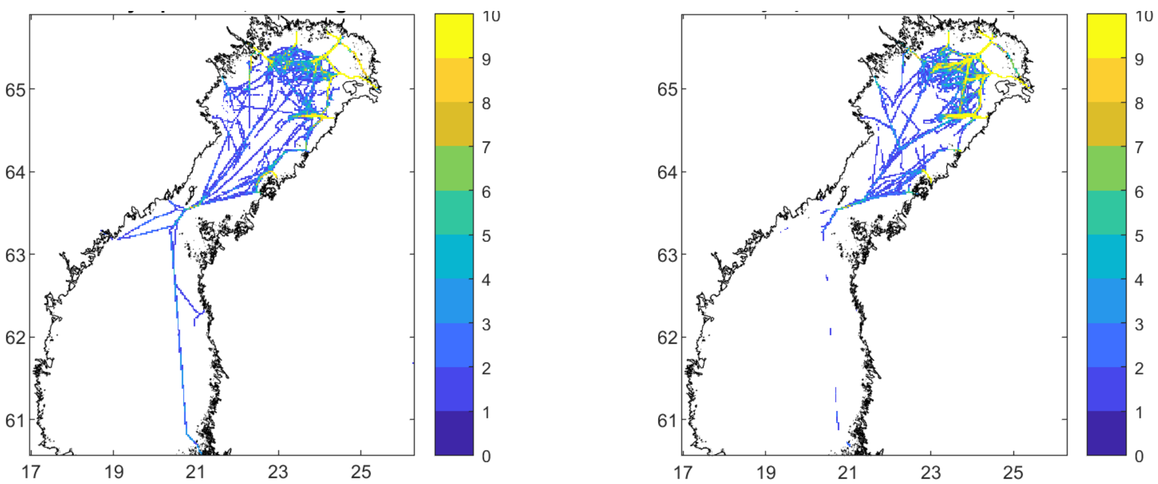

Figure 27. Non-assisting and assisting icebreaker traffic, season 2011-2012.

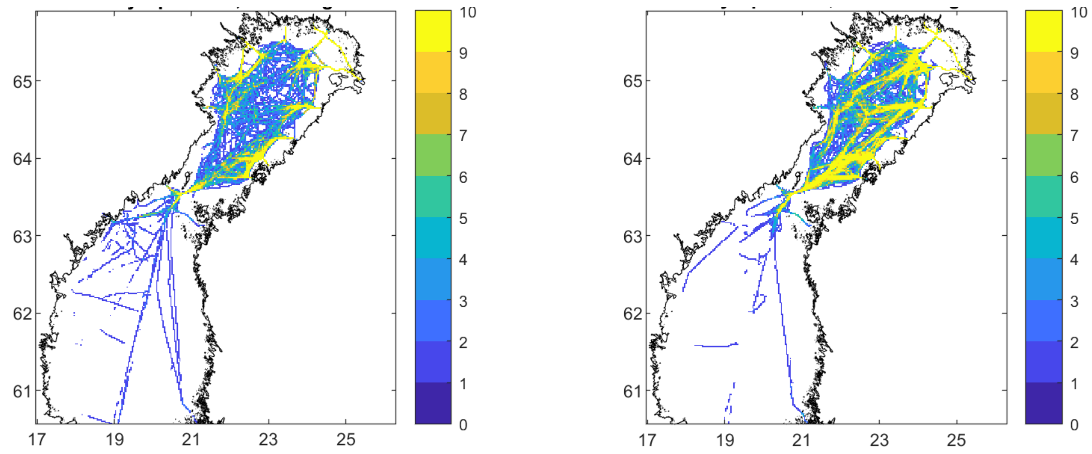

Figure 28. Non-assisting and assisting icebreaker traffic, season 2012-2013.

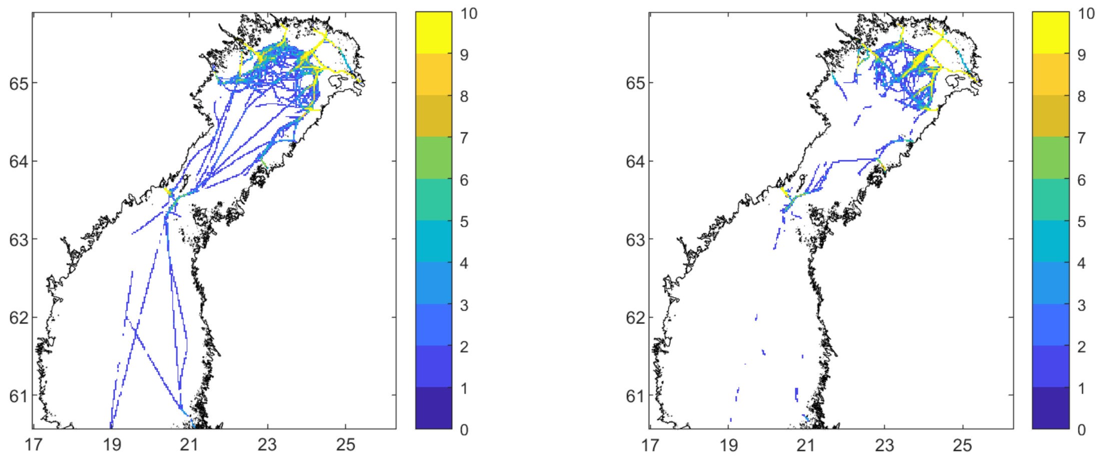

Figure 29. Non-assisting and assisting icebreaker traffic, season 2013-2014.

