STYRELSEN FÖR

**VINTERSJÖFARTSFORSKNING**

WINTER NAVIGATION RESEARCH BOARD

Research Report No 95

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**INVENTORY OF ICE PERFORMANCE FOR BALTIC IA SUPER TRAFFIC 2007-2016**

## FOREWORD

In this report no 95, the Winter Navigation Research Board presents results of a research project conducted by the Finnish Meteorological Institute. A database containing Baltic AIS data, data concerning ship particulars and ice information obtained from various sources.

The effect of ice conditions on the speed of vessels with ice class IA Super was investigated. Ship speeds were generally reduced by worsening ice conditions but the scatter in the results was significant indicating that other parameters than ice thickness have an important role in vessel speeds, as was expected.

The Winter Navigation Research Board warmly thanks Mikko Lensu and Iiro Kokkonen
 for this report.


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## Preface

The present report presents analyses utilising a database that comprises Baltic AIS data, ship particular data and ice information from various sources. Each AIS-retrieved message reporting basic navigation data is linked with ice parameters and ship particulars.

The work was conducted in the Finnish Meteorological Institute and  was initiated in 2013 with a funding from the Winter Navigation Research Board for  project AISCHART (Comparing AIS-retrieved ship performance with charted ice conditions). Preliminary results for the severe ice season 2010-2011 were obtained and presented in conferences. Due to the sheer magnitude of the task the comprehensive objectives were not attained in 2013. Moreover, it was felt important that the database comprises several ice seasons before extensive derivations of ice related speed statistics are embarked on and that there are effective functionalities for selecting data and processing the results. The work was continued in several projects where ship ice performance and winter navigation have been central issues: in EU TEN-T project WINMOS (Winter navigation motorways of the sea), in project VORIC  (Vessel operations and routing in ice conditions) funded by TEKES, and, most importantly, in BONUS project  STORMWINDS  (Strategic and operational risk management for wintertime maritime transportation system)supported by EU and the Academy of Finland. The database covers presently nine seasons 2007-2016 and about two billion AIS position reports and will continue to become updated with further seasons, new functionalities and new data sets.

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# INTRODUCTION

## AIS data and winter navigation research

Data on how ice cover affects ship performance is needed on several levels of planning. In ice performance considerations there are two main aspects: ice induced loads against the ship hull or propulsion system, and ice resistance. The ships should be designed so that the probability of severe ice damage resulting, for example, to an oil spill is minimal during the lifetime of the ship. The ship should also be able to maintain sufficient speed in the ice cover and be manoeuvrable. On the other hand, unnecessarily heavy structures and excessive propulsion power increase construction costs and fuel consumption. To get these just right for the intended operation profile is a design task with boundary conditions set by agreed rules on iceworthiness, safety, and energy efficiency. Both for the formulating of these rules and for the ship design the understanding of ice performance should extend to the detailed level of ship types and hull forms.

On the other hand, during the ice season estimates on the travel time and on the ability of the ships to navigate unassisted are needed. Reliable estimates would assist individual ship in their route planning and scheduling, shipowners in the strategic planning of fleet operations, and icebreakers in their planning of assistance configurations. In addition, the ports would benefit from increased predictability which would also allow better real time assessing of maritime risks. There are needs both for short term planning, aiming for optimising the present traffic situation, and for long term planning extending up to tens of years and aiming, for example, to the assessing of future icebreaker needs

The traditional approach to ice resistance has been in terms of analytical and numerical modelling combined with model scale tests and full scale campaigns for selected vessel types (e.g. Myland and Ehlers 2014 ). However, resistance formulas exist only for certain homogenous ice types like level ice and uniform channel rubble although these are seldom encountered pure in the pack ice. On the other hand, the formulas have been validated for certain ship types and hull forms only. Most seriously, even if the full understanding of resistance would be at hand, the quality of ice information is not sufficient for realistic simulations. This is mostly due to the fact that ice thickness cannot yet be remotely sensed and thickness information relies on scattered observations and ice model results.

The AIS (Automatic Identification System) data offers here a possible way forward as it contains, among other things, the location and speed of vessel. Since 2002 IMO's SOLAS convention has required AIS data to be transmitted by internationally voyaging ships with gross tonnage exceeding 300 and by all passenger vessels (IMO 2002). As of 2014 AIS is running on more than 300 000 vessels. The transmitted data can be received by other ships in the same sea area, by terrestrial stations to about 100 km offshore, or by satellites. The broadcasting interval is of the order of ten seconds during regular steaming. Such full update rate data can be obtained in the Baltic via terrestrial receiving stations. After combining AIS data with sea ice information it is possible to study how the changes in concentration, thickness, ridging and other parameters of ice information are reflected by the speed of the ships.

The applicability of AIS data to wintertime navigation research purposes has been realised but the applications are still few. Löptien and Axell (2014) made a study focusing to the Quark entrance on

the northern part of Sea of Bothnia and to the severe winter 2011. They used archived AIS data with 5 minute intervals. The AIS-retrieved performance was compared with ice parameter fields from a forecast model. Icebreakers and ships closer than 0.2 NM to icebreakers were excluded leaving about 14000 data entries. Statistical analyses indicated that about 2/3 of the ship variation could be assigned to ice conditions. Otherwise Baltic AIS data has been used in winter navigation research and in maritime risk modelling (e.g. Montewka et al. 2015, Goerlandt and Kujala 2014) in routing scheme developments (Guinness et. al 2014) and in oil pollution monitoring (Bulycheva et al. 2014). Emission modelling has been the only Baltic application utilising full temporal, areal and ship coverage of the AIS while the others have used selected AIS data samples.

## Present report

This report present basic results on the speed response of ships to ice conditions. It is based on a database that combines the AIS messages archived by the Finnish Traffic Administration, ice information products of Finnish Meteorological Institute, and a ship particulars database. The data covers nine ice seasons 2007-2016. The ice information consists of ice chart data (whole period) and ice model data (selected years). The basic AIS-retrieved position reports include ship identifier, time, location, speed, course and heading. Each report is linked with ice parameters found at the time and location of broadcasting the report.

The results are long term, usually covering all nine years of data, and pertain to all sea areas that are covered by the available AIS data. Ice parameters are from ice charts as this data covers the whole period. The results are presented as charts showing the regional variation of speed or as curves of speed reduction as a function of thickness characteristics. Most results are for independently navigating IA Super ships. For this category it is possible to find indications that power setting is not varied much during ice transit. Otherwise it is the main shortcoming of AIS data that propulsion power is not reported. This affects essentially all other categories than independent IA Super navigation. Although a wealth of results on the efficiency of winter navigation system can be obtained for them these results cannot be interpreted simply as following from increased ice resistance.

The report can be understood as 'ice performance climatology' that characterises Baltic winter navigation on a very general level, applying low level methods. This is motivated as comparable comprehensive inventories do not exist yet although more restricted studies based on similar ideas have been developed also in the WNRB series (Berglund and Molinier 2014). Climatological performance statistics is also background for assessments of ice class rules (Juva and Riska 2002) and, more recently, energy efficiency (Eronen and Riska 2014, Riska 2014, Westerberg 2014) and ship emissions (Jalkanen et al. 2013). It server also as a background for addressing more detailed research questions. It is clear that more definite answers, especially concerning ice resistance, would have been obtained for individual ships, ship types, and for restricted regions and periods. These are out of the scope of the report, at least on the level of analysis. Quicklook type results for ships, ship types and regions are in the appendices.

It is also evident from the results that modelling of Baltic wintertime navigation as a collection of ships experiencing speed reduction due to physical ice resistance is a narrow picture. Independent ice transit is not the rule and cases of independent icebreaking transit by merchant vessels are rare exceptions. For the majority of the fleet the indirect effects of ice conditions dominate: the

location, age and condition of the channels, navigating in convoys and the proximity of other ships in general, scheduled meeting times and other icebreaker assistance practices. The patterns that emerge from the general performance climatology are also expected to give insight how the winter navigation should be approached by more holistic, system oriented methods.

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**THE DATA**

## AIS messages

AIS messages are broadcasted by vessels, navigation structures, and certain shore stations and received by other vessels or onshore. Messages containing basic navigational information are automatically transmitted. The IMO convention for the Safety of Life at Sea (SOLAS) requires AIS transmitters on all international cargo vessels of more than 300 tons displacement, all cargo vessels more than 500 tons displacement, and all passenger vessels.

There are 27 basic message types containing different information. The basic navigational information is contained Type 1 or Position Report messages, which are most common and automatically transmitted. Types 2 and 3 are identical in content to Type1 but serve special purposes. Type 1-3 messages received by Finnish terrestrial stations are coded into sentences of the following type:

2011-02-26 00:00:00 !AIVDM,1,1,9,A,1CQCCt0uPw1eUi@R9@@2<1b006h0,0*5A
2011-02-26 00:00:00 !BSVDM,1,1,5,A,1CadJt0005QLUhFSllg@iUL00D0@,0*35
2011-02-26 00:00:00 !AIVDM,1,1,8,B,3CKbif01hU1f6IlR:PiSS2un0P00,0*2B

Date and time are added by the receiving stations and their form is specific to Finnish system, while the remaining part is common the all AIS data. The following field is sentence type identifier. In the Baltic are AIVDM, ABVDM and BSVDM sentences which all contain more or less similar data. The following three fields (for example 1,1,9) are message structure identifiers: number of message fragments, fragment number, and sequential message identifier. The actual coded message, or payload, appears as a string of 28 characters in the Position Report messages. The payload length is generally different for different message types. For Types 1-9 messages the type number appears as the first character of the payload. The last field is a checksum.

The payload represents a 6-bit binary coding of the message. The decoding is described by decoding manuals that are readily available (e.g. http://catb.org/gpsd/AIVDM.html ). From Type 1-3 message the following data is extracted

        Message Type
        MMSI number
        Navigation Status
        Rate of turn (ROT)
        Speed over ground (SOG)
        Longitude
        Latitude
        Course over ground (COG)
        True heading (HDG)

## The coverage and quality of AIS data

This employs AIS data received by Finnish stations and archived by Finnish Traffic Administration. The data coverage depends on transmission conditions but close to full coverage is obtained north of 59°N with the exception of westernmost coastal waters of the Sea of Bothnia. The archived data includes all messages (full update rate data). The main AIS data source for the remaining Baltic is HELCOM archive which, however, contains the data in reduced rate. Only the full update rate data has been used here. The interval between the broadcasted messages depends on the operation mode but is most commonly 10 seconds when steaming. Figure 1 shows the message intervals for all icebreakers during the season 2010-2011. The message interval depends somewhat on speed except and drops to 6 second interval for speeds higher than 13 knots (Figure 2). Otherwise the overall the distribution of intervals does not depend on speed (Figure 2) and 90 percent of intervals are 12 seconds or less. This is enough to resolve local variations of ship speed, for example the effect of ice ridges.
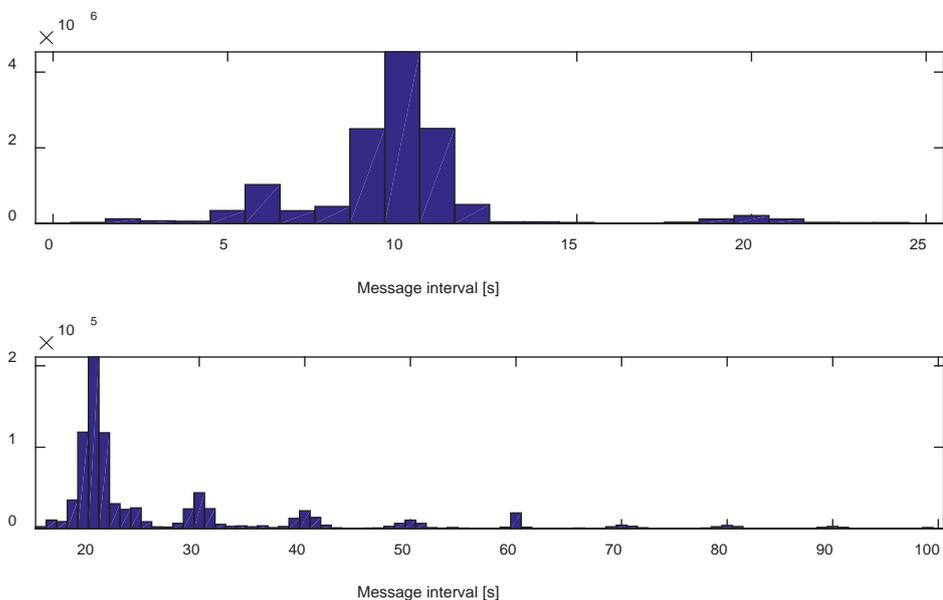


**Figure 1**. Histogram of Position Record Message intervals for all icebreakers 2010-2011.
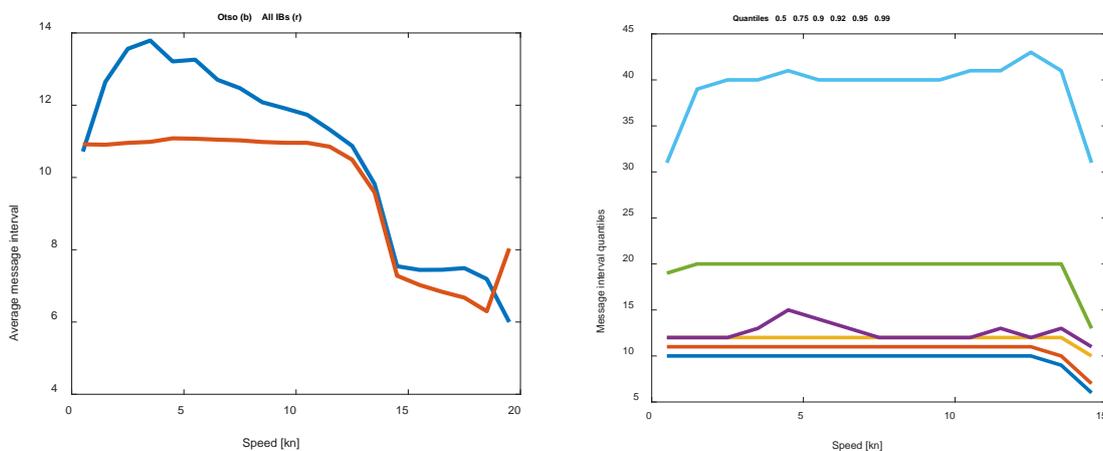


**Figure 2**. a) Average Position Record message interval as a function of speed for IB Otso and all received icebreaker data. b) Quantiles of message interval for all icebreaker data.

## Ship data

The ship data is from a database collected in FMI Air Quality unit for ship emission research purposes. The basic data is from IHS Fairplay from where the basic ship data is obtained. This data has been amended with additional hull and engine parameters from various sources. The number of ships is close to 100 000 and the coverage is close to 100% for the Baltic navigation. The basic particulars and machinery data are:

1 MMSI number
2 IMO number
3 GRT (Gross Registered Tonnage)
4 DWT (Deadweight Tonnage)
5 Length Overall
6 Length Between Perpendiculars
7 Breadth
8 Draught
9 Bulb present?

10 Number of propellers
11 Propeller RPM (revolutions per minute)
12 Main engine power
13 Main engine stroke number
14 Main engine RPM (revolutions per minute)
15 Number of engines
16 Build year
17 Ship type numeral
18 Ice Class numeral

The ice class can be one of Finnish-Swedish ice classes, 'icebreaking', or 'ice strengthened'. The ship types are:

1 BARGE      Self-propelled barge, usually minor and flat bottomed cargo ship
2 BULK       General Bulk Carrier for the carriage of bulk dry cargo of a homogeneous nature
3 CONT       General container ship
4 DREDGE     General dredge
5 FERRY      General ferry
6 FISH       General fishing vessel
7 GC         General cargo ship, multipurpose carrier
8 IB         Icebreaker
9 OILRIG     Drilling rig
10 OTHER     Type not specified
11 PAS       Passenger ship, minimum capacity 12 passengers
12 PAS_CR    Passenger cruise ship
13 POLICE    State owned: patrol vessels, non-armed naval vessels,
14 RC        Refrigerated cargo ship
15 ROPAX     Ro-ro ship that can carry passengers
16 RORO      General ro-ro ship
17 S         Supply vessel, usually small and rather fast multipurpose
18 S&R       Salvage and rescue vessel
19 SAIL      Sailing vessel
20 TUG       General tug
21 T_CHEM    Chemical Tanker ; a tanker for the bulk carriage of chemical cargoes
22 T_CRD     Crude oil tanker
23 T_LNG     LNG Tanker; a tanker for the bulk carriage of Liquefied Natural Gas
24 T_LPG     LPG Tanker;    a tanker for the bulk carriage of Liquefied Petroleum Gas
25 T_PROD    Products Tanker; a tanker for the bulk carriage of refined oil products
26 V         Vehicles carrier
27 YACHT     Usually leisure boat

## Gridded ice chart data and its quality

The ice data consists of gridded ice charts and reanalyses with FMI operative ice forecast model HELMI. The ice chart grid corresponds to that of HELMI model. It 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 16.72 E 56.74 N, north/east corner coordinates 30.48 E 65.99 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.

The ice model data is not applied in this report and is not described in detail. However, it provides quantitative estimates of the of the amount of ridged ice, ice drift, and ice pressure which are not given by the ice chart. The gridded ice charts express the graphical information of ice charts in a grid format: the grid values correspond to the chart values at the given location. For the 1 NM resolution this conversion is almost lossless for thickness and concentration. The gridded charts include also some additional information as the express deformation in terms of numeral instead of qualitative symbols of graphical charts. On the other hand, cracks and other local features indicated by symbols in graphical charts are not included to gridded charts.

The gridded charted variables are 1) sea surface temperature, 2) ice concentration, 3) ice thickness, 4) minimum ice thickness, 5) maximum ice thickness, and 6) deformation type. The ice thickness refers predominantly to level ice types. The deformation type numerals are

| | |
|---|---|
| 0 | Level ice |
| 1 | Rafted ice |
| 2 | Slightly ridged ice |
| 3 | Ridged ice |
| 4 | Heavily ridged ice |
| 5 | Windrow (brash barrier) |

The charted concentration and thickness values are based on different sources and are not evenly spaced. In this repot the concentration values are rounded to steps of 10 % except additional value at 95%. There are more concerns about the thickness data that relies much on observations made by icebreakers. These may be thickness drilling data or estimates from floes turned to upright position by the ship during transit. The observations are from level ice types for which thickness can be easily determined by these methods. In the pack ice zone level ice types usually show local thickness variation which indicates that they are not purely thermally grown but have experienced deformation.

