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Safety Science 95 (2017) 198–209

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Special Issue Article: Harsh Environments

An analysis of ship escort and convoy operations in ice conditions

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ARTICLE INFO

Article history:
Received 22 June 2015
Received in revised form 11 November 2015
Accepted 6 January 2016
Available online 29 January 2016

Keywords:
Winter navigation operations
Finnish–Swedish winter navigation system
Ship domain
Automatic Identification System
Maritime safety

ABSTRACT

Winter navigation is a complex but common operation in the Northern Baltic Sea areas. In Finnish waters, the safety of the wintertime maritime transportation system is managed through the Finnish–Swedish winter navigation system. This system results in different operational modes of ship navigation, with vessels either navigating independently or under icebreaker assistance. A recent risk analysis indicates that during icebreaker assistance, convoys operations are among the most hazardous, with convoy collisions the most important risk events. While the accident likelihood per exposure time is rather low, accidents occur almost every winter. Even though these typically lead to less serious consequences, accidents leading to ship loss and oil pollution have occurred and may occur in the future. One aspect of ship convoy navigation in ice conditions is the distance kept between the icebreaker and the ships in the convoy, a form of the well-known ship domain concept. While operational experience naturally is a valuable source of information for decision making about the distance of navigation in convoys, systematic analyses are lacking. The aim of this paper is to investigate selected operational aspects of convoy navigation in ice conditions in the Finnish waters of the Gulf of Finland, based on data of the Automatic Identification System and sea ice hindcast data. Focus is on obtaining qualitative and quantitative knowledge concerning distances between vessels in escort and convoy operations and the respective transit speeds, conditional to ice conditions. Such empirical knowledge can support operational decision making, contributing to wintertime maritime safety.
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1. Introduction

The Northern Baltic Sea area is a relatively busy area for maritime transportation, with maritime trade of vital economic importance several countries in the area. Simultaneously, this area is characterized by the presence of ice during the winter season. This leads to a harsh environment for ship navigation, which has important implications for managing the safety of the vessels operating in this area.

In Finland, winter navigation is organized by means of the Finnish–Swedish winter navigation system (FSWNS). This is a system which governs the implementation of ship transportation in winter conditions, ensuring the maritime accessibility and safety (FTA, 2014; Riska et al., 1997). It consists of five main components, which together ensure that the vessel design and operational environment is such that vessels navigating in Baltic ice conditions can proceed safely. The components are ice class regulations, additional requirements, ice services, traffic restrictions and icebreaker assistance; see TraFi (2010) for further details.

When vessels are authorized to proceed to their destination, they either navigate independently or are assisted by icebreakers. In icebreaker assistance, five practical operations are commonly distinguished (Rosenblad, 2007). In escorting, an icebreaker breaks a channel and a vessel follows the icebreaker at a certain distance. In breaking loose operations, an icebreaker passes a ship beset in ice to break the ice beside and in front of the assisted ship, releasing the ice pressure. Convoy operations are similar to escorting but with several ships following the icebreaker. In double convoy operations, one icebreaker travels slightly ahead of the other icebreaker, to assist a vessel with a larger breadth than the icebreakers. Finally, in towing operations, the assisted vessel is towed as it cannot follow the icebreaker because the ice pressure makes the channel close too quickly, or because the channel has too much slush ice. An icebreaker may have a vessel on tow, while simultaneously leading a convoy.

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http://dx.doi.org/10.1016/j.ssci.2016.01.004
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As in open water conditions (Klanac et al., 2010; Kujala et al., 2009; Qu et al., 2012) and in Arctic navigation (Kum and Sahin, 2015), ship collisions are one of the most frequently occurring accidents in Finnish sea areas during winter (Valdez Banda et al., 2015a). Navigational accidents occur more frequently in ice conditions than in open water, but typically lead to less serious consequences. A recent risk analysis suggests that among accidents occurring during icebreaker operations, convoy operations are among the most hazardous situations in the wintertime conditions. Collisions between the following vessel and the icebreaker and vessels in a convoy are the most important related risk events (Valdez Banda et al., 2015b).

The icebreaker crew may advise the crew of assisted vessels, but the crews of vessels in convoy operations are responsible for arranging and maintaining a suitable distance between individual vessels. Simultaneously, a relatively high speed is typically maintained in the convoy to ensure efficient transport flows. The distance is important from a safety and operational perspective. If a ship shortens the distance to a preceding ship, a collision is more likely to occur. However, if a longer distance is maintained, the following ship may be hampered by the ice (slush in the channel and especially compressive ice) and get stuck in ice as a result.

In maritime safety research, it is known that vessel crews aim to keep a certain area around the vessel clear from other vessels, an area commonly known as the ship domain (Goodwin, 1975). Various analytical models have been proposed for ship domains (Pietrzykowski, 2008; Wang et al., 2009; Zhu et al., 2001) and empirical studies on the ship domain sizes have been made based on ship traffic data in open sea areas (Hansen et al., 2013; van Iperen, 2012, 2015) and port environments (Debnath and Chin, 2010; Rawson et al., 2014). Hsu (2014) has performed an empirical study on ship domains in overtaking situations using a ship handling simulator. Ship domains have also been used in studies on collision avoidance (Szlapczynski and Szlapczynska, 2015) and developing collision alert systems (Chin and Debnath, 2009; Goerlandt et al., 2015).

For independent navigation in ice, some methods have been proposed to determine the safe speed (ENFOTEC et al., 1996; Tunik, 2000). For convoy operations, mathematical models have been proposed to model the ship dynamics (Tsoy, 1983). However, empirical research on the operational characteristics and ship domains in convoy operations in Baltic sea ice conditions have not been performed. According to navigators and icebreaker crew, establishing such systematic knowledge would be beneficial for safety-related decision making, especially to substantiate experience-based rules of thumb (Rosenblad, 2007).