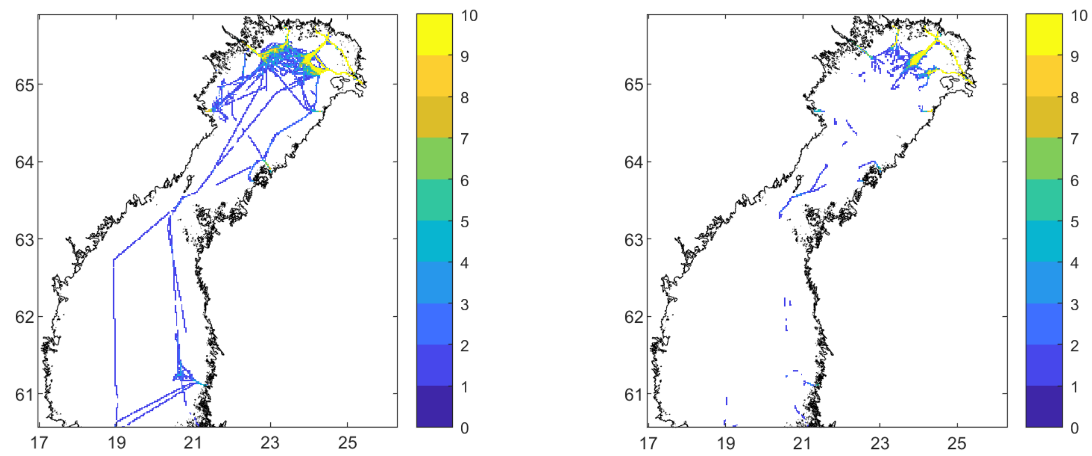

Figure 30 . Non-assisting and assisting icebreaker traffic, season 2014-2015.

In order to have a better view on how the dirways and the assistance configurations in general evolve during the ice season, monthly icebreaker track patterns are shown for the two severe ice seasons in the database, 2009-2010 and 2010-2011. It should be noted again that the AIS data collected by the Finnish stations do not well cover the Swedish side of the Sea of Bothnia.

The ice season 2009-2010 (Figures 31-34) started slowly and at the end of December only coastal areas were ice covered also in the Bay of Bothnia that then quickly froze over as temperatures plunged in January. Windy but still cold phases created coastal leads on both sides of the basin while the midbasin pack grew increasingly ridged and consolidated. At the end of the month also the eastern third of the Sea of Bothnia had ice cover that was compressed close to the Finnish coast in February. After alternating phases of freezing and deformation the Sea of Bothnia got ice cover during the latter half of February while in the Bay of Bothnia ice conditions remained stable and no coastal leads were opened. Some were opened in March but less on the Finnish side, and also in the Sea of Bothnia the conditions were more difficult on the Eastern half of the basin. In April the ice cover in the Sea of Bothnia deteriorated rapidly and disappeared at the end of month, while in the Bay of Bothnia westerly winds kept coastal leads open at the Swedish side while on the Finnish side the midwinter conditions continued.

The icebreaker traffic had a remarkably stable pattern where the navigation concentrated to coastal areas while the midbasin pack was avoided. This was particularly so in March-April where a single midbasin traverse connected the coastal channel systems. It appears that although in April the Swedish side had coastal leads most of the time, it was a more efficient option to follow the established coastal channels on the Finnish side than to move from side to side through the consolidated pack.

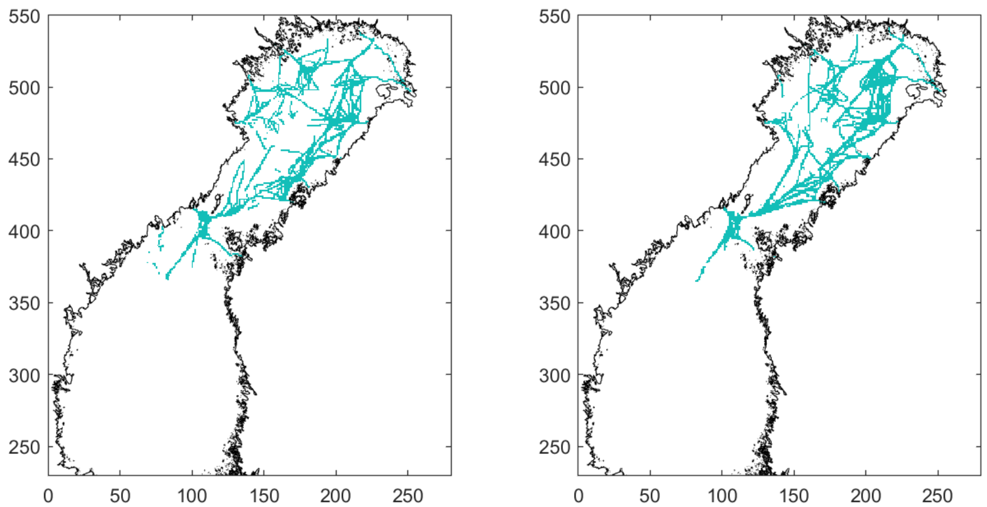

Figure 31. Non-assisting and assisting icebreaker traffic January 2010.