The two different methods may introduce some methodological bias to the thickness data. From Figure 3 it is seen that decadal centimetre values dominate the data. Possible reason is that observations made from the bridge are more often reported in 10 cm intervals especially for thicker ice due to felt inaccuracy of the method. In this report the thickness is rounded to 5 cm intervals which keeps the observed values for thicker as they are. This may generate some systematic bias to the data as the error margin of bridge estimates is wider than that for drilling data and they may systematically over- or underestimate the thickness. This may affect the results that often seem to have traits of the zigzag pattern in Figure 3.  However, as no criteria of how the

5 cm interval data should be combined to 10 cm thickness intervals could be found, the 5 cm interval was retained.
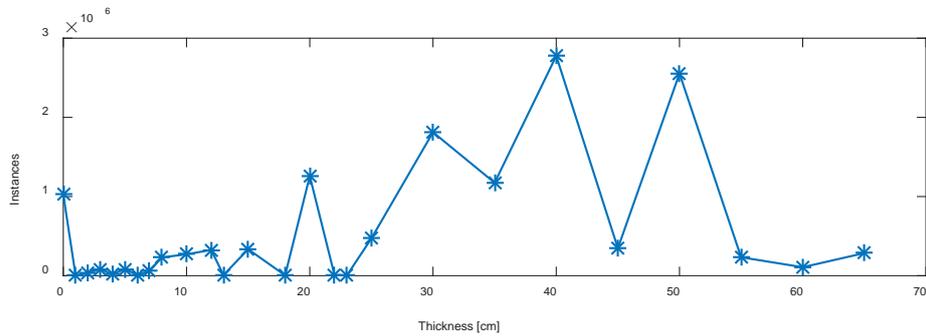


**Figure 3**. Histogram of charted thickness values for 2010-2011

## Arranging AIS data, ship data, and ice information

A navigation season is defined to be from 1st of July to 30th of June next year. The reason is that latest observations of ice in the Bay of Bothnia are from late June. Ice season is the period from the first appearance of ice to FMI ice charts to the announced end of the season (the last ice chart of the season).

Archived AIS data has been available from the season 2007-2008 to the latest season 2015-2016. For these seasons gridded ice chart data and ice model data are also available. These data sets were combined by linking navigational data from each AIS Position Report with charted and modelled ice parameters. This was done by identifying the grid cell in which the ship was located. On the other hand, the MMSI number of the message links it with the ship particulars database (Figure 4).

The analysis then proceeds by selecting suitable subsets of the data in terms of geographical area, time period, ice conditions, ship performance, ship type, ice class, and ship parameters. The basic dichotomies (filters) are
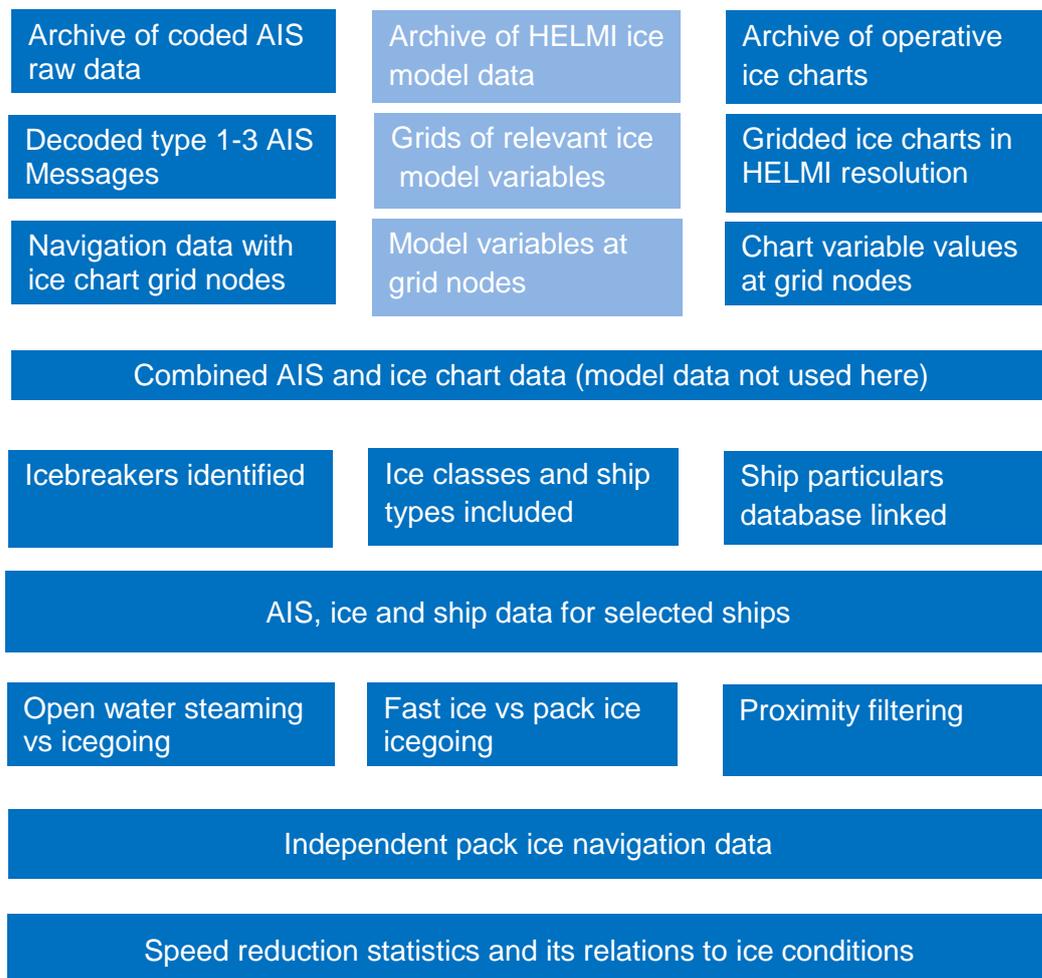
- open water navigation / ice navigation
- navigation in fast ice / navigation in pack ice
- steaming / idling
- independent navigation / non-independent navigation

Open water is equivalent to zero concentration. The ice charts report fast ice as a separate category. The criterion for steaming is that speed is at least 0.5 knots, otherwise the ship is idling.

The applied criterion of independence was rather stringent in order to exclude the effect the proximity of other ships may have to the power setting also in non-assisted situations, for example when an encounter is approaching. In more detail, for proximity a 10 minute time window around the time instant is applied and the tracks of the ships during this interval are considered. If some point of the 10 minute track of a ship is closer than 3 NM to the 10 minute track of some other

ship, the ships are proximate. If the ship has no proximities with other ships, it is navigating independently.

The criterion seeks to take into account not only the distance but the speed changes due to anticipating of navigational situations or distancing from them. For example, if two ships are following each other with the same speed of 18 knots, they are proximate if they maintain a distance smaller than 3 NM. If the first ship suddenly stops the follower should reduce its speed in less than 10 minutes. On the other hand, if the ships are approaching each other with 18 knots each, they are proximate when the distance is reduced below 6 NM, or 10 minutes before the encounter. After passing, the ships are proximate until the distance has grown to 6 NM or 10 minutes after the encounter.

| Archive of coded AIS raw data | Archive of HELMI ice model data | Archive of operative ice charts |
|---|---|---|
| Decoded type 1-3 AIS Messages | Grids of relevant ice model variables | Gridded ice charts in HELMI resolution |
| Navigation data with ice chart grid nodes | Model variables at grid nodes | Chart variable values at grid nodes |

Combined AIS and ice chart data (model data not used here)

| Icebreakers identified | Ice classes and ship types included | Ship particulars database linked |
|---|---|---|

AIS, ice and ship data for selected ships

| Open water steaming vs icegoing | Fast ice vs pack ice icegoing | Proximity filtering |
|---|---|---|

Independent pack ice navigation data

Speed reduction statistics and its relations to ice conditions

**Figure 4**: Schematics of combining AIS messages with ice data and the subsequent analysis.

## The analysed data

The results are based on the AIS data received by Finnish terrestrial stations which is accumulated to the server of Traffic Safety Administration, and transferred daily to FMI. The analysed data subset comprises all ships with IA Super ice class and, on the other hand, all icebreakers.

The ship data is first divided to open water navigation and ice navigation and then arranged according a fourfold table using the criteria of independence and idling threshold (see preceding section). The open water steaming speed is used as a reference to icegoing speed but otherwise the open water navigation is not analysed. The results on speed variation are reported both in terms of absolute speed and relative speed; in the latter case average open water speed is 1. The icegoing is generally approached according to the fourfold table

| Independent ice steaming | Non-independent ice steaming |
| --- | --- |
| Independent idling in ice | Non-independent idling in ice. |

The icegoing is further divided between fast ice zone and pack ice zone. Most of the results in present report are for the pack ice zone where the independently navigating ships to some degree are free to select their route. Ships with IA Super ice class and icebreakers are treated separately. For the IA Super the following groupings of ship type were applied (see Table on page)

CARGO      BULK,CONT,GC,RC,RORO,V
TANKER     T_CHEM, T_CRD, T_LNG, T_LPG, T_PROD

Another grouping is in terms of northernmost port of destination

Area 1      Ships that have visited Bay of Bothnia ports
Area 2      Ships that have visited Sea of Bothnia ports but not Bay of Bothnia ports
Area 3      Ships that have not visited Gulf of Bothnia ports

The amounts of icegoing IA Super AIS data is given in Table. There are in total about 800 million AIS position reports. There is an essential data gap for the second and third season during which no AIS data from the Gulf of Bothnia is available. Thus all icegoing statistics for the Gulf of Bothnia is for seven winters only. This affects most the Sea of Bothnia as the AIS data from the severe winter 2009-2010 is missing and the results for the basin are mostly from two seasons only. Also the percentages of independent navigation in Table are lower for the two seasons with incomplete data. Otherwise the percentages of non-independence increase with the severity of the season.

About 53 percent of the IA Super data is independent ice steaming, 40 per cent non-independent ice steaming, and 7 per cent idling. The traffic intensity for the whole period and for ice steaming is shown in Figure 5 from which the regular fairways emerge clearly.  It is seen that from the Gulf of Finland and the Gulf of Bothnia there is almost complete coverage for the navigable parts of the basins while in the Sea of Bothnia there are sea areas that have not been visited. This is in part due to the said data gap for the Sea of Bothnia The geographical bounds in Figure 5 correspond to the ice data grids. The limited range of Finnish terrestrial stations shows along the western coast of the Sea of Bothnia where the coverage grows intermittent and lacks completely nearshore, as well as in the Baltic proper close to the southern boundary of the grid.

**Table**: Icegoing AIS data for IA Super ice class

|  | Season | Million messages | Independent steaming % | Independent idling % | Non-Independent steaming % | Non-independent idling % |
|---|---|---|---|---|---|---|
| 1 | 2007-2008 | 45.1 | 72.9 | 0.8 | 22.3 | 4 |
| 2 | 2008-2009 | 7 | 36.4 | 5.2 | 55.3 | 3.1 |
| 3 | 2009-2010 | 74.7 | 44.6 | 0.6 | 54 | 0.9 |
| 4 | 2010-2011 | 288.4 | 47 | 2.9 | 42.1 | 8 |
| 5 | 2011-2012 | 68.4 | 59.1 | 2.4 | 35.2 | 3.3 |
| 6 | 2012-2013 | 203.6 | 54.3 | 2.7 | 40.5 | 2.4 |
| 7 | 2013-2014 | 58.7 | 64.7 | 1.4 | 29.6 | 4.3 |
| 8 | 2014-2015 | 32.6 | 57.4 | 1.5 | 37.5 | 3.6 |
| 9 | 2015-2016 | 25.9 | 67.3 | 0.6 | 30.4 | 1.7 |
| Total |  | 804.5 | 53.4 | 2.3 | 39.7 | 4.6 |
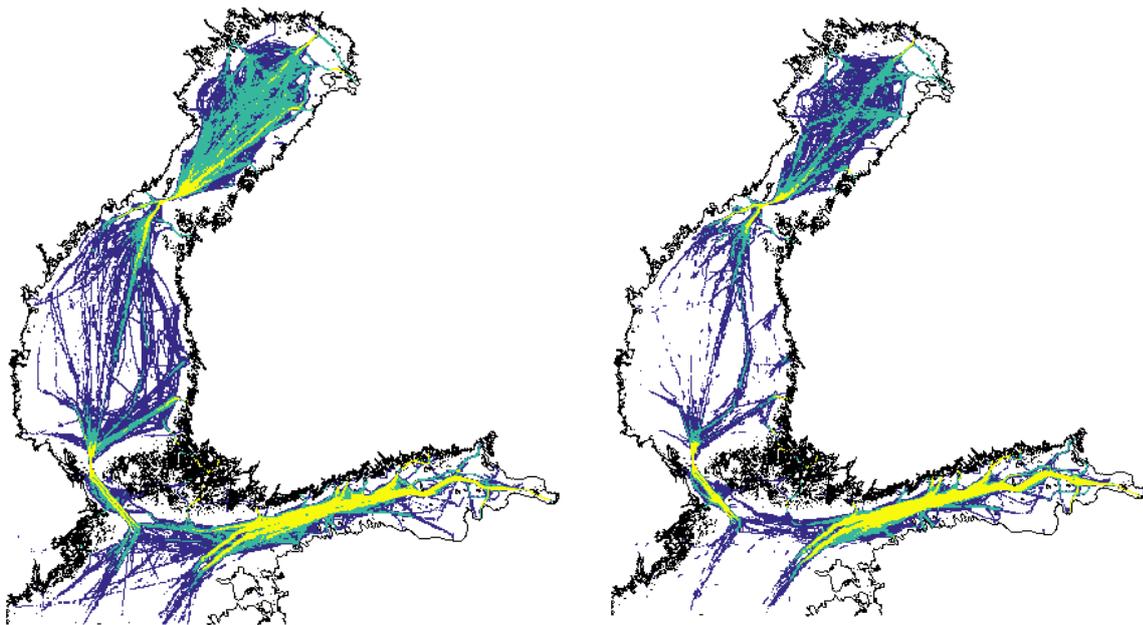


**Figure 5.** Number of different IA Super ice steaming ships that have visited the same 1x1 NM cell: from 1 to 5 ships blue, from 6 to 15 ships green, more than 15 ships yellow. Independent ice steaming left, non-independent right.

## ICE CLIMATOLOGY

The ice climatology was calculated from gridded ice charts. The number of ice days for the ice seasons during 2007-2016 are shown in Figure 6. This periods includes two severe winters (2009-2010 and 2010-2011) and two extremely mild winters (2007-2008 and 2014-2015). The number ice days in the north-eastern part of the Bay of Bothnia does not vary much seasonally though.
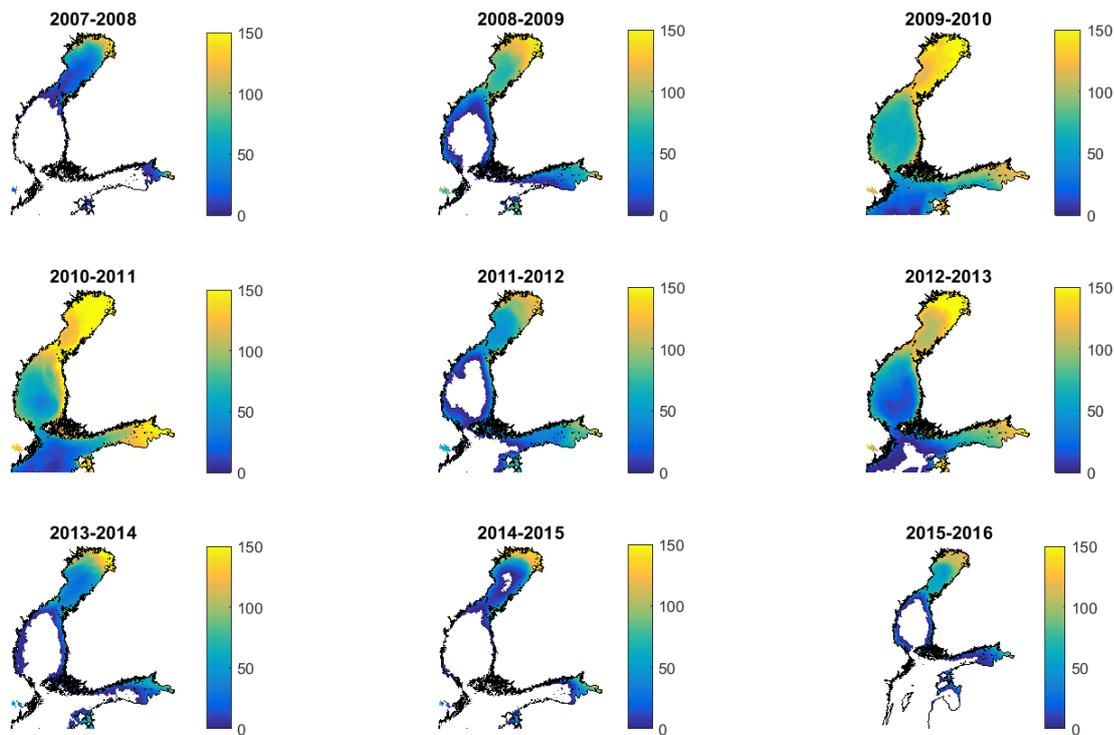


**Figure 6**. The number of ice days for the nine ice seasons.

The basic ice climatology based on charted ice variables for the period is shown in Figure 7. The nine year period is generally too small for a representative ice climatology although the typical regional variations and zonal gradients appear. Also, to remind, the charted thickness values refer to level ice thickness observations. They do not include the fraction of ridged ice and do not represent the overall ice thickness.

In Figure 7 the average thickness and concentration values are calculated over the 9-year period. The weight of a season in these values is proportional to the season ice days at the location, or generally to the severity of the season. They does not well represent an 'average ice season' which would be better defined as an 9-year average of seasonal averages. In addition, also the length of the ice season belong to the assessment of ice conditions. This gives four climatological averages that can be used projectively as expectations for the next ice season. For thickness these are, referring to a certain location,

1. Expected thickness on a randomly chosen ice day of the season.
2. Expected thickness on a randomly chosen day of the season.
3. Expected average thickness for the season.
4. Expected average thickness for the season, including open water.
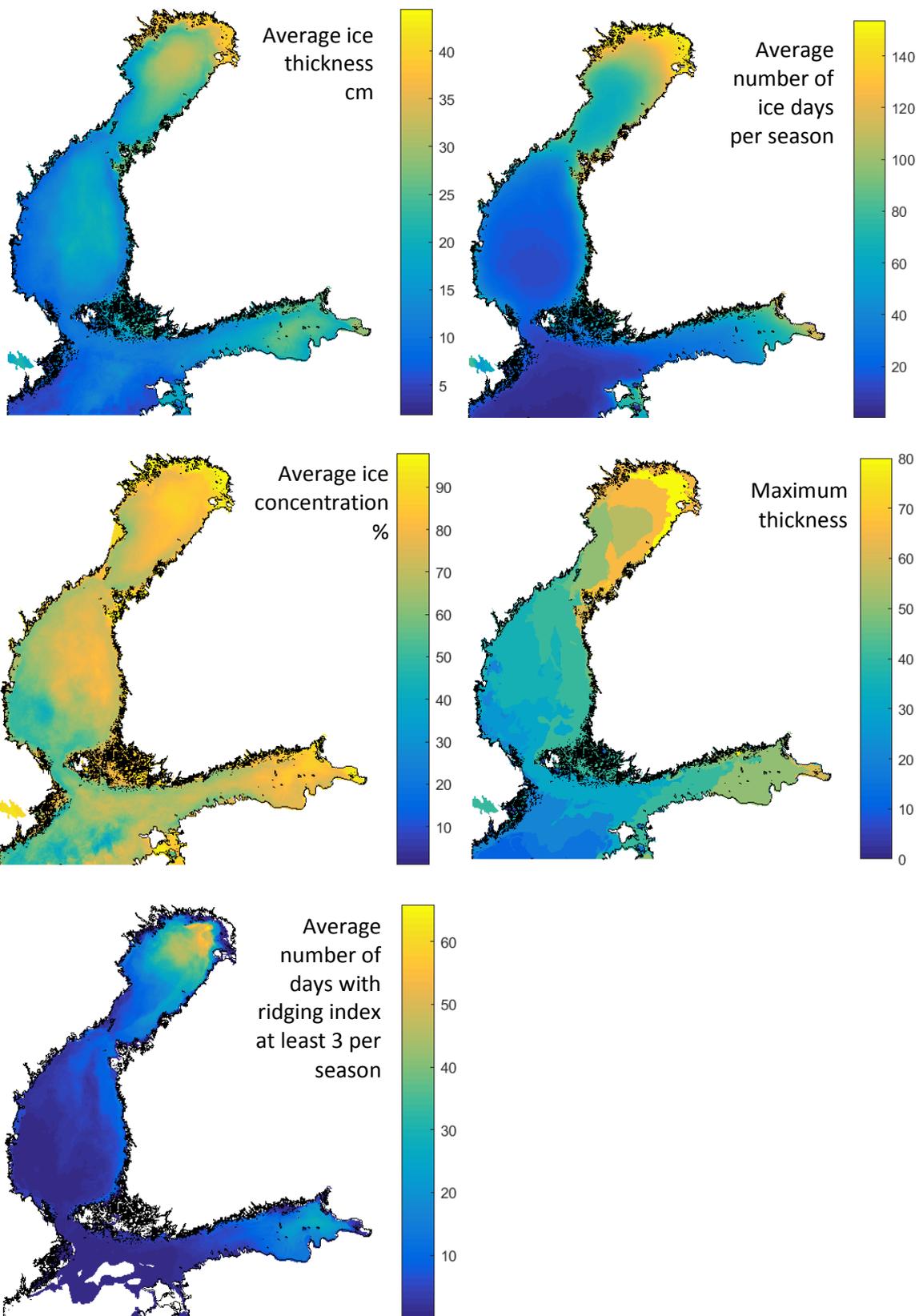
**Figure 7**. Ice climatology for the period 2007-2016 and for selected ice chart variables. Thickness and concentration are averages over the whole period, assuming that ice is present. Maximum thickness is the maximum for the whole period.

The charts of Figure 7 correspond to the first definition. The relevance of the options to the navigation depend on the viewpoint. Sweepingly, the first and third are a proxies of the difficulty of navigation, the second and fourth proxies of the effect of ice to transport. The first two are relevant for the long term ice performance of ships (navigational capability and travel time), and the two latter to the winter navigation system. This report concentrates on the ice performance, usually quantified as speed reduction, and the first climatology is relevant. The maximum thickness in Figure 7, on the other hand, is not an average but the maximum value found during the whole period 2007-2016. It may be used as a proxy of icegoing capability (ice class) required from the ships.

The number of ice days per season and the maximum thickness show the geographical variation from the typical advance of the ice season and the number of degree days. In ice thickness and concentration the effect of coastal leads and the dominance of south-westerly winds is seen. The average concentration is generally high and in the Bay of Bothnia the ice cover is closed most of the time. The equivalent thickness, defined as the thickness multiplied by concentration and divided by 100, is not significantly lower than thickness in most sea areas. In coastal sea areas number of ridging days shows a signal somewhat opposite to thickness and concentration. Both features are due to the same alternating coastal processes of divergence and deformation however. The northern part of the Bay of Bothnia stands out as an area with difficult ridging conditions affecting approaches to Oulu, Kemi and Tornio.

## REGIONAL VARIATION OF ICE NAVIGATION SPEED

### Ice steaming speed

The regional variation of ice navigation speed is described in terms of average speed calculated in the cells of the 1 NM grid of ice information. The results are presented as colour coded charts with pixels corresponding to the 1 NM cells. The results are for IA Super ice class or icebreakers and for the whole period 2007-2016. They comprise thus both the seasonal and interannual variation and represent 'navigation climatology' of the long term response of ship traffic to ice at different sea areas. The weight with which a certain ice season contributes to the average at an ice covered grid cell is proportional to the number of AIS messages from the location during the season. This is, on the other hand, is proportional to the severity of the season. The results have relevance to the ice performance of the ships and match the presented ice climatology. The other three ways, discussed in the preceding section, to define ice climatology have their counterparts in terms of ship speed but are likewise not considered here.

As quantified by ice navigation speed decrease, the response to ice conditions generally follows climatological thickness characteristics in a regional scale. However, in 1 NM resolution the correspondence is much obscured by the patterns of the winter navigation system, especially the standard locations of icebreaker dirways on which most of the traffic concentrate (Figure 5 ).  This feature is emphasized for shorter time periods.

The spatial distribution of ice steaming speed over the whole period is shown in Figure 8. The values in the grid cells are averages over all speed values exceeding 0.5 knots. As concerns the IA Super icegoing speed as a proxy of ice thickness this applies generally in a basinwide scale. In the

Bay of Bothnia the climatological ice gradients do not show strongly but the basin appears as a single ice regime when described in terms of speed and with fairway dominance. In the eastern Gulf of Finland and in the Sea of Bothnia the ice conditions the speed is more clearly related to regional ice conditions.
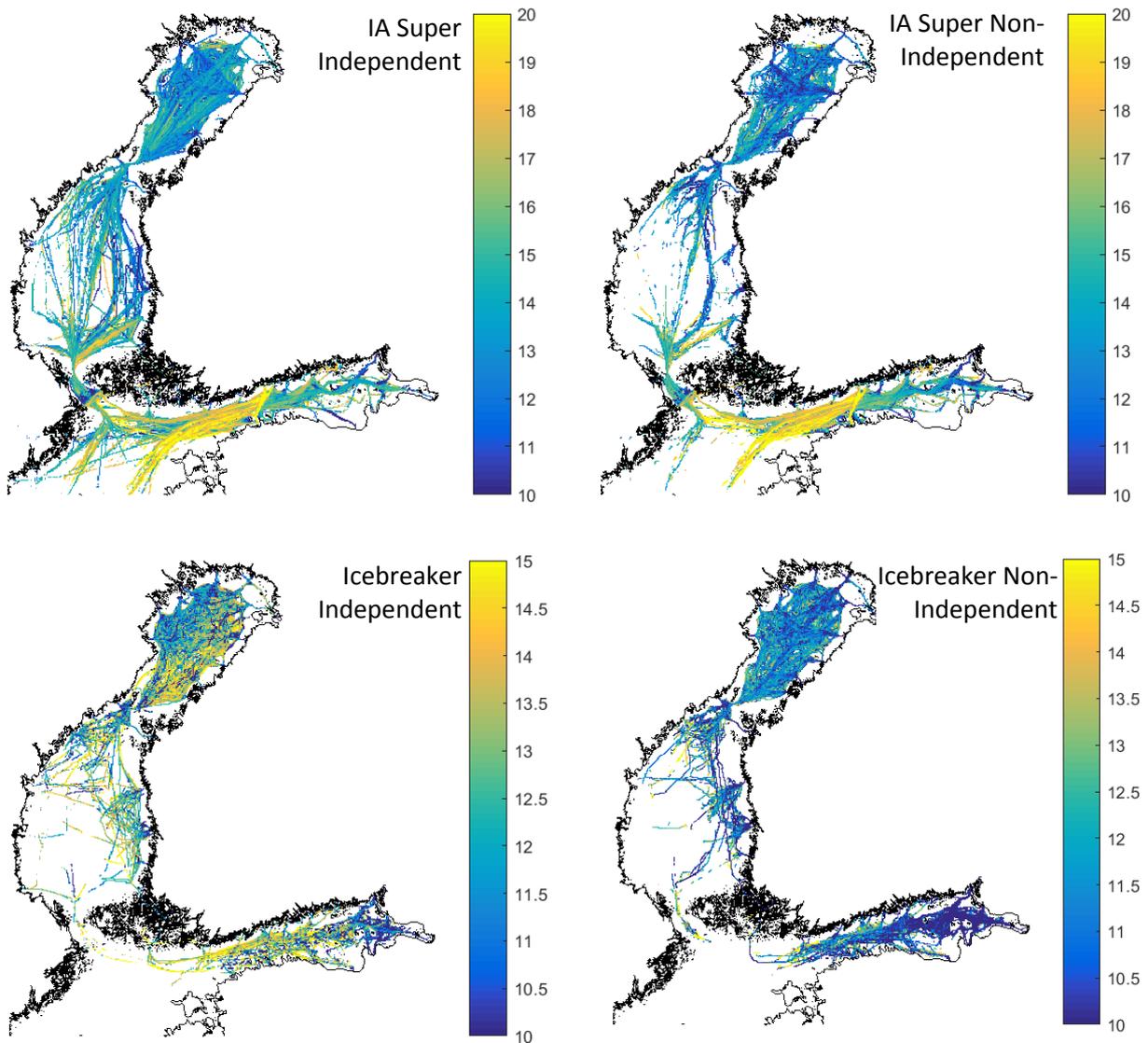


**Figure 8**. Average independent ice steaming speed (kn) for 2007-2016. The colour scale reaches 20 knots for IA Super and 15 knots for the icebreakers.

The non-independence of IA Super ships in the Gulf of Finland, in the Sea of Åland and the Quark is likely to be due to high areal density of ships. The average IA Super speed in these areas has about the same spatial distribution for independent and non-independent modes but is different from the spatial distribution of icebreaker speeds. In the Sea of Bothnia the network of independent steaming is more extensive but the speed is about the same in areas where both modes have been frequent. The main difference is in the approach to the Quark that slows down non-independent steaming speeds.
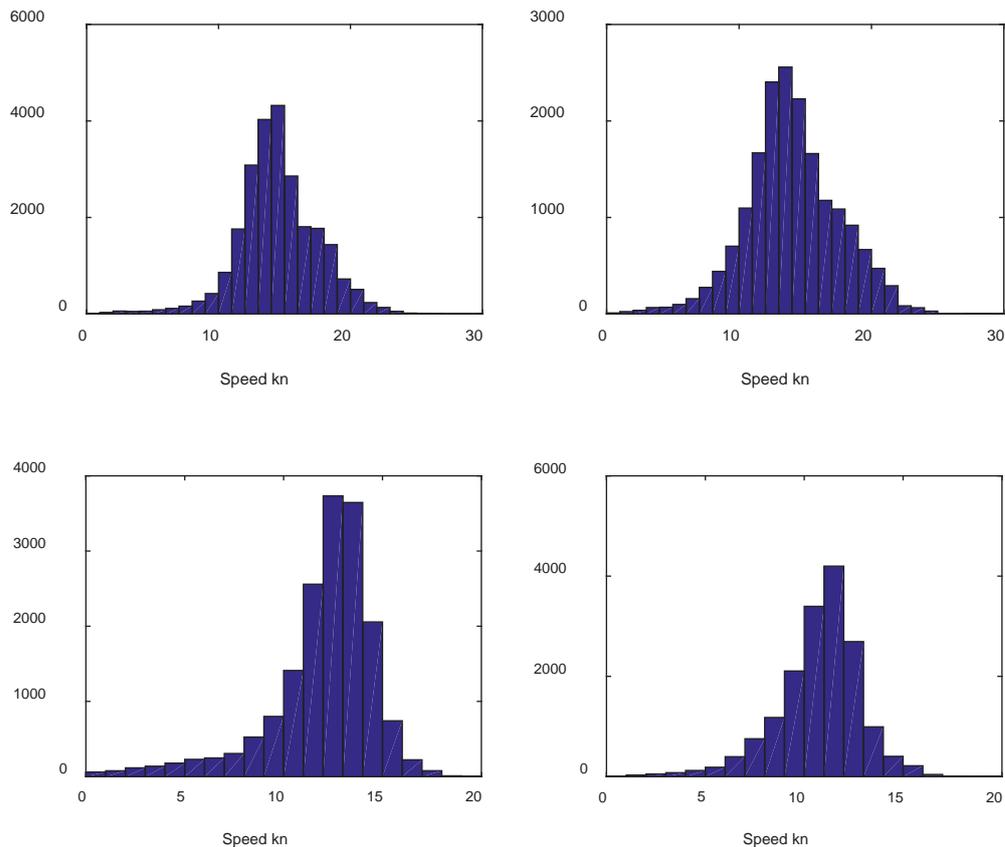
**Figure 9**. Histograms for grid cell speeds for IA Super traffic 2007-2016 (upper panels) and icebreakers (lower panels). On the left, independent ice steaming ; on the right, non-independent ice steaming;

In the Bay of Bothnia there is a clear difference between the two modes and the spatial speed distribution for the non-independent steaming has similar pattern for both IA Super and icebreakers. This is likely to be due of convoys and assistance and also correlates with the. However, the icebreaker speeds are about 75% from the IA Super speed as the number of assisted slower ships in lower ice classes is higher. Comparing to the traffic intensities (Figure 5) it is seen that IA Super traffic generally speeds up in main fairways (ice channels) when independent and slows down when non-independent, while when steaming independently in the less densely navigated parts of ice cover they cannot maintain their ice channel speed.

Apart from the non-independent steaming in the Bay of Bothnia the spatial distribution of icebreakers is very different. Their independent ice steaming is characterised by fast and usually short transits interspersed by tracks of slow progress and the typical fairway patterns do not emerge. There is a clear difference between independent icebreaker speeds between the western and eastern part of the Bay of Bothnia. This cannot be related to ice conditions. As the operation profiles are much more complicated for icebreakers than for IA Super vessels, a manifest connection between speed and thickness statistics is not expected. The icebreaker results are presented mostly for reference purposes only.

## Relative steaming speed

The spatial statistic of absolute speed generally follows the gradients in the ice conditions but is as much affected by traffic density, ship assignments and the location of the fairways. The weight of individual ship or certain ship type in a grid cell average is proportional to the number AIS messages from the ship. The speed averages are then rather a proxy of traffic flux or the number of ships passing through the grid cell in a unit time.

These effects of ice cover to the performance of individual ships are more clearly seen from the distribution of relative speed, or the ice steaming speed scaled by the open water steaming speed, Figure 10.  In the charts the grid cell value is the average of all relative speeds in the cell. Each relative speed value is the observed icegoing speed value of a ship divided by open water steaming speed of the ship in question. Open water speed is the average for 2007-2016 and does not include coastal zone corresponding to average fast ice extent. Archipelago and channels to ports are thus excluded.  Assuming normality for the variation in the grid cell, value 1 means that half of the observations in the cell have relative speed less than 1, another half exceeding 1. Values smaller or greater than 1 indicate dominance of speed reduction or increase in the cell.

The first observation is that a large fraction of independent IA Super traffic is likely to increase its speed when navigating in ice, especially outside the regular channels. This indicates that they increase their power setting as well. A possible explanation is that power is increased to maintain steady progress in an ice cover with variable thickness and especially to avoid slowing down too much in ridged sections. In densely trafficked channels the thickness variation has been smoothed and the power can be reduced. However, a customary expectation that ice resistance is larger outside channels may determine the choice of power setting irrespective of actual experienced difficulty of navigation.

 It is observed that pattern of fast traffic west of Helsinki-Tallinna line is not as striking as for the absolute speed so the latter feature is mostly due to faster fleet in this area. Otherwise in the Gulf of Finland there is a gradient following the climatological ice conditions which is even more clear for non-independent steaming. Independent and non-independent approaches to the quark have clear difference in speed distribution.

The steaming speed decrease along the main fairways in the Bay of Bothnia are clearly seen. On the average, outside the main fairways the IA Super ships maintain or exceed their open water steaming speed. This is found for both modes. In some areas of the Bay of Bothnia, especially on the western half of the basin, there are opposite signals for absolute and relative speed. The evident explanation is that the iceworthiness of ships heading to different ports varies. Less powerful ships heading to the Swedish ports increase their power but still do not quite attain the speeds observed in the eastern half. Once and for all, it appears that the ships in the Bay of Bothnia thrive to maintain a common 'navigation system standard speed' to improve the predictability of travel times and thereby increase the efficiency of the system.

The relative speed of icebreakers in Figure 10  is less informative as open water steaming does not have the same significance for them as for commercial vessels and the icegoing speed is determined rather by fixed arrival times to certain waypoints than by need of effective progress. In independent steaming the fairway patters disappear and in the Bay of Bothnia the east/west