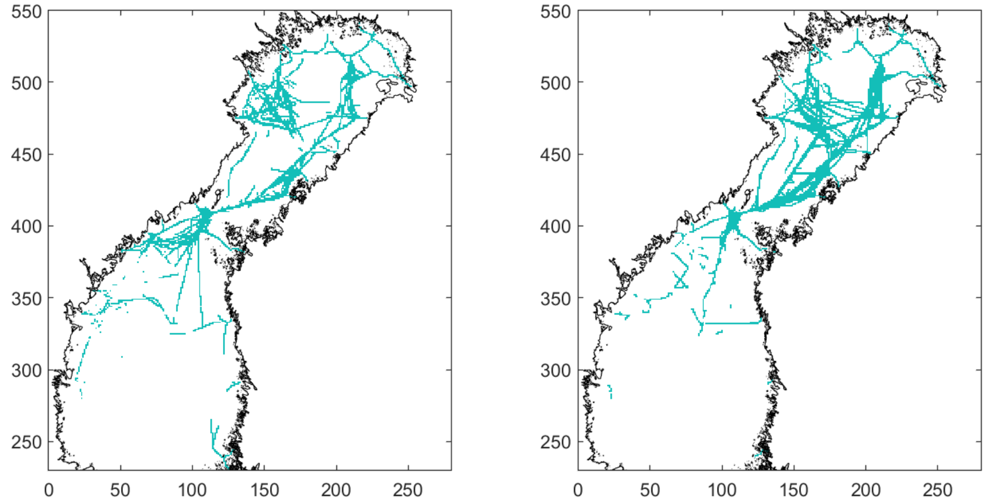

Figure 32. Non-assisting and assisting icebreaker traffic February 2010.

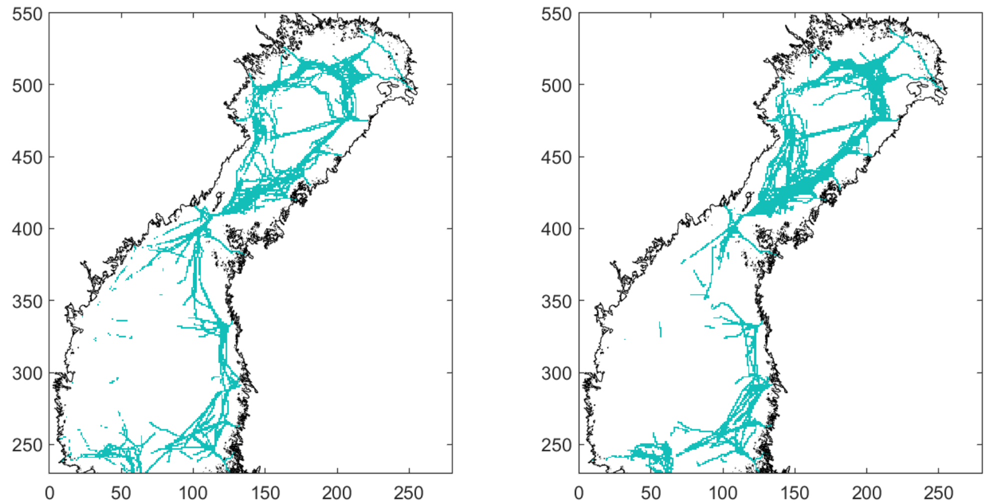

Figure 33. Non-assisting and assisting icebreaker traffic March 2010.

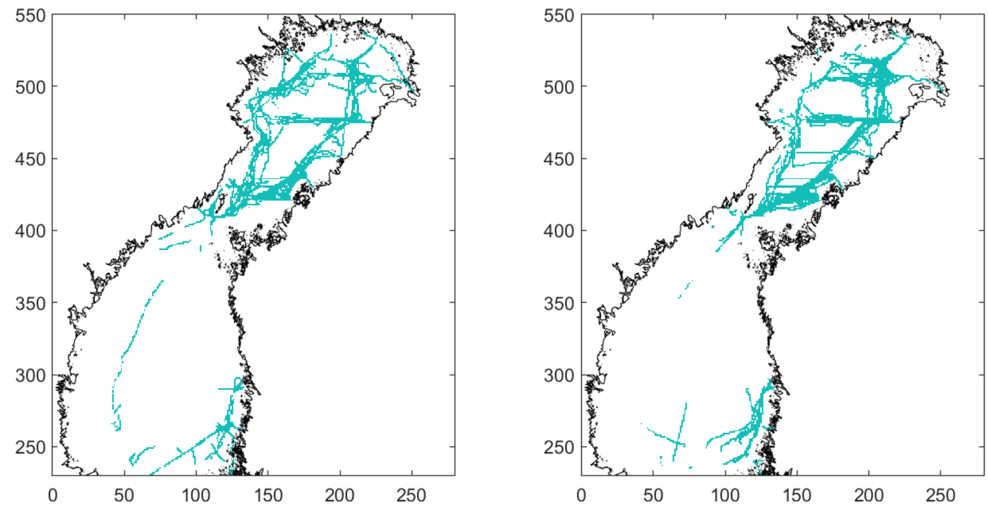

Figure 34.Non-assisting and assisting icebreaker traffic April 2010.