division is again apparent. Together with observations from Figure 8 it is evident that on the western side the icebreakers increase and on the eastern side decrease their power setting to maintain about the same average 'system speed' in assisting configurations.
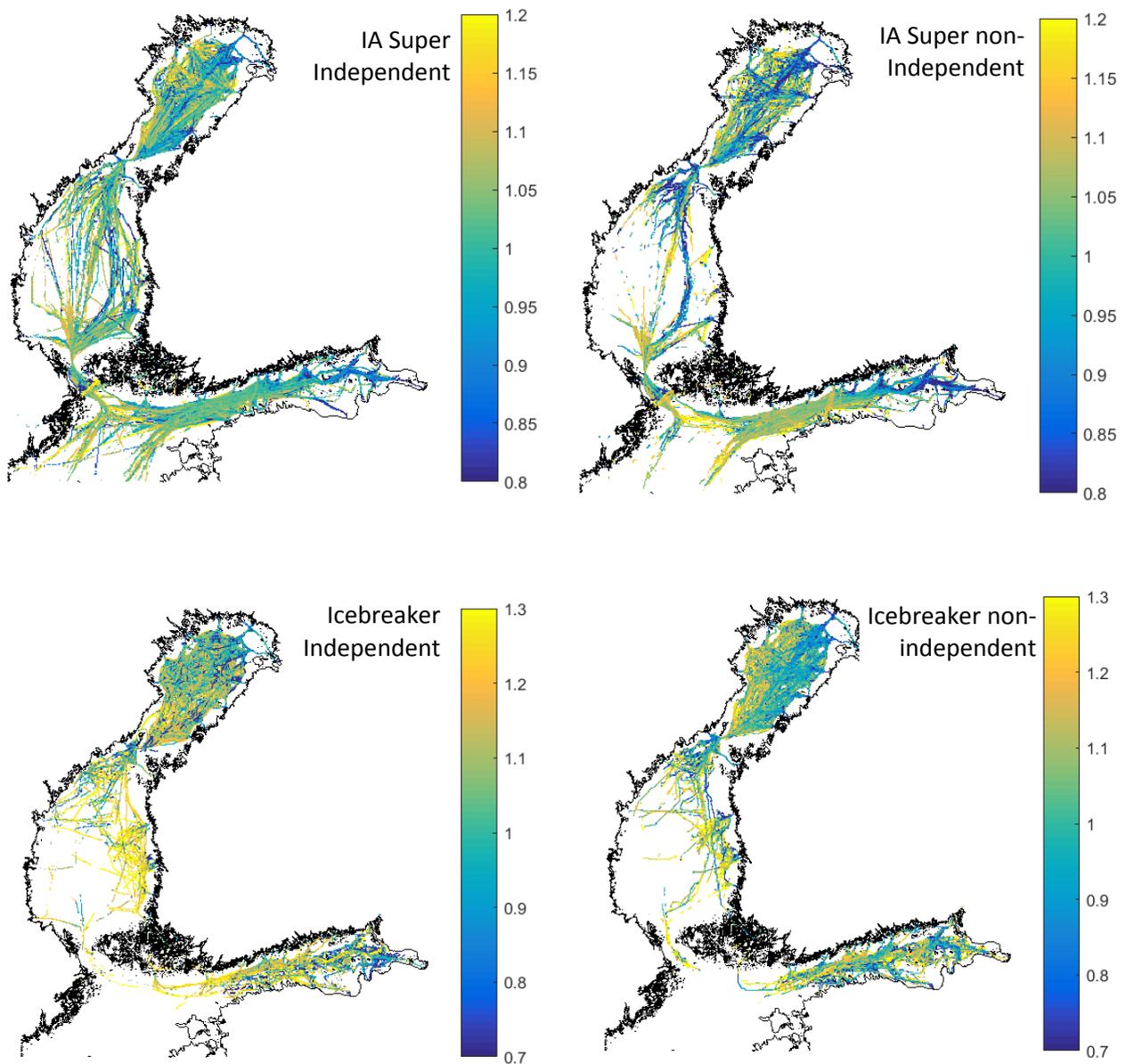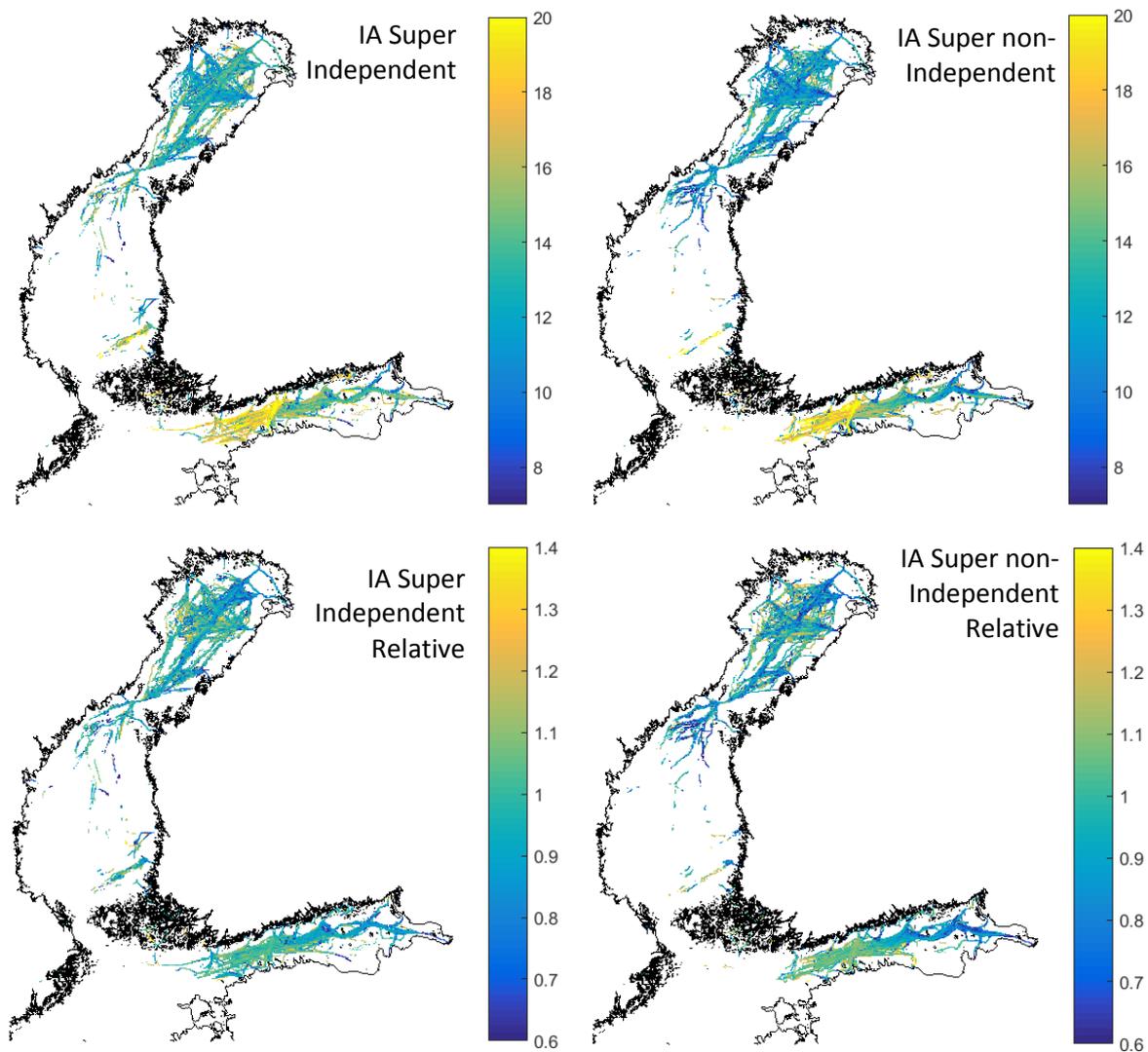


**Figure 10.** Ice steaming speed relative to open water steaming. All traffic 2007-2016.

## Steaming speed in more difficult ice conditions

The previous climatologies of ice steaming speed relate to the average ice conditions that include also thin ice types and low concentrations. Only in the central Bay of Bothnia does the climatological average thickness reach 30 cm. To find out the ship response to more difficult midwinter ice conditions a subset of data with ice thickness at least 30 cm and ice concentration at least 90% was selected and steaming speed climatology was calculated (Figure 11).

The averages of absolute and relative speed are reduced but not excessively. The speed reduction is more clearly seen from the relative speeds that exceed unity considerably only sporadically.

Along the fairways of the Bay of Bothnia the speed reduction is about the same as before suggesting again that the ships seek to maintain about the same 'system speed' irrespective of ice conditions. Regional speed variation follows the same patterns as before but is generally smaller. Especially in the Bay of Bothnia the spatial speed distribution is more uniform and about the same for fairways and ice cover outside them.



**Figure 11.** Average ice steaming speed. All IA Super traffic 2007-2016. Ice concentration at least 90%, ice thickness at least 30 cm. The scale of the colorbars for absolute speed is the same as in Figure 8, the relative speed colorbar has a double range in comparison to Figure 10 upper panel.

It was seen before that especially in the Bay of Bothnia the absolute ice induced speed decrease was smaller in the main fairways than outside them for independent traffic. For the non-independent traffic this pattern was opposite. For relative speed the decrease was larger in channels for both modes. These observations suggest that various decisions which depend on the expected icegoing capability of the ships have a large effect. In Figure 12 the ratio of independent to non-independent speed is shown for all ice types and for difficult ice conditions. The spatial

distribution is almost identical in both cases which suggests it is a traffic system feature that depends at most weakly on ice conditions.
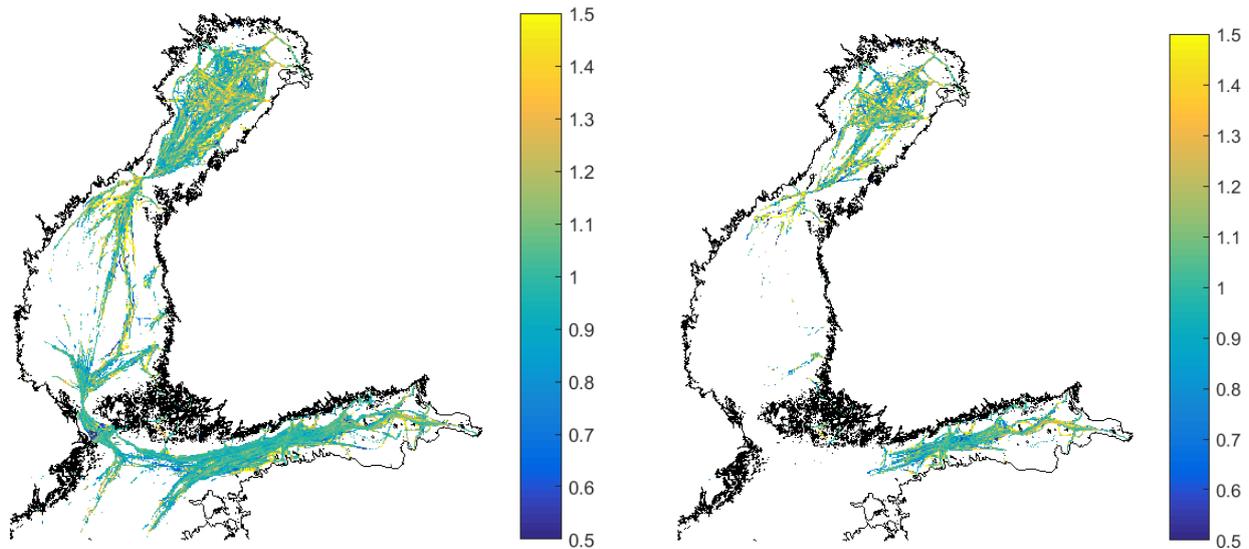


**Figure 12**. Ratio of independent/non-independent ice steaming speed. All IA Super traffic 2007-2016. On the left all ice types, on the right ice concentration at least 90% and ice thickness at least 30 cm.


## Effect or ridging on steaming speed

Degree of deformation is a numeral 1-5 described in section . To study the effect of ridging the numerals were arranged to groups 1-3 and 4-5 which are here called, following the largest numeral per category, 'slightly ridged' and 'heavily ridged'. The spatial distribution of speed average was calculated for the Bay of Bothnia only. It was also required that ice thickness is at least 30 cm and concentration at least 90%. Increased ridging affects average speeds considerably and the speed reduction is more pronounced for non-independent steaming (Figure 13, two upper panels). The most difficult area is in the mid basin, another is Oulu-Tornio entrance sector. The ridging appears to obstruct traffic more in west-east direction. This can be also due to compression present in ridging ice fields. The patterns of speed variation emerge more clearly than in Figure 11 as the colour code is scaled to the Bay of Bothnia speed range.

A different picture emerges from the third panel of Figure 13 giving the ratio of speed in heavily ridged ice type to that in all ice types. It is seen that the ratio is close to 1 in most areas. Although the deformation numeral has effect to ice navigation speed its value for closed ice types of midwinter is mostly 4 or 5. The ice thickness itself is thus sufficient proxy for the difficulty of ice conditions in the long term speed climatology although for studies of ship performance the ridging parameter is relevant.
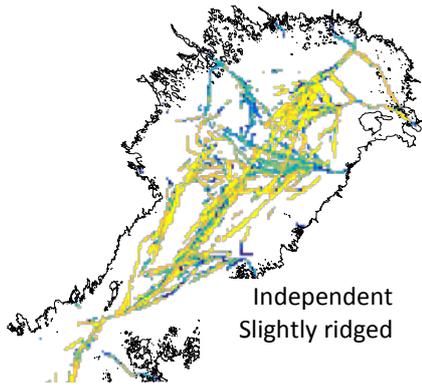
Independent
Slightly ridged

Independent
Heavily ridged
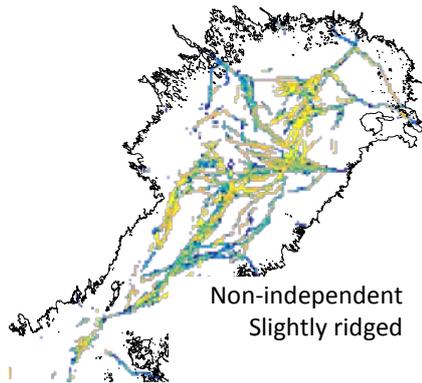
Non-independent
Slightly ridged

Non-independent
Heavily ridged
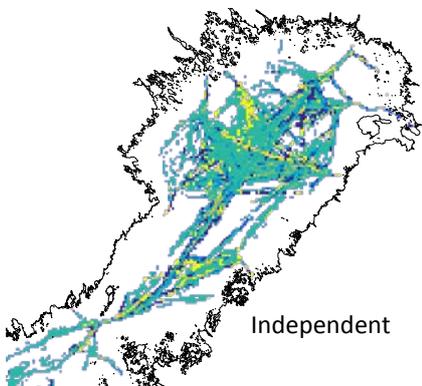
Independent

Non-independent

**Figure 13**. In upper two pairs mean steaming speed for the two ridging categories. The lowest pair gives the ratio of steaming speed in heavily ridged ice to that in all ice types. Concentration at least 90%, ice thickness at least 30 cm. All IA Super traffic 2007-2016.

## SHIP SPEED REDUCTION IN ICE

### Introduction

The speed reduction is a relation $v(h)$ of ship speed on ice thickness. This is considered here as a statistical sense, as the average over many observations of speed corresponding to same ice thickness value. The term $h$-$v$-curve is often used for $v(h)$. The thickness values refer to the gridded charted ice parameters which are defined for 1x1 NM cells. This is the maximum resolution for the present thickness data. In many contexts it is useful to decrease the resolution of ice information by using parameter averages for $nxn$ blocks of grid cells, usually to decrease local variation or variation due to small data sets.

The thickness may refer here to the charted values of typical, maximum or minimum thickness; or it may to equivalent thickness $h*C$ or typical thickness multiplied by concentration defined as areal fraction $0{\leq}C{\leq}1$. Equivalent thickness is then the same as areally averaged ice volume. Equivalent thickness in terms of maximum or minimum thickness is not well defined. The charted thickness values refer to level ice thickness that is easily measured and can be estimated from moving ships. The contribution of deformed (rafted, ridged) ice to the total ice thickness is not given in quantitative terms in the ice chars but only as a qualitative index. In principle ridging can be included to the equivalent thickness if the volume of ridged ice as volume added to the volume of level ice is known, but the estimation of this from the ridging index is not attempted here.

### Speed averages

The present results are calculated from the data connecting for each AIS position message the ship speed to the ice parameters found in the grid cell where the ship is located. This report aims at very general characterisation of $v(h)$, usually averaging over the nine-year observation period. Interannual, seasonal and regional variation is only occasionally addressed. Equivalent thickness is most commonly used for $h$. For a certain region $R$ and time period the calculation of $v(h)$ may refer to the following

1. The AIS messages of speed, indexed by $m$,
2. The grid indices $(i,j)$ of the gridded charted ice parameters
3. The individual ship, indexed by $k$

These allows a large number of different definitions. The terms *message average*, *ship average*, *fleet average*, *climatological average* and *grid average* are used accordingly and explained below. In addition to $v(h)$ the speed normalised by open water speed

$$V(h) = v(h)/v(0)$$

is used especially when the speed reduction is quantified. The simple message average

$$v(h) = \frac{1}{N(h)} \sum_m v_m(h)$$

is calculated over all AIS messages m for which thickness value $h$ is found. For a certain ship having index $k$ in the ship catalogue, the ship message average is

$$v_k(h) = \frac{1}{N_k(h)} \sum_m v_{k,m}(h)$$

The overall average message average is obtained as an average over $v_k(h)$ using ship message numbers $N_k$ as weights. Another definition, without the weights, gives the fleet average

$$v_F(h) = \frac{1}{N_F} \sum_k v_k(h)$$

or the average over speed reduction relationships of $N_F$ individual ships. All these can be normalised with the open water speed. For the fleet average two normalisations are relevant

$$V_A(h) = \frac{v_F(h)}{v_F(0)}, \qquad V_R(h) = \frac{1}{N_F} \sum_k \frac{v_k(h)}{v_k(0)}$$

The first considers the speed reduction in terms of absolute values, i.e. knots, the other in terms of relative reduction from the ship's open water speed. The first is more proper average if the absolute reduction does not depend on speed, the latter if the absolute reduction is proportional to speed.

For a certain time period $T$ and region $R$ the grid averages are defined in terms of grid cells. The data links AIS message speed $v(ij)$ in a grid cell with grid cell thickness $h(ij)$. The averages of these over $T$ are $\bar{v}_{ij}$ and $\bar{v}_{ij}$. The simplest definition uses the averages only

$$v_C(h) = \frac{1}{N(\bar{h}_{ij} = h)} \sum \bar{v}_{ij}(\bar{h}_{ij} = h)$$

which is termed here climatological average. It does not use the link between AIS retrieved speed and grid ice thickness but considers speed and thickness as independent quantities. Similar definition is possible whenever averages of speed and thickness from the same period and region are available. This is the usual approach when detailed navigation and ice data are not at hand. In a more detailed approach the grid cell average is taken first over messages that are linked with thickness $h$

$$v_{ij}(h) = \frac{1}{N(h_{ij} = h)} \sum v_{ij}(h_{ij} = h)$$

The overall message average $v(h)$ is obtained by averaging over all grid cells and using the numbers of messages $N(i,j)$ per grid cell as weights. Another way is to have the same weight for all grid cells,

$$v_G(h) = \frac{1}{N(G)} \sum_{ij} v_{ij}(h)$$

This is called here the grid average. These averages referring to grid indices are defined as message averages but can be defined as fleet averages (vFc(h)) as well. If the 1NM resolution is too fine, or if regional variation is at focus, the averages can be defined in terms of grid cell blocks or subdivisions of R defined as grid cell lists. These are not elaborated here.

## Interpretation of the speed averages

The different averages describe different manifestations of the speed reduction: efficiency of the transport system, ice performance of ships, or regional variation. The averages have also different probabilistic interpretations which must be taken into account when inferences on the performance of individual ships is based on $v(h)$. Behind each $v(h)$ is a probability distribution $f(v|h)$ of thickness dependent speed. These distributions, although readily available, are not studied here further.

The number of AIS messages received from a ship is proportional to the time the ship is within the reach of the receiving stations. The speed reduction as message average $v(h)$ quantifies how ice conditions affect the general flow of ship traffic. This can be understood as ship flux, or a number of ships passing through a control surface in a unit time. The flux decreases with the decreasing average speed of the ships. The flux can be defined in terms of tonnage instead by weighting speed averages by the ship tonnage. This measure is not applied here but would better quantify the actual transport efficiency.

In a probabilistic interpretation the message average $v(h)$ is the expected speed for a randomly chosen ship traversing ice with thickness $h$. Some care is due in considering what 'random choice' means in each context. As considers the data applied here, the choice is in terms of a random AIS message over the time period which is usually the whole period considered, 2007-2016. This averages over interseasonal variation. The seasonal number of icegoing messages is proportional to the severity of the season and thus severe winters dominate the average

If instead speed reduction during an average season, or in other words, for a ship chosen randomly from a randomly chosen ice season is desired, the average must be weighted with the seasonal numbers of messages from icegoing ships. The same holds for shorter time periods, for example for a randomly chosen day of ice season. If $v(h)$ is calculated by weighting with daily message numbers then, as ice conditions and traffic situation do not change much during a day, this can be taken to refer to 'random ship selected from the traffic map at random time instant'. If the simple, unweighted message average $v(h)$ is used here this assumes that $v(h)$ does not depend on ice situation in general but only on $h$. This is not likely to be so, as the ship assignment decisions depend on the severity of ice situation. The severity, on the other hand, is expected to be proportional to daily numbers of AIS messages from icegoing ships.