In contrast to the 2009-2010, the 2010-2011 (Figures 35-39) proceeded rapidly from the onset so that at the end of December the Bay of Bothnia was ice covered and the ships were assisted through the Quark and to the ports. Coastal leads were common on the Finnish side in January but not anymore in February so that traffic evolved to a pattern where the channels to ports branch out from the highway channel aligned with the basin's longitudinal axis. A similar solution evolved in the Sea of Bothnia that had generated difficult ice conditions on the Finnish side. The Swedish side north of the Quark was avoided in January-February but the very same area opened up in March. As also the Quark was opened in April, the assisting needs were concentrated on the Finnish side in the southern half of the Basin. In the northern half of the Basin the channel pattern did not change much during February-April, indicating that the deformation of the pack had reached already earlier a stage where subsequent windy periods could not change the situation. In the Sea of Bothnia the ships were proceeding in March-April from the easy conditions of the western side of the basin as far as they could and were then assisted to the ports along changing routes.

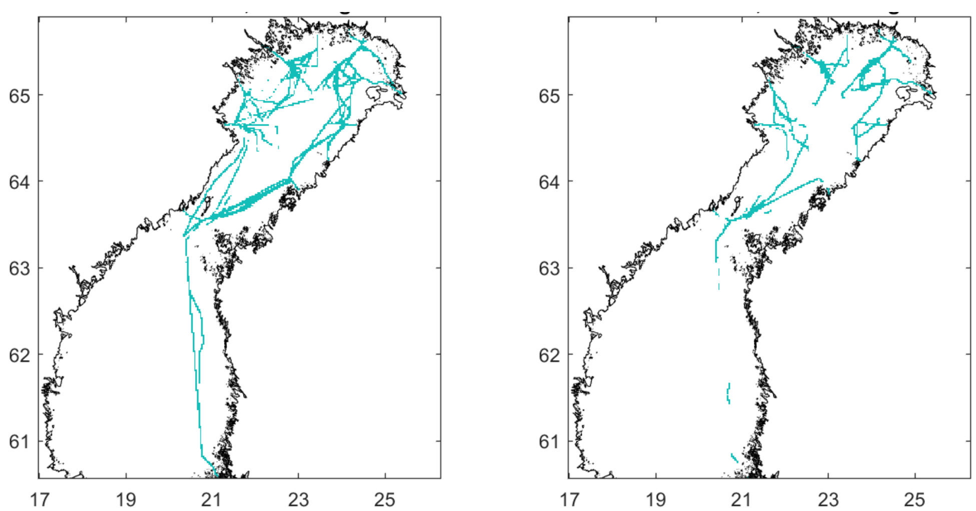

Figure 35. Non-assisting and assisting icebreaker traffic, December 2010

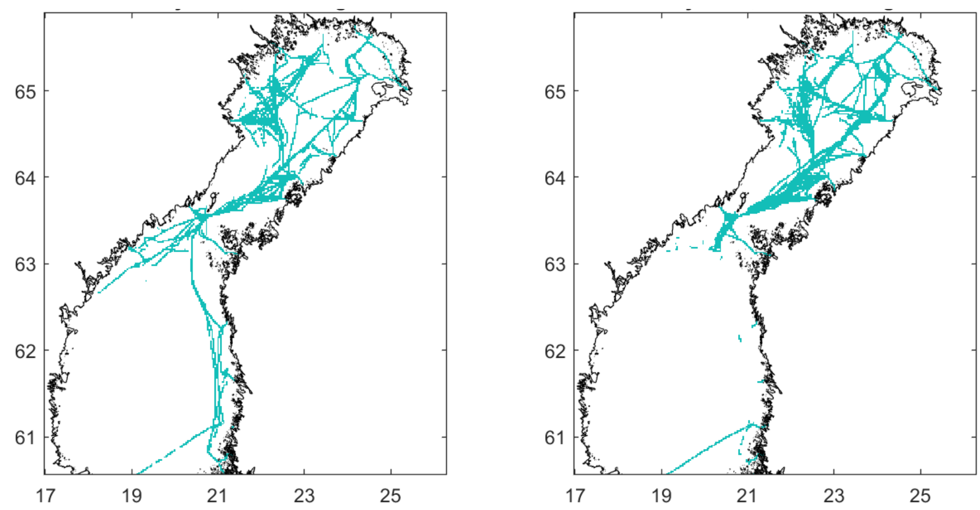

Figure 36. Non-assisting and assisting icebreaker traffic, January 2011

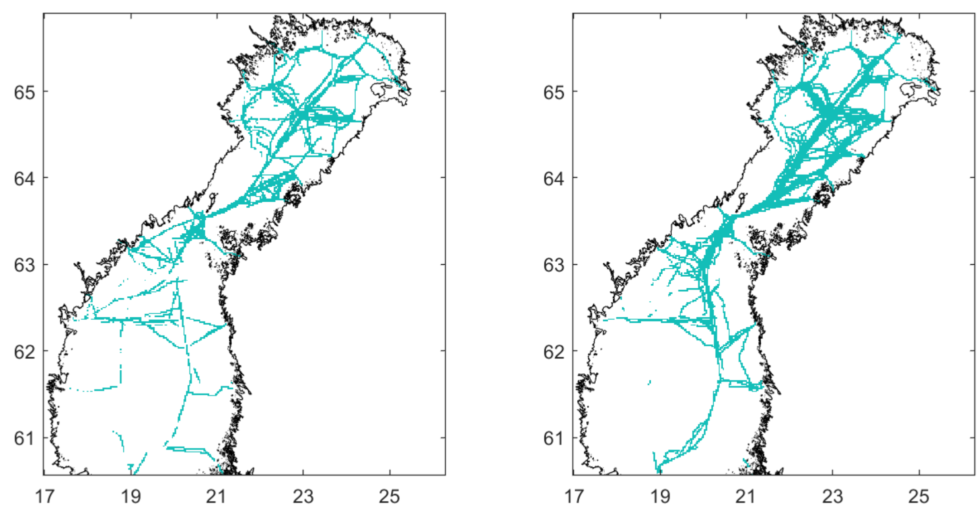

Figure 37. Non-assisting and assisting icebreaker traffic, February 2011

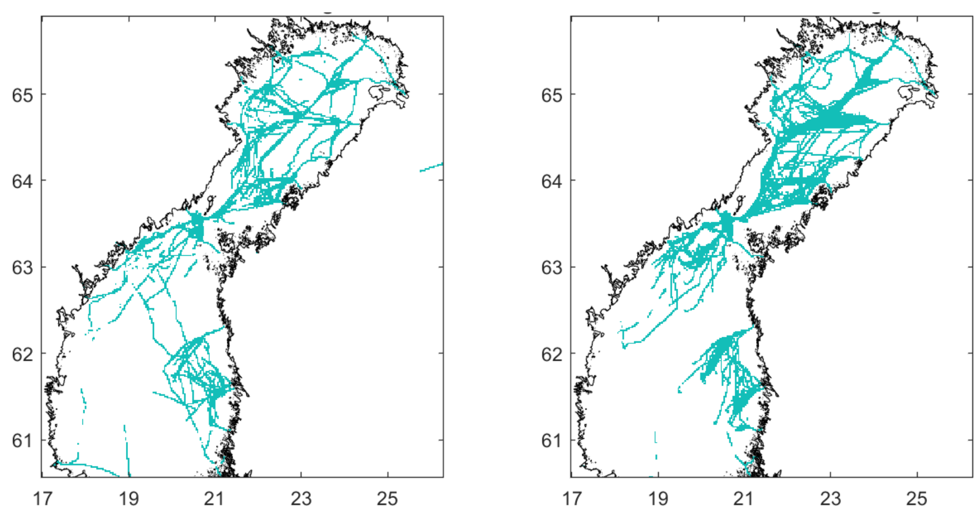

Figure 38. Non-assisting and assisting icebreaker traffic, March 2011

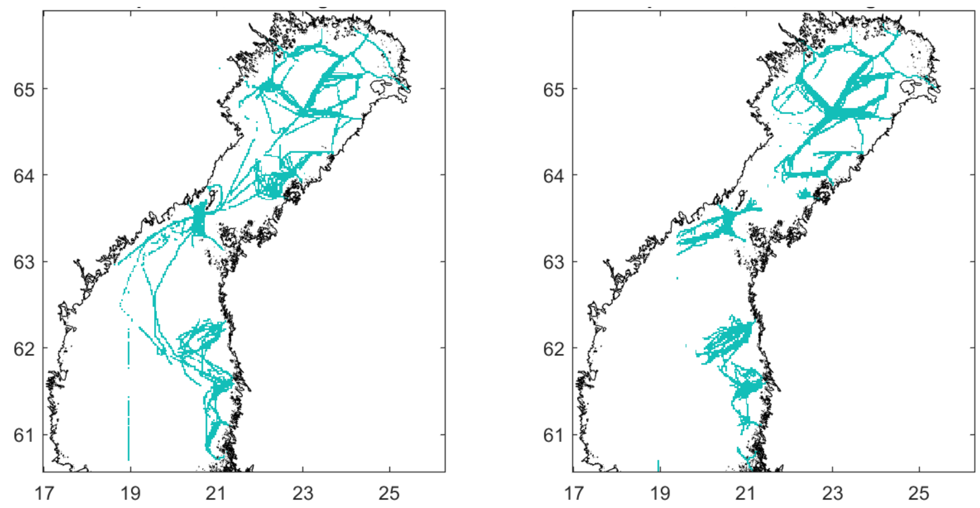

Figure 39. Non-assisting and assisting icebreaker traffic, April 2011

5.6 Idling, besetting and drifting

Ships are idling within the ice cover while waiting on purpose or when beset. If the ice cover is drifting at the same time, the ice drift speed shows as ship speed in the AIS data and is typically at most 1 knot. To identify drift it is required that the period of low speed is not short, say less than half an hour, as the speed may drop to zero due to difficult ice during a normal transit. If the ship is stopped by a ridge, it may take some time before it is able to free itself by backing.

The season 2010-2011 contained several phases when almost all traffic was stopped by persistent compressive conditions. The most difficult one was in the beginning of March and prevailed both in the Sea of Bothnia and Bay of Bothnia. In Figure 40 a large number of ships are beset in the southern half of the Bay of Bothnia, waiting to become freed one by one. For almost half of the ships the waiting time was from 50 to 100 hours. The drift speeds were up to 0.5 knots. During the same period, about 20 ships were beset in the Sea of Bothnia and drifting NE with speeds up to 0.9 kn. As a worst-case scenario in a 100 hr drift with 0.5 kn speed a conservative safety margin of 50 NM to an OWF would be required.