The averages defined in terms of individual ice transiting ships can be assumed to be less strongly dependent on the severity general ice conditions, and $v_k(h)$ or normalised $V_k(h)$ has the interpretation of expected speed reduction for randomly chosen instance of transit for a certain

ship. The fleet averages $v_F(h)$, $V_A(h)$ and $V_R(h)$ are a summarising characterisation of ice performance of ships. They give the speed reduction for a 'representative' ship or for a ship randomly chosen from the ship catalogue. More specific information on ice performance is obtained by going into subdivisions in terms of classifications and ship hull and engine particulars.

The grid cell averages seek to have more emphasis on the geographical variation of the data. The climatological averages $v_C(h)$ and $v_{CF}(h)$ have simple interpretations. Referring to some period T they give the expected speed at a location (or area) for which the thickness time average is $h$. This the more meaningful the longer the time period is (ice season or longer) as the speed and thickness values are not linked on message level in the derivation. Thus the term 'climatological' is warranted.

The variations of traffic intensity is large and most ships follow the main fairways and existing ice channels. Thus the speed averages are dominated by channel resistance. The channel ice conditions relate to the thickness characteristics of surrounding but depend also on the other processes of channel rubble evolution. This is more so for frequently transited and old channels. In grid cell averages all cells with same thickness have the same weight. They can be interpreted as speed reduction in a randomly chosen grid cell with thickness $h$. The number of grid cells covering main fairways is usually smaller than the number of cells transited outside them. The latter contains instances of independent icebreaking transit as well. The grid average $v_C(h)$ is thus expected to be more close to speed reduction in icebreaking transit and more applicable when regional navigability and routing are considered.

## Basic subdivisions and practices

The various $v(h)$ -curves can also further restricted in terms of time, region, ice parameters, ship identifier, ship type, ice class, hull and engine particulars, frequency of visiting, mode of navigation, modes of assistance and proximity, and special navigational situations.

Here the winter navigation system in general and summarising characterisation of how ice conditions affect speed is at focus. First, ice navigation is divided into ice steaming and idling with 0.5 knot threshold. Speed variation is not considered relevant for idling that is characterised by relative time fraction. Ice steaming is categorised in terms of the following fourfold field:

| Independent absolute speed | Non-independent absolute speed |
|---|---|
| Independent relative speed | Non-independent relative speed |

Regional subdivisions are not used due to the large variation in the severity of the seasons in the data. Instead, the fleet is divided into three classes in terms of the northernmost port visited or in terms of ship type groups (section ). In addition, in fleet averages a threshold for the minimum number of messages may be set.

The general practice is to find speed records that correspond to certain ice conditions and study how the average speed depends on the ice conditions. Fast ice is treated separately and most results pertain to pack ice only. After rounding intermediate values, the ice conditions are defined in terms of pack concentration $C$ that ranges from 10% to 100% in steps of 10 and with value 95% added, and thickness $h$ that ranges from 5 cm to 90 cm in steps of 5 cm. This generates two-

dimensional speed reduction tables $v(C,h)$ or 'speed matrices'. Although complete characterisation in the context these provide rather an overview and material for further analysis than immediate quantitative observation of the speed reduction.

To get more applicable relationships between speed and thickness characteristics the description is simplified in one of the two ways: 1) using equivalent thickness or the product of thickness and concentration divided by 100, or 2) selecting data with concentration threshold for closed ice cover. Figure 14 shows the histogram of concentration values for IA Super speed messages, and the same as two-dimensional histogram in *C-h*-space. It is seen that the majority of speed data from high concentrations especially for thick ice types. There is considerably data in the lowest concentration category but the equivalent thickness is less than 5 cm. The mid-range of concentration has little weight in the equivalent thickness, and for the dominating 90%-95% the equivalent thickness is close to normal thickness.

Thus the alternatives 1) and 2) do not differ much especially for thicker ice classes and the equivalent thickness is close to actual thickness in classes that are relevant. In the sequel equivalent thickness is used systematically, usually termed 'thickness' and denoted by $h$. The ice navigation in the Baltic is mostly navigation in closed ice cover. On the other hand, this means that the results in terms of equivalent thickness are not readily applicable to polar seas where mid-range concentrations are commonly encountered.
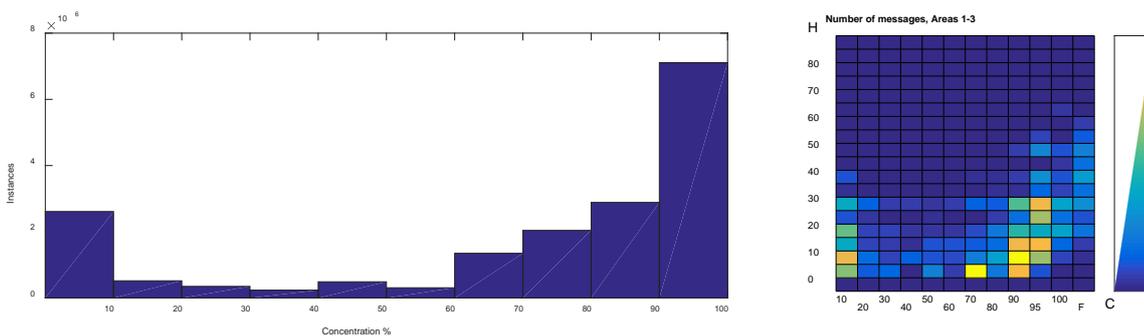


**Figure 14**. Histograms of ice concentration values for IA Super independent ice steaming, and the numbers AIS messages for each thickness-concentration category.


## IA Super ice class and power setting changes

The main shortcoming of AIS data is the lack of propulsion power. In ice steaming the decrease of speed can be due to the increase of ice thickness or reduced power setting. The ships may also increase their power setting with increasing thickness to maintain steady progress. Different navigational situations and proximity of other ships may have effect as well for which reason independent and non-independent navigation are treated separately. The criterion demarcating the two modes was set rather strict.

Figure 15 gives a scatterplot of ship specific speed reductions for IA Super independent steaming when going from 10 cm thick ice to 20, 30 and 40 cm thick ice. The scatter increases with thickness change. There are also values above the diagonal suggesting that power setting is increased with thicker ice. However, for ships with at least 10000 messages (about 500 miles of ice steaming) in

the thicker ice the scatter is smaller and the values are below the diagonal or at it. This strongly suggests that independent IA Super vessels with regular icegoing generally keep their power setting throughout their ice transit. Figure 16 compares IA Super and IA classes. The data is restricted to the Gulf of Bothnia and severe season 2010-2011 and the ships have at least 3000 messages. While IA Super shows consistent speed decrease the scatter of IA class speed decrease is much wider and about similar for transitions to 25 or 45 cm thick ice. A considerable number of vessels increase their speed. The likely reason is that otherwise they cannot maintain steady progress in an ice field with variable thickness, especially ridge zones. Unlike for IA Super no assumption that variations in power settings are small can be made. Thus all analyses of speed reduction in this report address IA Super class only. This does not include here icebreakers.
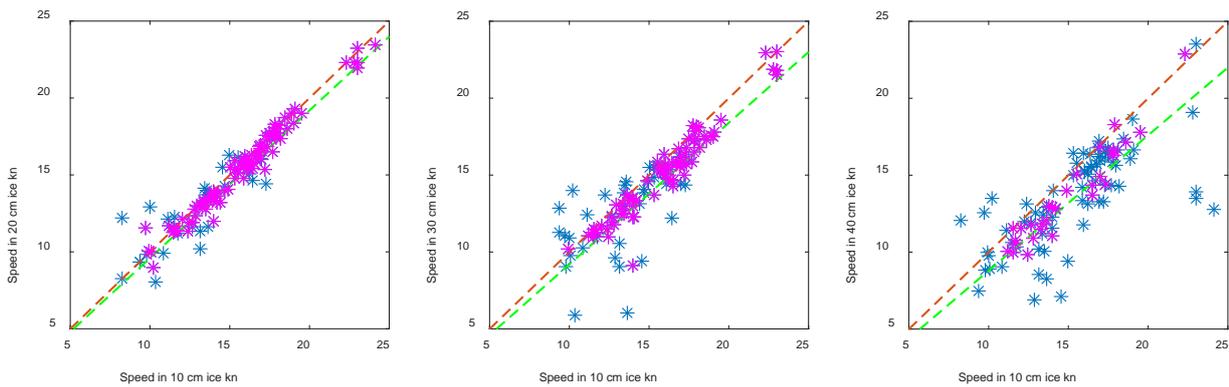


**Figure 15**. Speed reduction for individual independent IA Super vessels. Magenta indicates ships that have at least 10000 messages.
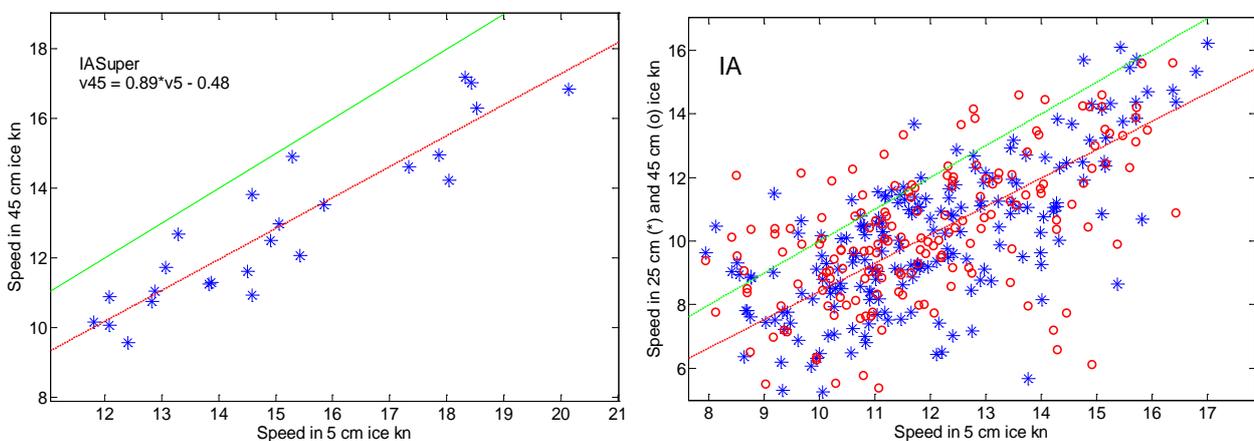


**Figure 16**. Speed reduction for individual independent IA Super and IA vessels. Gulf of Bothnia data 2010-2011. Along green line no reduction. Ships have at least 3000 messages.

The analyses are based on 139 IA Super vessels. The basic message statistics is as follows.

- There are somewhat less than 200 million messages.
- 35 vessels have more than 2 million and 104 more than 200 000 messages.
- About 25 % of messages are from ice transit.
- 31 vessels have more than 500 000 and 100 more than 50000 ice transit messages.
- About 40% of ice transit is independent ice navigation.

- For independent ice navigation, 33 ships have more than 200 000 and 96 more than 20000 messages.
- From independent icegoing 92% is steaming (speed > 0.5 knots).
- From non-independent icegoing 74% is steaming.

On day of navigation comprises on the average 5000 messages so that 500 000 messages is 100 days of navigation. Figure 17 shows the numbers of icegoing and independent ice steaming messages for 100 first IA Super vessels. The fraction of independent navigation is of the same order for all ships.
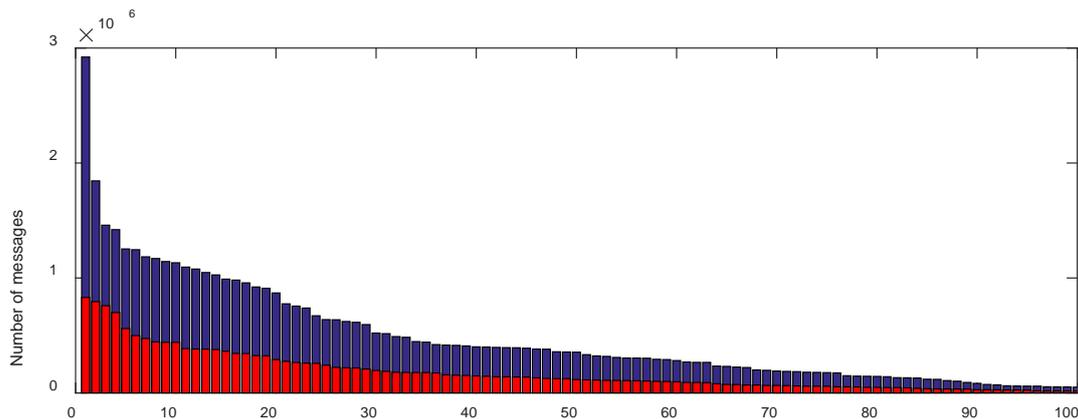


**Figure 17**. The number of icegoing messages (blue) and independent ice steaming messages (red). First 100 IA Super ships included.

## Speed reduction, message average

Message averages are taken over all AIS speed messages with the same values of thickness $C$ and concentration $h$, or with same values of equivalent thickness $h$. The results for *(C,h)-space* are collected into tables (speed matrices) and illustrated with colour code. The speed matrices include both the mean speed and speed standard deviation. If relative speed (icegoing speed divided by open water speed) is used, coefficient variation is tabulated instead (standard deviation divided by mean). Figure 18 shows speed matrices for all IA Super ice steaming. All speed reports from grid cells with concentration C and thickness H have been collected and their average and standard deviation have been calculated.

The observed speed gradients in the *(C,h)-space* are not as smooth as could be expected from the large numbers of data, especially for dominating higher concentrations. In part this may due to the possible systematic bias in thickness determinations discussed in Section . However, a steplike 'phase transition' is apparent when speeds increase over 30 cm. For ice at most 30 cm thick the speed variation has no clear dependence on $C$ and $h$ and the speed can also increase with ice thickness. The dependence on the concentration is weak in all thickness categories. For 40 cm thickness the speed is almost constant over the whole concentration range for independent navigation and no clear gradient is found for non-independent navigation either. This hints to a strategy of avoiding risks rather than maximising transit speed.

For thicknesses exceeding 30 cm speed reduction is observed in the transition from 95% to 100% concentration but for independent navigation only. Generally the variation when C ranges from

80% to 100% and h from 35 cm to 50 cm is small. As was discussed, the message averages quantify rather the winter navigation system speed than response of ship speed to ice condition. It appears that the system seeks to maintain a certain 'system speed' that is independent of thickness and concentration variations, and this speed is set to lower level when ice thicknesses exceed 30 cm.
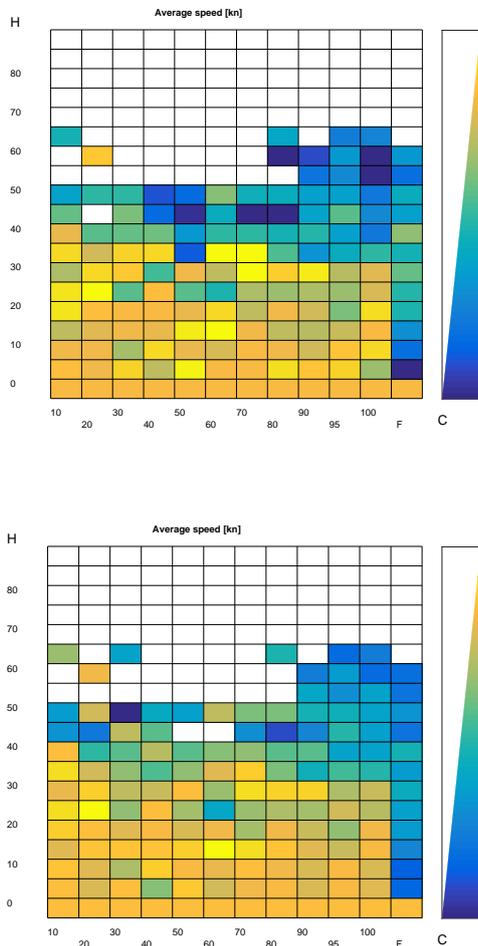


**Figure 18**. Speed matrices for all IA Super ice steaming 2007-2016. Upper panel independent steaming, lower panel non-independent steaming. F denotes fast ice.

The effect from the fact that different ships have different operating speed can be reduce by considering speed normalised by open water speed. The speed matrices in Figure 19 are averages of all relative speeds observed for the given pair of values *(C,h)*. For thicknesses not larger than 30 cm the icegoing speed more or less equals open water speed. The larger variation for absolute speed is therefore due to variation on how ships are assigned to different ports. For thicknesses exceeding 30 cm the speed matrix has slightly more pronounced dependence on *C* and *h* than was the case for absolute speed. This is likely to be due to the assignment of more powerful ships to more difficult ice conditions. These experience then larger speed reduction when they seek to adjust to the 'system speed'
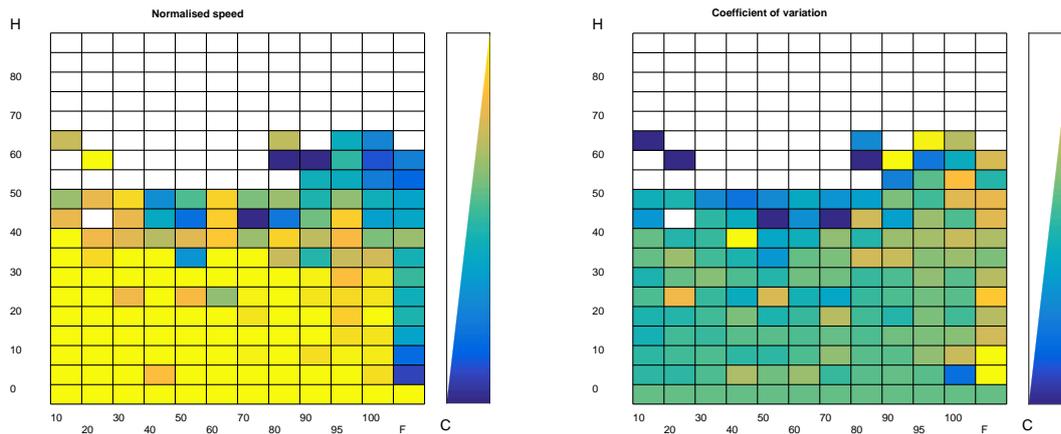
**Figure 19**. Speed matrices for relative speed. Independent IA Super steaming.