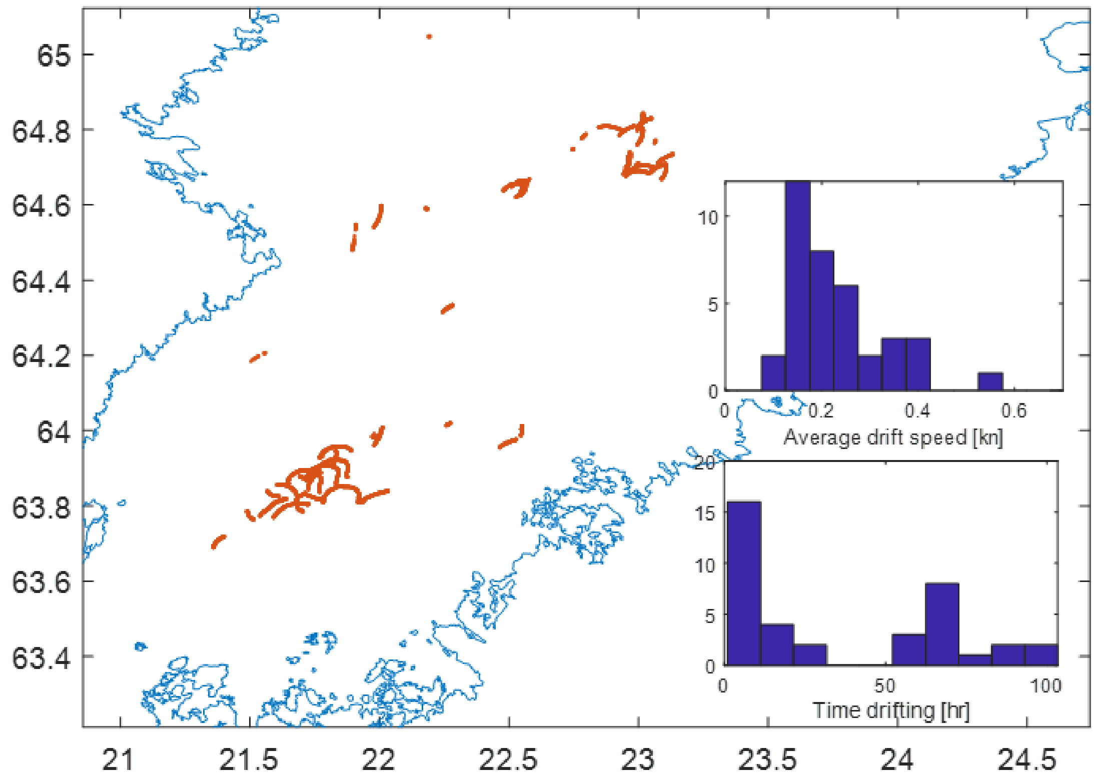

Figure 40. 38 ships beset in drifting compressive ice in the Bay of Bothnia 1-5 March 2011, waiting for assistance.

5.7 Case studies on leads

The formation of coastal leads greatly facilitates the winter navigation system. The icebreaker can utilise even very narrow leads to make quick progress, and in a wider lead commercial vessels may navigate independently further than they would be able to do otherwise. In Figure 41, selected lead formation events from the season 2010-2011 are shown, and in Figure 42, the tracks of assisting icebreakers for the matching periods. Independent navigation appears as gaps in track pattern, and when an icebreaker is not assisting its track is not shown.

The leads show in the track patterns but do not dominate them. They are utilized in an opportunistic manner as their persistence is not guaranteed for any longer period. If a lead is blocked by an OWF, it cannot be used (assuming it forms at all).

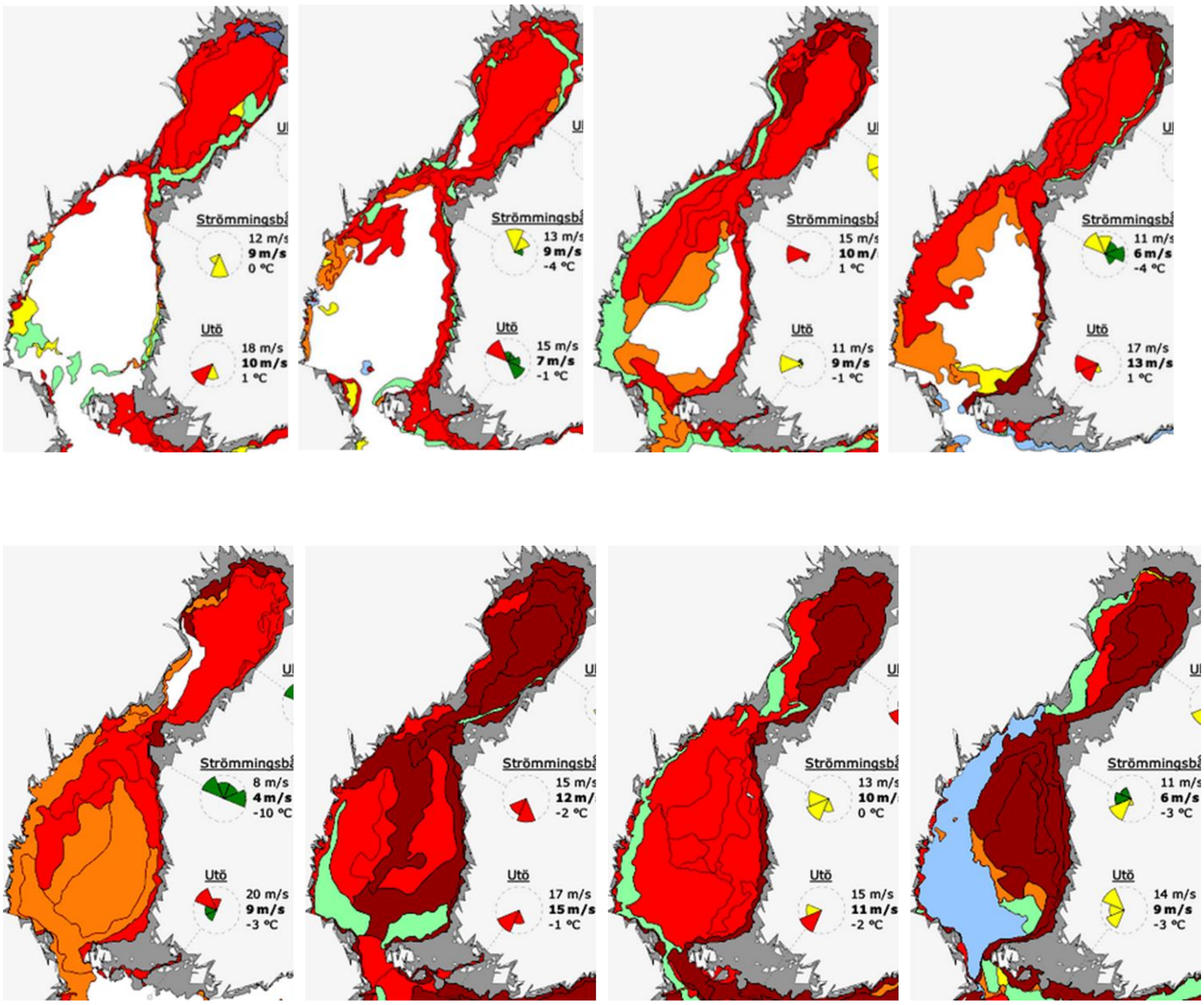

Figure 41. Selected coastal leads during season 2010-2011. First row 10th, 13th and 28th January, and 4th February. Second row, 10th and 26th February, and 3rd and 7th of March.

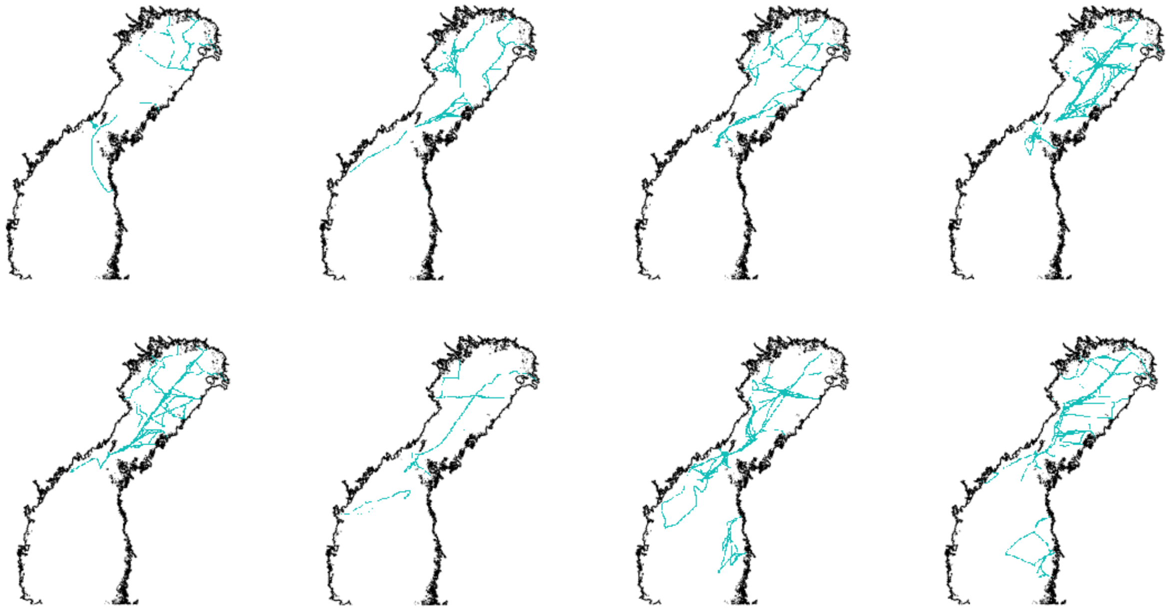

Figure 42. The tracks of assisting icebreaker for the eight cases in Figure 41.

Reference:

Pärn, Ove, and Jari Haapala. "Occurrence of synoptic flaw leads of sea ice in the Gulf of Finland." *Boreal environment research* 16.1 (2011): 71.

6. Conclusions and recommendations

A large number of offshore wind farms (OWFs) are being planned to be installed in the northern Baltic Sea. About fifteen of the planned farms are located in the Bay of Bothnia that freezes over and can generate difficult ice conditions also during mild winters. Twenty of the planned farms are located in the Sea of Bothnia that becomes ice covered during climatologically average winters that are likely to be more and more infrequent in the warming climate. A little less than ten farms are planned in the northern Baltic proper where ice is found only during severe winters. The planned OWFs often occur close to each other in suitable sea areas. Such groups appear as a single farm when the impact to the environment and other maritime uses of the sea areas are considered, especially if the interdistance does not allow safe passage between the farms.