The discussed features emerge clearly in the speed reduction plots of Figure 20. A steplike speed reduction occurs when ice thickness increases from 30 cm to 35 cm. For the thicker ice regime the speed reduction is also steeper. The wiggling of the line in steps of 5 cm is likely to be due a systematic bias following from different observational methods; as the total message number is 20 million a smoother behaviour is expected. The steplike speed reduction at 30 cm is very likely real phenomenon however although it may be in reality less pronounced. For thicker ice the speed reduction reaches 30%. This is to be interpreted as a reduction of ship flux. If the speed reduction does not depend on ship size, which is probably not the case, it means also 30% reduction in transport flux, or more qualitatively stated, in the efficiency of the navigation system.
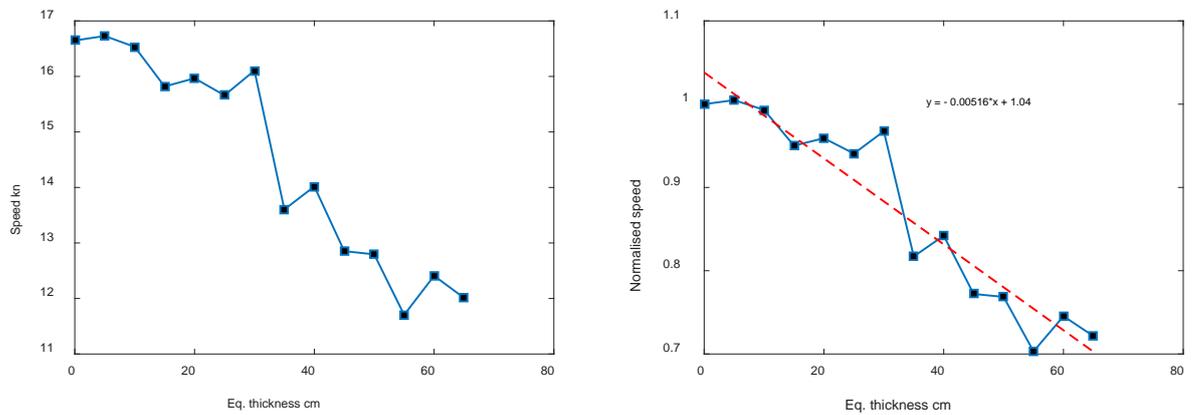


**Figure 20**. Speed reduction (message average) over all independent IA Super ice steaming. The speed value is the average of all AIS-retrieved speeds in ice cover of given equivalent thickness. The right panel shows the same plot normalised.

## Speed reduction, fleet average

Fleet averages are taken over a family speed reduction curves for individual ships. Here these are *h-v*-curves for equivalent thickness. In Figure 21 these are calculated in two ways: first for the absolute speeds of the ships after which the result is normalised, and secondly for the relative speeds of the ships. The results of the two methods do not differ for thicknesses less than 50 cm. The result for higher thickness values is affected by the decrease in the number of ships. As most powerful ships are assigned to the most severe conditions, these also have less steep speed reduction curves which shows as levelling or even increase of the averages for very high thicknesses. More powerful ships are also likely to be more frequently assigned to ice transit which shows as the less steep slope in the right panel of Figure 21. For the whole IA Super fleet the speed reduction is at most 30% or the same as for message averages.

The steplike speed decrease between 30 and 35 cm thicknesses does not emerge as clearly as from the message averages. However, the steepness of the slope increases similarly for the complete fleet. In almost all speed reduction plots there is an upward wiggle when thickness increases from 35 to 40 cm. This is likely to be due to methodological bias as more consistent slope is expected for fleet averages in the mid thickness range.

Figure 22 compares the fleet averages of absolute speed for all and, on the other hand, frequently navigating IA Super ships. These are thus *h-v*-curves for a 'typical' ship in the category. The curves have different levels, but when normalised they are almost identical (the normalised curves appear also in Figure 21). In the message average a step like speed decrease was found after 30 cm ice thickness while in the fleet averages this step is not prominent although the steepness of the curves increases with thickness. The origin of the step is unclear but it indicates that the relative contribution of slower ships to the message average increases. A more precise answer is not attempted here, but one possible reason is that the frequent fast ROPAX traffic has a large weight in the message averages but is mostly operating in sea areas where thickness seldom exceeds 30 cm.
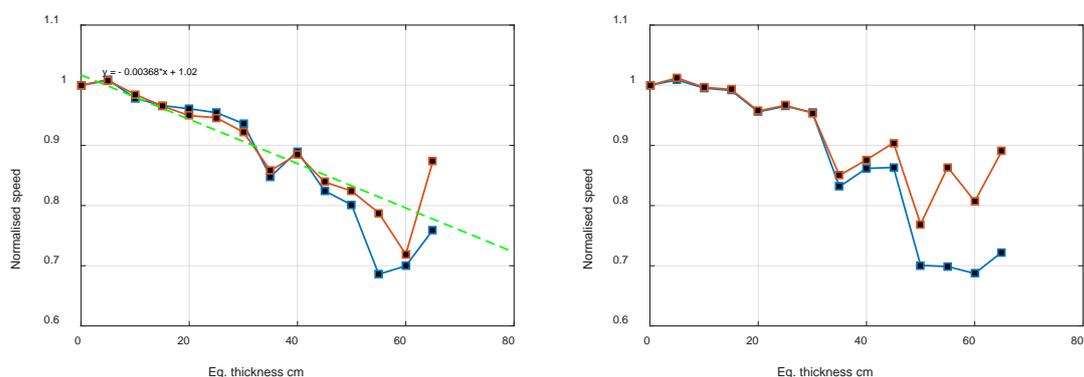


**Figure 21**. Speed reduction (fleet average) for IA Super ice steaming. Blue is average over speed profiles normalised, red average over normalised speed profiles. On the left all independent ice steaming, on the right independent ice steaming for ships that have at least 200 000 AIS messages.
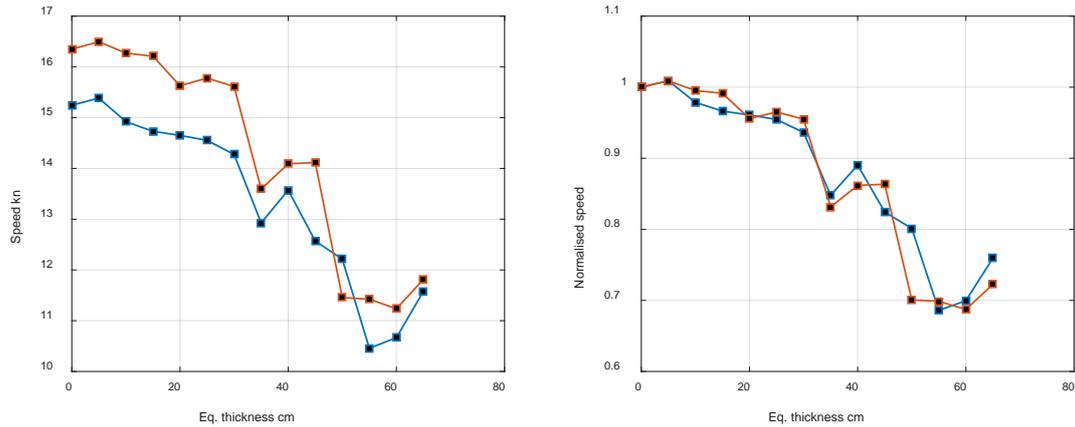
**Figure 22**. Speed reduction (fleet average) for IA Super ice steaming. Independent ice steaming for all ships (blue) and for ships with at least 200 000 AIS messages (red). On the left speed profile average, on the right the same averages normalised.

## Effect of ridging to speed reduction

In the speed climatology sections it was found the for Bay of Bothnia that ridging increases speed reduction considerably from nondeformed ice values but that in long term statistics ridging numerals are less relevant as ice is nearly always ridged. Figure 23 shows the effect of ridging to all IA Super traffic in all basins. The ice is categorised into slightly and heavily deformed types and speed reduction calculated as message and fleet averages. The results are inconclusive. The *h-v*-curves seem to indicate that ships perform better in heavily ridged ice but the apparent reason is that more powerful ships are assigned to difficult ice conditions, especially to the Bay of Bothnia. Also, the power setting may have an effect. To get a better picture, more detailed studies targeting individual ships or classes of comparable ships is required. This is out of the scope of the present report.
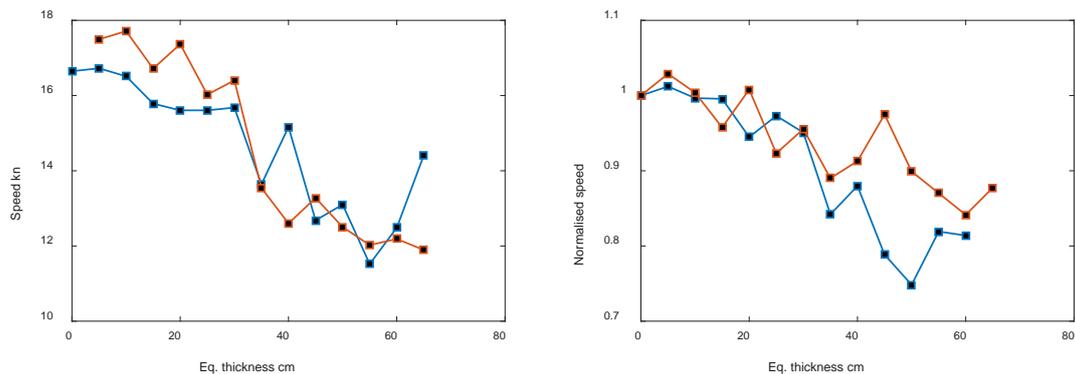


**Figure 23**. Speed reduction in level and slightly deformed ice (blue) and in heavily deformed ice (red). On the left message averages over all IA Super traffic, on the right fleet average over IA Super ships with at least 200 000 messages.

## Independent and non-independent navigation

Cases of independent steaming are more relevant when the effect of ice cover to the performance of the ships and to the efficiency of winter navigation system is considered from the viewpoint of increased resistance. However, for studies of navigation system the non-independent steaming as well as idling are as important. These are affected by the ice conditions also indirectly through icebreaker assistance and other operations involving several ships. As expected, the speed reduction curves in Figure 24 for non-independent steaming are steeper and the separation from the independent navigation increases with thickness. The speed reduction is roughly two times that for independent navigation.

The stepwise decrease of speed when thickness increases from 30 to 35 m is even more prominent for non-independent ice steaming. It was suggested that this may be due to the fast ROPAX traffic that is less frequent in thicker ice types. Unlike for independent traffic, the step is clearly present also in the fleet average. More regular behaviour is expected when similar studies are conducted regionally and for classes of comparable ships.
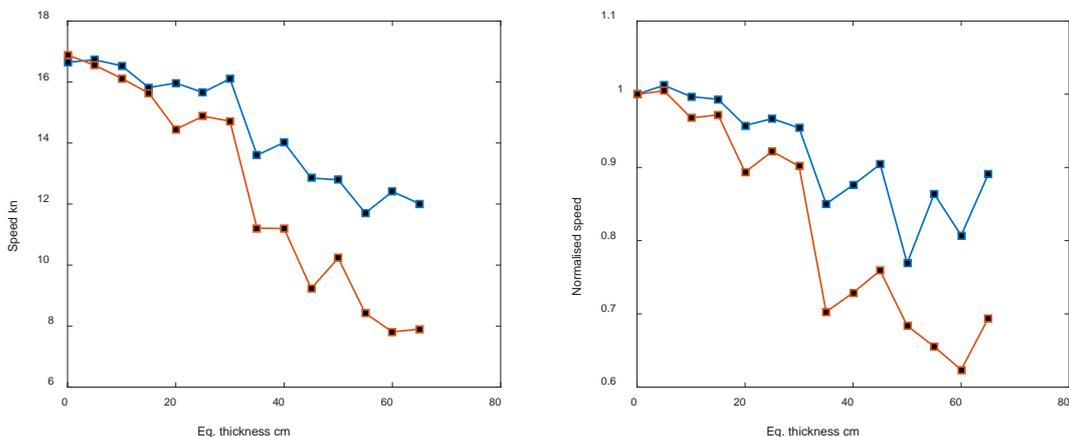


**Figure 24**. Speed reduction for independent (blue) and non-independent (red) IA Super ice steaming. On the left message average, on the right fleet average for ships with at least 200 000 messages.

## Speed reduction, grid average

The weight of a certain area or grid cell in the above averages is proportional to the number of AIS messages received from it, or in relative terms message intensity, Figure 25. This weight is very large for the main fairways and much smaller outside them. Thus the fairway ice conditions and channel transit dominate the average. In a larger regional scale Gulf of Finland dominates other sea areas.

Grid averages use the same weight for all grid cells instead. This emphasises especially independent transit outside channels and the resulting speed reduction curves can be assumed to be closer to icebreaking mode and thus better describe the actual ice performance. Also, the weight of different sea areas is proportional to the number of visited cells in the area, which puts Bay of Bothnia and Gulf of Finland on the same line. The grid averages were obtained by first calculating message averages for all grid cells and then averaging over these values with the same

weight for all cells. On the other hand, if the weight is proportional to the number of messages per cell, the overall message average used above is obtained.

The results in Figure 26 confirm expectations. The speed reduction is more consistent. For independent ice steaming the grid averaged speeds are lower for thicknesses up to 30 cm after which they match closely message averaged speed. The stepwise speed reduction after 30 cm is not prominent. For non-independent ice steaming the grid averaged speeds are likewise lower to 30 cm after which the order changes. The step at 30 cm is still visible but less prominent.
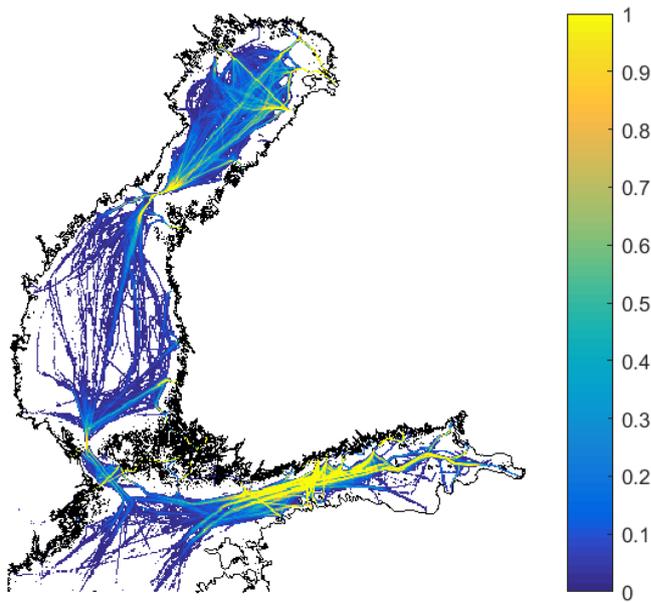


**Figure 25**. AIS message intensity for independent ice steaming of IA Super ice class (maximum scaled to 1).
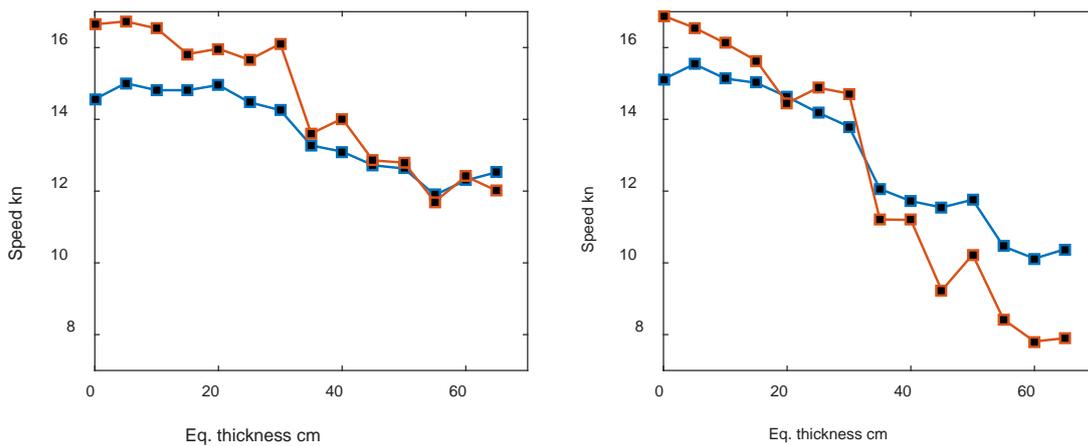


**Figure 26**. Grid average (blue) and message average (red) for IA Super ice steaming. On the left, independent navigation, on the right, non-independent navigation.

## Climatological speed reduction

In a climatological approach to speed reduction the average performance of all ships that have visited a grid cell is compared to the average ice conditions in the grid cell. These two data sets are considered independent. Although summarising, such analysis smooths out the variation due to the diversity of performance capabilities as it does not go to the details of individual ship response to ice parameters.  Also, the methodological uncertainties of ice thickness determination affect less. On the other hand, the link to the actual ship ice performance is weak and the results cannot be readily interpreted as $h$-$v$-curves.

Figure 27 gives scatter clouds of independent steaming speed observed in grid cell against equivalent thickness observed in the grid cell. Cloud points present grid cell averages over all IA Super ice steaming during 2007-2016. The average speed reduction diagram is calculated as scatter cloud averages for thickness categorised in 5 cm intervals so that zero corresponds to very thin or very sparse ice types (H<2.5 cm). The linear fit corresponds to the manifestly linear parts of the diagram (5-30 and 5-35 cm respectively). The slope for the absolute speed is steeper; if the speed axis is scaled to correspond to the right hand side plot, the slope is *0.0076* or almost two times larger. For H<10 cm the icegoing speed is larger than the open water steaming speed, which result is consistent with previous findings. This increase was observed also in the charts of regional speed distribution. Thus the 10 cm steaming speed appears to be a better reference for the speed reduction. The linearity of V(H) does not extend well to thicker ice types but is generally much better than for the performance oriented averages of the preceding sections. The linear slope is in agreement with those found previously.
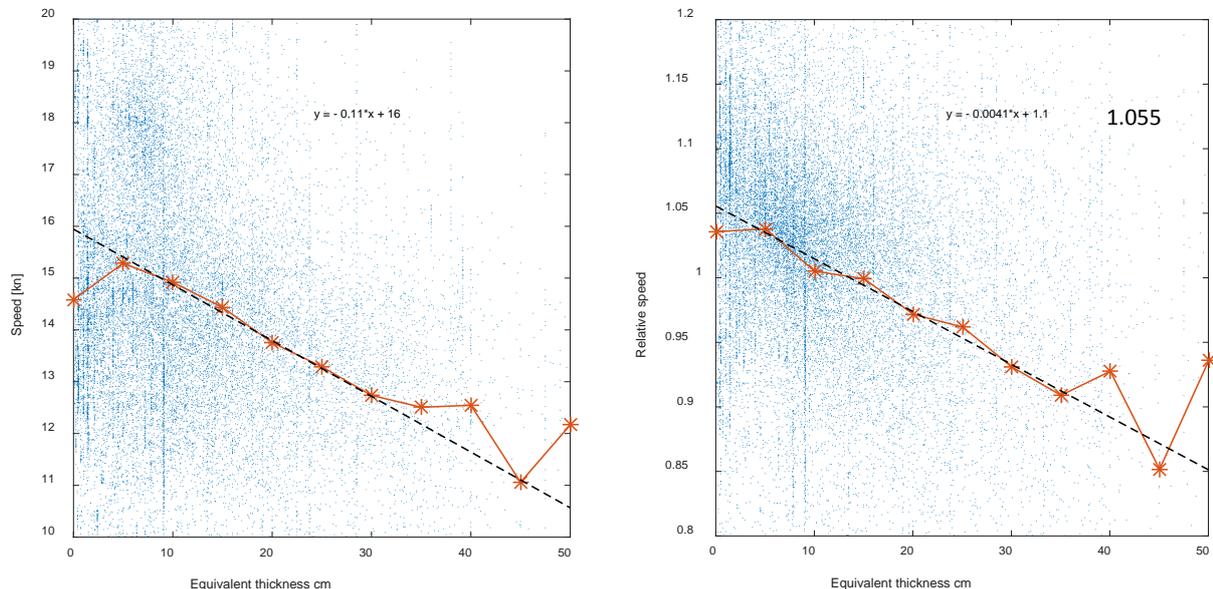


**Figure 27**. Climatological scatter cloud of speed observed in grid cell against equivalent thickness observed in the grid cell and average speed reduction curves. All independent IA Super ice steaming during 2007-2016.