Presently, the impact assessment processes for the OWFs are at different stages. A completed assessment typically includes a large number of specific reports. The results related to marine traffic may be divided into several reports, for example into traffic analysis and risk analysis. The downloadable traffic impact assessments do not have similar structure or answer all the same questions, and there are no detailed rules for what kind of analyses should be included. The environmental conditions data may either be scattered between reports or be repeated in each of them. However, for the open water season the reports have more or less the same content, and this style has become customary in similar assessments worldwide.

OWFs in ice infested waters are found in the southern Baltic where the ice conditions are at most slightly difficult and do not essentially impact ship traffic beyond the open water case. The northern Baltic assessments appear to be at odds as to how deeply they should go into the impact of the farms on winter navigation, and the results vary in scope and depth. The same applies to the possible ways the farms can change the ice conditions and how this in turn may affect navigation.

However, the following features are common. The assessments compile rather haphazardly general environmental and ship traffic materials and data from various sources although such knowledge is common to all wind farms. Often the motivation appears to be to increase the length of the report. It would be better to collect relevant knowledge systematically into a single source, a report or web site, which could serve all assessments and improve their comparability. Second, the ice conditions for the farm and the surrounding sea area are presented descriptively, usually for a single ice season. Climatological data on ice conditions is not presented, for example and to start with, mean, variation, maximum and minimum thickness, concentration mean and variation, probability to encounter certain ice type, and statistics of ice drift. Third, the AIS data applied in traffic analyses, typically for the one selected season, is used only to generate route heatmaps and produce scenarios of traffic rerouting around the farms. Icebreaker operations and the impact of ice conditions on these, and on navigation in general, even for the selected season, are not analyzed. The defining of descriptors, quantifying the impacts in terms of increased travel times or otherwise, is not attempted and the meticulous risk calculations of open water season cannot include quantitatively the effect of ice conditions.

The reason why climatological ice data is not presented may be due to the difficulty of identifying data sources and compiling the data for analysis. This should be facilitated. The present report uses Baltic ice chart data gridded in 1 NM resolution. For any location and time instant the chart parameters in the grid cell containing the location are found. From stacked data, statistics for any period and any subarea can be studied. Gridded chart data is found at least for 40 years although shorter periods are used in this report. One problem with chart data is the underestimated ice thickness. Only level ice types are included, and ridging is not quantified. Another issue is that the chart data originates from different sources with different time stamps that can be up to 48 hours older than the chart time stamp. Satellite and ice model data with accurate timestamp, providing thickness, deformation, concentration and drift speed data could be integrated using the same basic grid. Ice thickness from model data is also more realistic and can include ridged ice types. If such data were made easily available, the assessments could be required to answer specific questions pertaining to the conditions for the farm and the surrounding sea area.

The present report has also utilized data where AIS data received by Finnish terrestrial stations is combined with environmental data, specifically ice conditions data from gridded ice charts. Each AIS message is linked with ship particulars data and the ice data for the location, and it can be analyzed how ships react to changes in ice conditions. The nine-year dataset has been generated for previous research projects and has not been updated recently but luckily includes two severe winters. The data has gaps, and the terrestrial data does not reach well to the Swedish side of the Sea of Bothnia. Similarly as for the ice conditions, the AIS data should be collected systematically and with proper coverage, linked with environmental data, and provided for assessment preparation purposes. This would allow detailed analyses of the wintertime traffic, including icebreaker assistance configurations and convoy operations.

Such detailed analyses are not included in this report but would be motivated when targeting a single OWF or farm group. In this report, the winter navigation system is approached qualitatively in terms of icebreaker tracks. The icebreakers are either assisting commercial vessels or independently steaming to locations and areas where assistance is needed. The tracks follow the dirways agreed jointly by the icebreakers, or are alternative routes and shortcuts. A common event of the latter is the utilization of coastal leads. Vessels not requiring assistance mostly follow the ice channels opened by the icebreakers.

A general conclusion is that even though ice winters of similar severity may have ice conditions resembling each other, the winter navigation system is idiosyncratic for each season, except perhaps for the very mild ones. Basing a traffic assessment on only one season cannot be considered proper as the results cannot be generalized. The more severe the winter, the more conspicuous are the differences in traffic patterns. This is particularly so for the two severe winters 2009-2010 and 2010-2011 that have completely different traffic patterns for the Bay of Bothnia. The severe winters should get more emphasis in the traffic impact assessments, but this clearly cannot be done in terms of a kind of climatological average. Each severe winter should be analyzed separately, and the analysis should preferably cover all available AIS data.

Although coastal leads have received emphasis in this report, they are perhaps not decisive for the winter navigation system. Their occurrence and persistence is contingent, and the navigation system must function smoothly also without them. On the other hand, the presence of very difficult deformed ice fields is seen from the track maps. Their generation is a cumulative process that depends on the windiness history of the season, and their thickness can be several meters over kilometers as seen in Section 4.5. It should be noted that although icebreakers may be able to open channels in such ice fields, they are not necessarily navigable by commercial vessels due to the resistance of thick channel brash. In the track maps they are discerned as white areas that are not entered even by non-assisting icebreakers in search of shortcuts. They can occur also during milder winters and it is possible that the OWFs may make them more frequent by fragmenting ice and increasing their mobility.

Blocking the possibility to go around such difficult ice fields would hamper the functioning of the winter navigation system to some degree. Such a situation could occur when the gap between adjacent OWFs like the one between Halla and Polargrund, intended to allow ship passage, becomes obstructed. Generally the OWF traffic assessments should identify the historically most difficult ice conditions that have occurred in the target area and include the adjacent farms in the analysis.