The speed reduction for non-independent ice steaming in Figure 28 do not display linear slope. Rather, the speed reduces more steeply to 25 cm thickness and then gradually levels. For thicker ice the characteristic speed values are about the same, or around 11 knots, for independent and

non-independent steaming. It is informative to compare this with the speed reduction for icebreakers in Figure 29. A major part of non-independent icebreaker steaming is likely to be assisting. The speed reduction from 5 cm to 50 cm thick ice is only one knot while for the IA Super it was 5 knots. The speed values for thick ice are somewhat smaller for icebreakers which is expected as ships of lower ice classes are also assisted. For heavily ridged ice the climatological icebreaker speed is more or less constant. These results are in line with the previous observations that the navigation system seeks to maintain in thicker or otherwise more difficult ice certain 'system speed' which is about 11 knots.
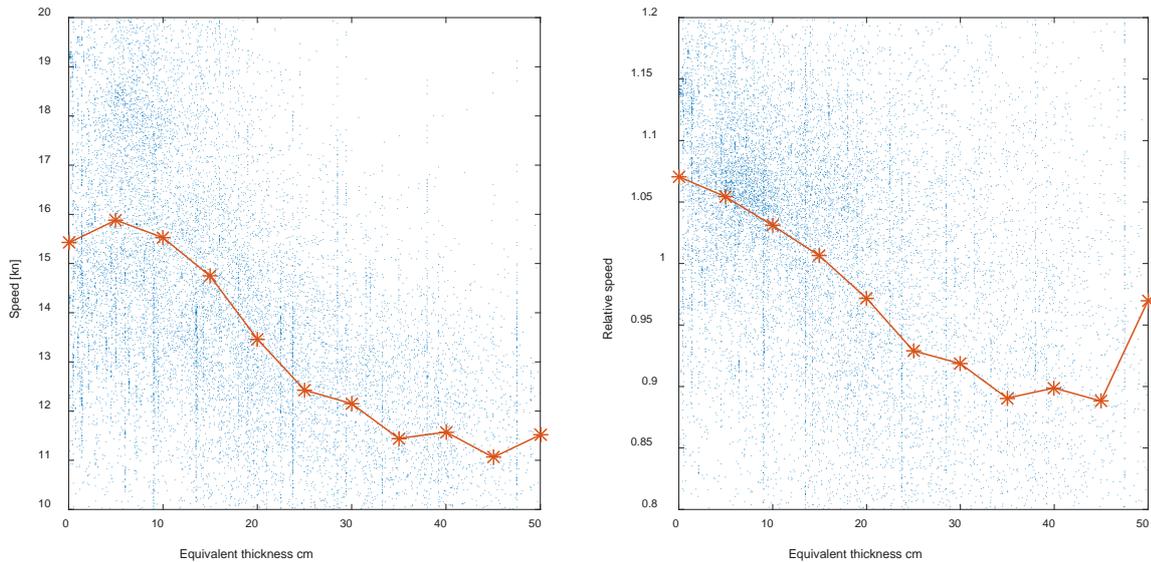


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**Figure 28**. As in Figure 27 but non-independent IA Super steaming.
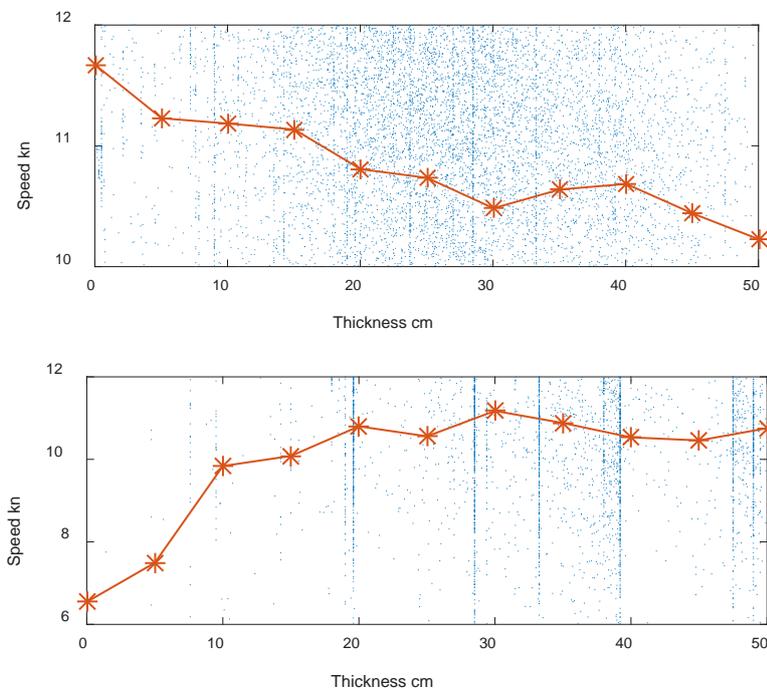


**Figure 29**. As in Figure 27, but non-independent icebreaker steaming. In upper panel all ice types, in lower panel heavily ridged ice types.

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To obtain climatological speed reduction curves in terms of fleet average the climatological fleet averages and ice parameter averages should be calculated in same grid cells. The basic 1NM grid has too fine resolution for this, and 8x8 blocks of cells are used instead. For each block the ships that have had ice transit in the block during 2007-2016 are found and the average relative ice steaming speed over the whole period is calculated for each. The block value is the fleet average over these relative speeds. This is compared to equivalent thickness calculated for the same blocks. The regional variation of the fleet average of relative independent ice steaming speed and equivalent thickness are shown in Figure 30. The period is 2007-2016. The use of 8x8 blocks improves the visual comparability of speed and thickness data as minor fairway details are smoothed out. To some extent the ship speed can be used as a proxy for regional ice thickness and vice versa.

The variation is still large as is seen from the scatter cloud in Figure 31. The average speed reduction curve is calculated similarly as above and is close to linearity. The linear slope of speed reduction is about 0.38 per metre of ice. This is close to the values found in Figures 21 and 27. A rule of thumb for Baltic independent ice navigation may round this value to 0.4 so that speed is reduced by 10% for each 25 cm thickness increase.
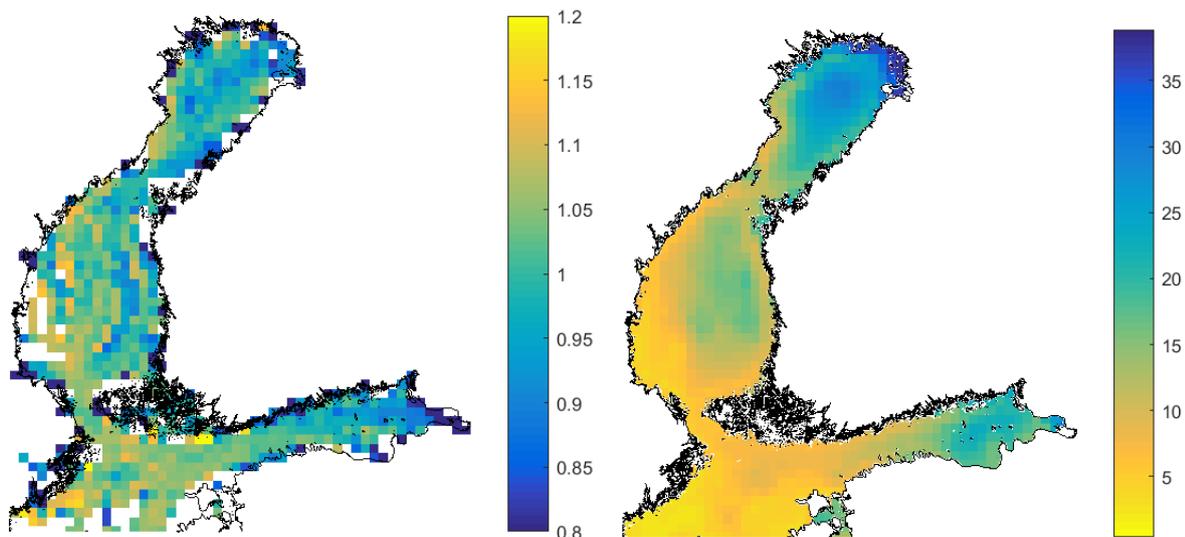


**Figure 30**. Fleet averages for relative independent ice steaming speed (left) and for equivalent thickness (right), both calculated for 8x8 NM blocks of grid cells.
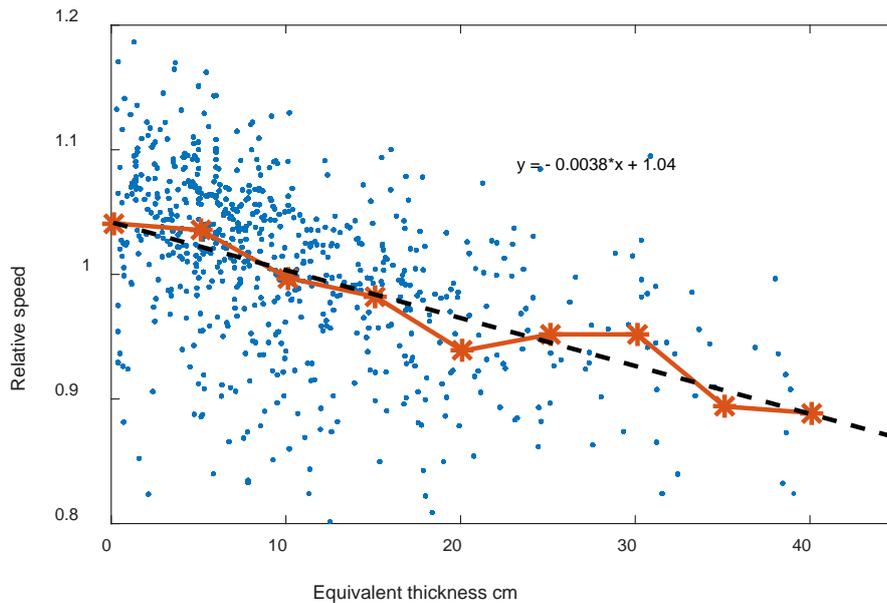
**Figure 31**. Scatter cloud and speed reduction curve generated by matching the 8x8 NM grid cell block data of Figure 30.

## Idling

Idling threshold was set to 0.5 knots. For ships of commerce idling may include voluntary waiting for assistance or piloting but ships can also become beset for shorter or longer periods. Ramming transit in ridged ice includes also low or zero speeds but this contribution to the statistics is negligible. The ship may also drift with the ice cover. Ice drift speed is mostly below 0.2 knots although speeds as high as 1 knot have been observed during stormy periods.

The overall idling time fractions for IA Super traffic during 2007-2016 were 2.3 per cent for independent and 4.6 per cent for non-independent icegoing. These values are message averages so that the contribution of individual ship is proportional to the number of messages it has broadcasted. The regional variation is shown in Figure 32 for non-independent icegoing for all ice conditions and for closed, thick ice cover. Values up to 20 per cent are found at the Quark entrance and in the middle of the Bay of Bothnia. The histograms for the grid cell values is in Figure 33. The Increasing difficulty in ice conditions increases idling fractions but do not change the patterns regional variation.
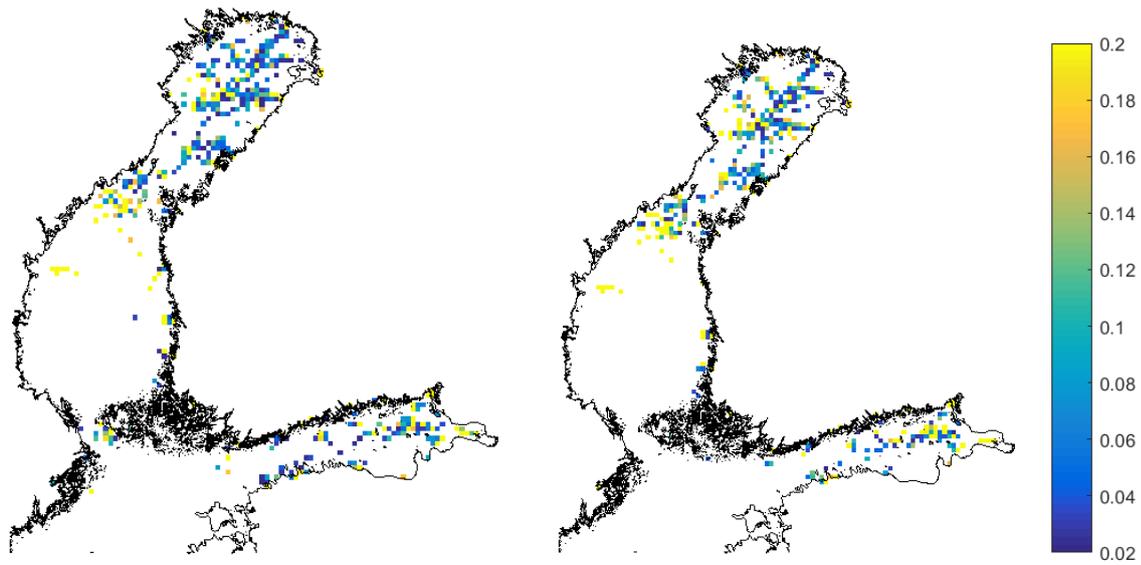
**Figure 32**. Idling fractions for non-independent icegoing. All ice conditions (left), ice concentration at least 90%, ice thickness at least 30 cm (right). Fractions <0.02 not included. All IA Super traffic 2007-2016.
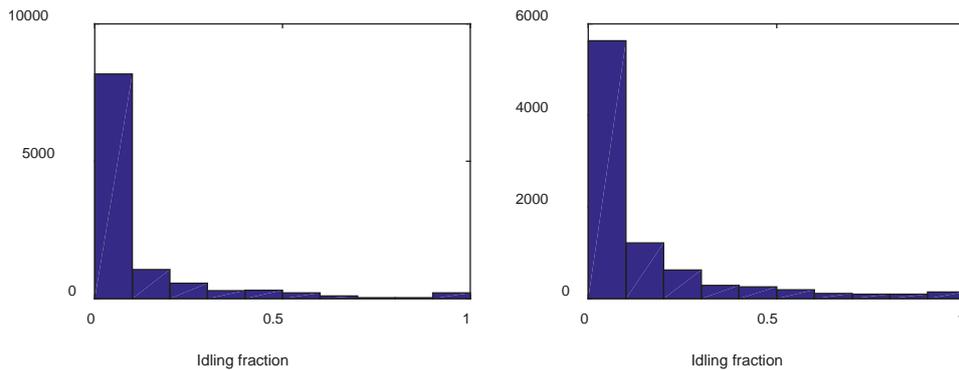


**Figure 33**. Histograms of idling fraction for non-independent icegoing. All ice conditions (left);  ice concentration at least 90%, ice thickness at least 30 cm (right). Fractions <0.02 not included. All IA Super traffic 2007-2016. Overall values 0.098 and 0.174.

For the icebreakers idling mode has a different significance related to the managing of assistance. This is characterised shortly. The regional variation in Figure 34 shows that idling is concentrated to certain areas where the idling fraction can be close to one, while in the remaining part the fraction is of the order of 0.1. Overall, the icebreakers spend about fourth of their icegoing time in idling. For independent navigating, which for icebreakers mostly means non-assistance, idling fraction is 47% and for non-independent navigating 14%. The idling fraction does not depend on ice conditions, Figure 35.

Together with the earlier results on non-independent ice navigation for IA Super ships and on IA class response to ice conditions these observations indicate that winter navigation analyses require systemic approach. The speed reduction curves derived for independent IA Super traffic provide data on how ice conditions change the speed statistics for this category. However, these

results are not expected to extend to the remaining categories of ice navigation so that analysis of the winter navigation system could be based on simple speed reduction rules. To this adds the basic uncertainty from lacking propulsion power.
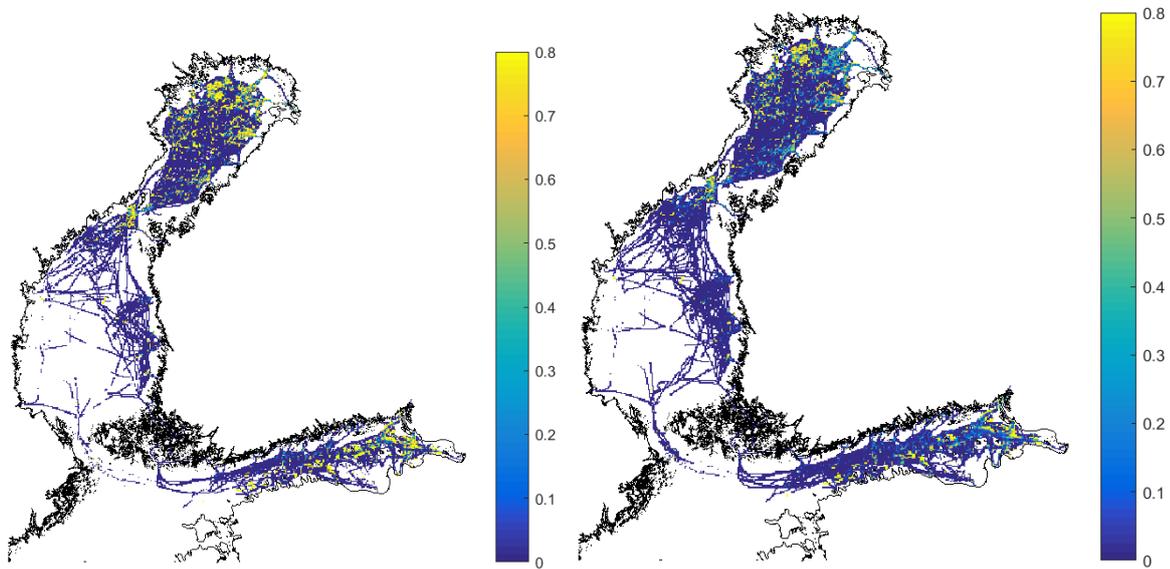


**Figure 34**. Idling fractions for icebreakers. On the left, independent navigation, on the right, all navigation. Overall values 0.47 and 0.25 respectively.
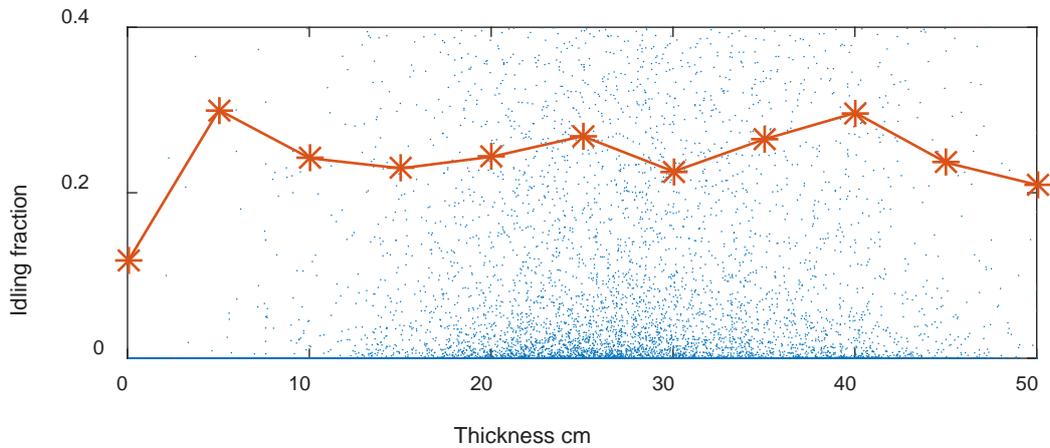


**Figure 35**. Icebreaker idling fraction as a function of thickness. Both independent and non-independent navigation.

## CONCLUSIONS

Various results on how Baltic ice conditions affect the ship performance have been presented. The performance is quantified in terms of ice induced speed reduction and the results are derived using a database that connects AIS-retrieved ship location and speed with the closest spatiotemporal match of ice parameters. The AIS data is from Finnish terrestrial stations and has about 10 seconds update interval for each ship. The ice parameters are from daily ice charts. The database covers nine ice seasons 2007-2016 and most results are for IA Super ice class. Icebreakers have been addressed to some extent. Only pack ice navigation outside the fast ice zone is included, and the basic classifications are between steaming and idling, and between independent and non-independent navigation.

As expected ship speeds are generally reduced. Depending on the focus of analysis the reduction can refer to the functioning of the whole navigation system or to the performance of ships. To assess performance it must be assumed that that power setting of the ships does not change much so that the speed reduction is due to ice conditions only. For independently navigating IA Super ships this assumption is warranted at least for charted ice thicknesses up to 30 cm. Three different approaches to the reduction gave roughly the same result that speed reduced by 10% for each 25 cm increase in ice thickness. For thicknesses larger than 30 cm the thickness reduction was less clear and for very thick ice the average speed levelled to about 11 knots. This was also the general speed average for icebreaker assistance which was moreover almost independent on ice thickness increase. Thus for difficult conditions the whole navigation system appears to settle in a holistic balance with little speed variation between ships, and the IA Super transit cannot be considered really independent even though the quite strict proximity condition for independence would be fulfilled.

That the winter navigation system is not a simple collection of transits with speed controlled by thickness characteristics become clear from various results. The large number of port calls and the billions of AIS messages lay basis for reliable analyses but also make the system spatially independent. One principal feature is the concentrating of traffic to the main fairways. This affects also thickness-speed connection as thicknesses refer to regional conditions and are not necessarily representative for heavily trafficked ice channels. Also, the charted ice thicknesses are based on estimates or measurements from non-deformed ice only. The charted ice parameters include a qualitative ridging index that correlated with increased speed reduction. However, no really quantitative analysis on how ridging, which is considered as the main impediment of ice transit, affects the speeds can be based on charted data only.

The presented results are mostly for the whole nine year period covered by the database. They have some climatological validity and represent long term expectations of conditions when used projectively. They amass together the seasonal and interseasonal variability of ice conditions as well as all different ship types in the IA Super class. The regional variations, which are evident in the chart graphics, are also not considered in the speed reduction diagrams. As such the results mostly quantify the functioning of the whole winter navigation system. As concerns the ice performance of ships it is evident that more robust results are obtained through restricting to comparable ship types, certain regions and periods of ice season, and paying heed to what is known on the regional characteristics of winter navigation system and its management.
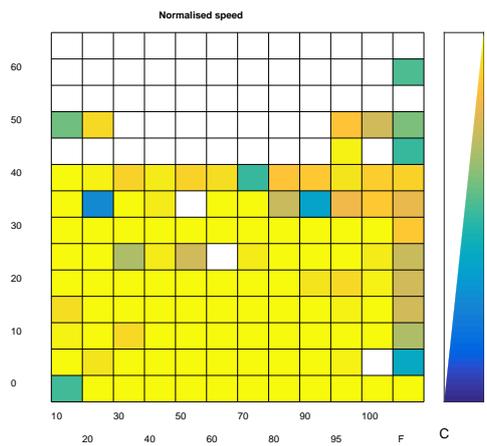
**Appendix 1:** Matrices for the reduction of relative independent ice steaming speed reduction for main ship type classes.
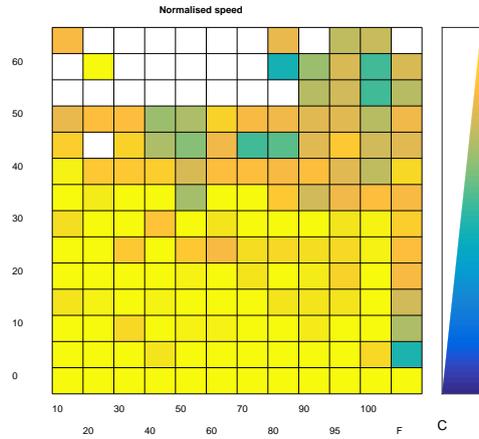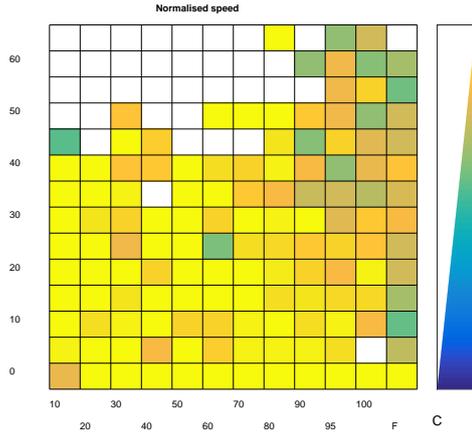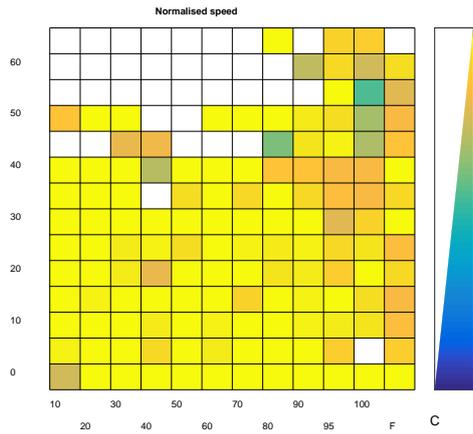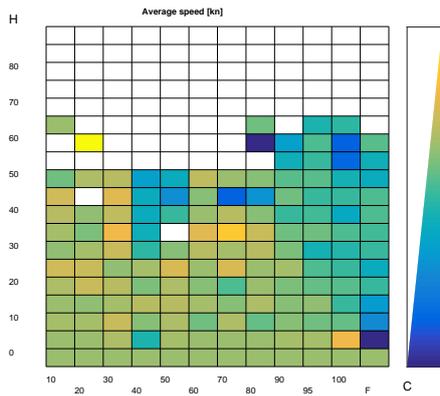


All IA Super
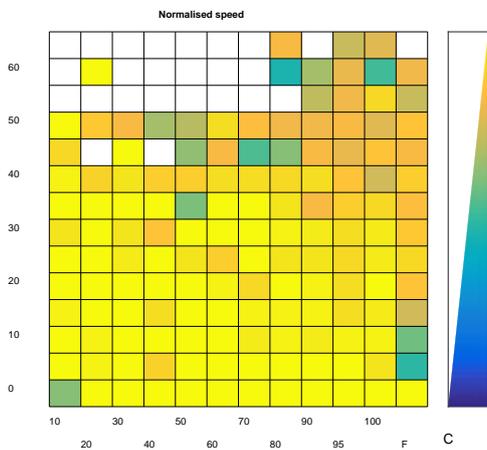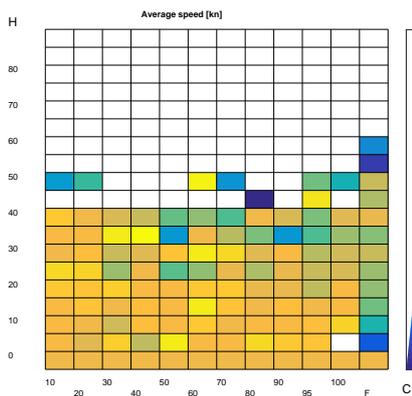


IA Super cargo



IA Super ropax

Normalised speed — IA Super tanker
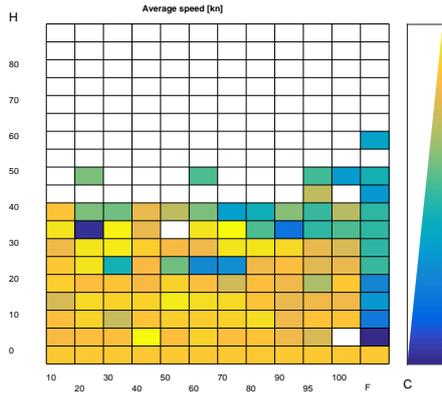
**Appendix2** : Speed matrices for independent IA Super ice steaming classified according to northernmost Baltic basin visited.
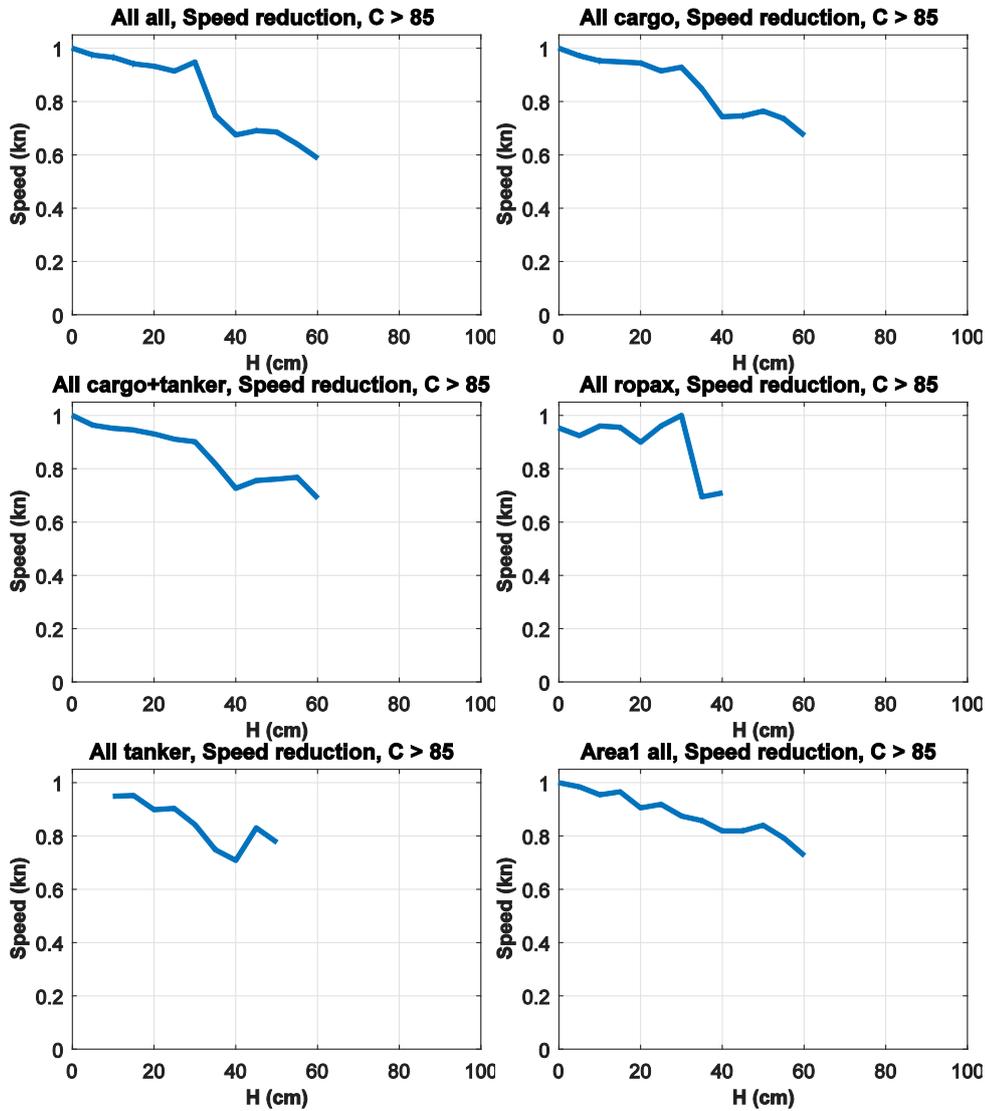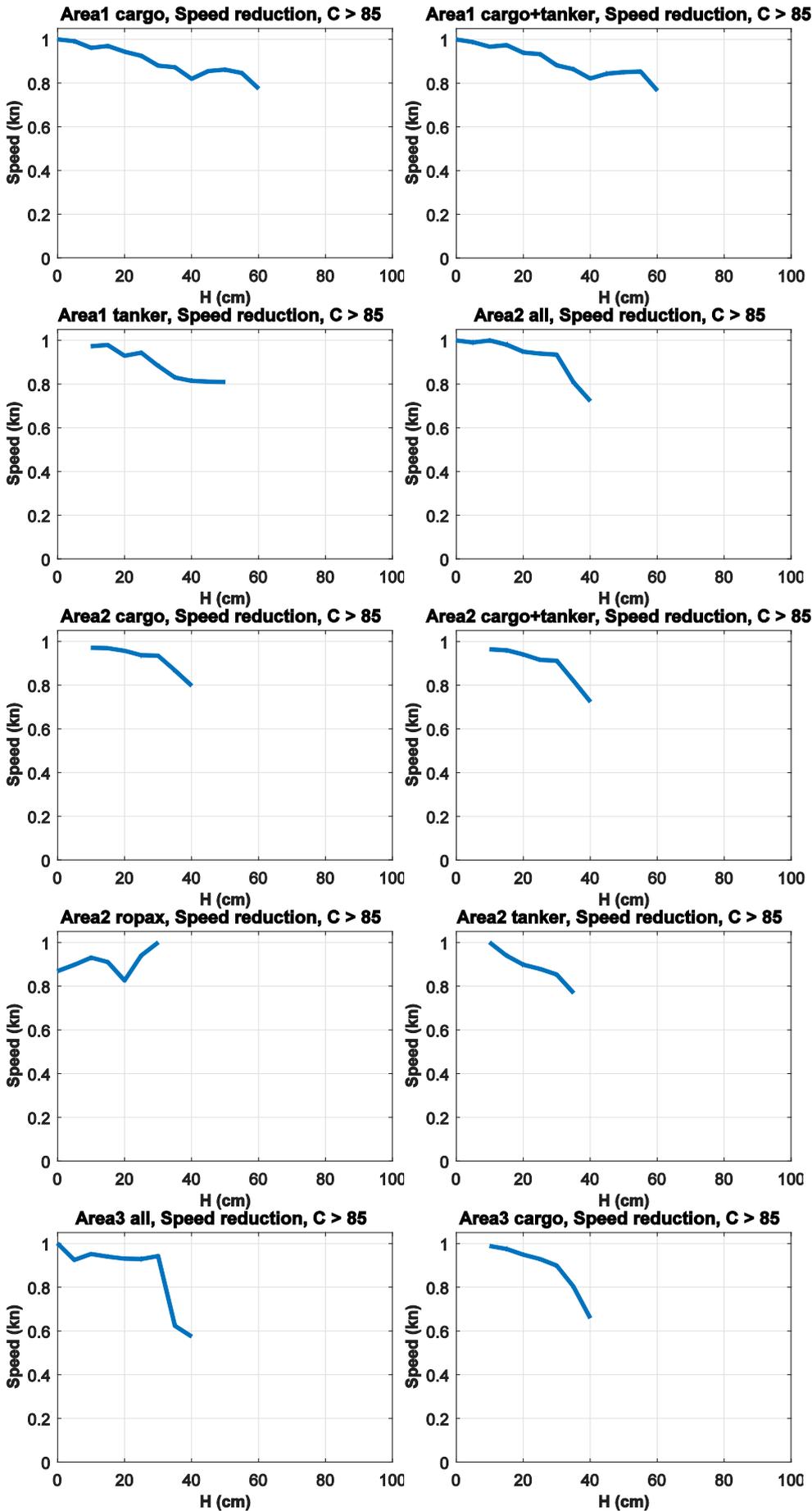


Average speed [kn] — Bay Of Bothnia



Average speed [kn] — Sea of Bothnia

Average speed [kn]

Remaining areas

**Appendix 3:** Reduction of relative independent ice steaming speed in high concentration     drift ice for IA Super ship type classes and areas of navigation.



All all, Speed reduction, C > 85



All cargo, Speed reduction, C > 85



All cargo+tanker, Speed reduction, C > 85



All ropax, Speed reduction, C > 85



All tanker, Speed reduction, C > 85
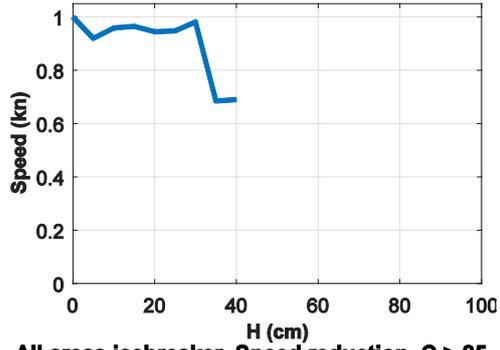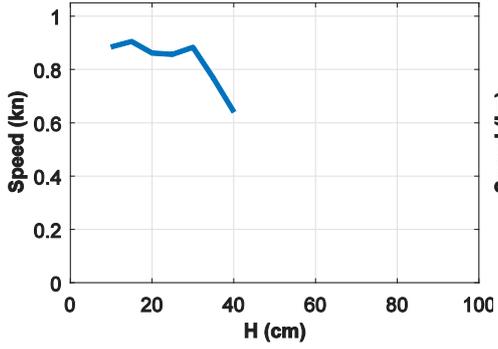


Area1 all, Speed reduction, C > 85

**Area3 cargo+tanker, Speed reduction, C > 85**
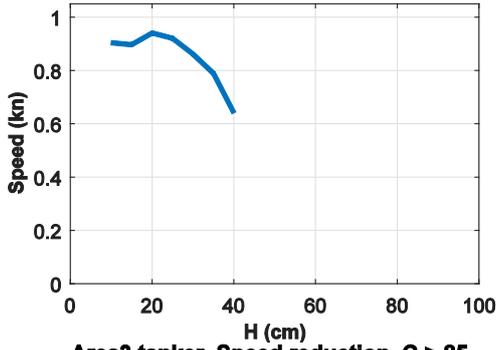
**Area3 ropax, Speed reduction, C > 85**

**Area3 tanker, Speed reduction, C > 85**

**All areas icebreaker, Speed reduction, C > 85**