Considering the above, this paper presents an empirical analysis of ship convoy operations based on data of the Automatic Information System (AIS) and sea ice hindcast data. In particular, the ship domain concept is investigated in ice escort and convoy operations. Insight is sought especially about the distance between vessels in convoys and the convoy transit speed. The influence of ice conditions on these convoy characteristics is investigated.

The remainder of this paper is organized as follows. Section 2 presents the data applied in this study. In Section 3, the method of data processing and analysis is outlined, with results shown in Section 4. A discussion is given in Section 5, whereas Section 6 concludes.

2. Data

2.1. Maritime traffic data

The 2002 IMO SOLAS Agreement included a mandate that required most vessels over 300GT on international voyages to fit a Class A type AIS transceiver. The data transmitted by this Automatic Identification System is commonly known as AIS data. As an information exchange platform between vessels and shore organizations, AIS contains, amongst other, time-dependent data about the location, speed, course and navigational status of vessels. While AIS data quality has been mediocre in its early implementation years (Graveson, 2004), the quality has improved significantly in recent years (Felski and Jaskolski, 2013; Felski et al., 2015), and further improvements are possible with proper antenna installation (Last et al., 2015).

The original purpose of AIS was solely collision avoidance but many other applications have since developed. In the scientific literature, following uses have been identified: ship surveillance, tracking and security (Cairns, 2005; Ou and Zhu, 2008), collision avoidance and decision support (Mazaheri et al., 2012; Mou et al., 2010), discovery of traffic patterns (Meng et al., 2014; Pallotta et al., 2013; Silveira et al., 2013; Xiao et al., 2015), traffic simulation (Miyake et al., 2015; Rong et al., 2015), ship routing development (Chen et al., 2015), near miss detection (van Iperen, 2015; Zhang et al., 2015), risk analysis (Goerlandt and Montewka, 2015; Mulyadi et al., 2014; Qu et al., 2011; Wang et al., 2014), emission estimation (De Meyer et al., 2008; Jalkanen et al., 2014), impact on marine ecology of shipping traffic (Merchant et al., 2012), accident investigation (Mazaheri et al., 2014; Wang et al., 2013), maritime spatial planning (Shelmerdine, 2015) and ship performance estimation (Montewka et al., 2015; Mou et al., 2013).

For the present study, data from the period 19 February 2011 to 18 March 2011 has been used, with data fields as shown in Table 1. The selected period corresponds to severe winter conditions in the studied area. Since the main interest is in the convoy operations, which are carried out by icebreakers, the traffic data is organized per assisting icebreaker. Relevant icebreakers were identified using ice charts (SMHI, 2015). Charts of ice patterns and icebreaker locations were viewed for the considered time period and a list of Finnish icebreakers present in the Gulf of Finland was compiled. These icebreakers are listed in Table 2 with their main characteristics.

2.2. Sea ice data

The ice data was obtained from the hindcasts performed with the HELMI multicategory sea-ice model. The model is described in detail in Haapala et al. (2005) and Mårtensson et al. (2012). Therefore, only fundamentals relevant to the scope of this paper, are provided in this section.

For the purpose of analyzing escort and convoy operations, the following ice related parameters are retrieved from HELMI model: level ice concentration, level ice thickness, ridged ice concentration, ridged ice thickness, rafted ice concentration, rafted ice thickness, direction of ice compression, ice compression magnitude, ice drift velocity, direction of wind, wind speed, air temperature and sea water temperature.

Table 1
AIS data fields available for the presented model.

Data field	Unit	Explanation
MMSI number	–	A 9-digit code uniquely identifying a vessel
Time stamp	s	Time at which the message is recorded [YYYY]-[MM]-[DD] [hh]:[mm]:[ss]
Position		Longitude and latitude of transmitted message, in WGS-84 coordinate system
Ship type	–	A 2-digit code identifying the type of vessel, see USCG (2012)
Ship length and width	m	Dimensions from bow to stern and side to side, see USCG (2012)
Ship speed	kn	Speed over ground
Ship course	°	Course over ground, relative to true north
Ship heading	°	Direction in which the ship is pointing, relative to true north

Table 2
Main characteristics of the considered icebreakers.

IB name	MMSI	Ice class	Length (m)	Width (m)	Draft (m)	GT (tonne)	Power (MW)	Max. speed (kn)
Urho	230290000	1A Super	104.6	23.8	8.3	7525	16.2	18
Voima	230291000	1A Super	83.5	19.4	7	4159	10.2	16.5
Fennica	230245000	POLAR-10	116	26.0	8.4	9392	15	16.5

The model resolves the mean ice velocity, internal ice stress, ice concentration and ice thickness. Thickness is resolved for seven categories: five level ice categories, rafted ice and ridged ice. The ice model is discretized in a curvilinear coordinate c-grid, a common solution when there are both fields of velocities and velocity-dependent properties to be solved. The grid has 415 nodes from west to east and 556 nodes from south to north. The SW lower corner coordinates are 56.74°N 16.72°E, NE corner coordinates 65.99°N 30.48°E and the increment is 1/30 degrees eastwards and 1/60 degrees northwards. This is approximately 1 NM in both directions at 60°N.

The equations governing the development of the non-deformed ice categories, in terms of ice concentration and thickness, are as follows (Haapala et al., 2005):

$$\frac{\partial A_u}{\partial t} = -\nabla \cdot (\vec{u} A_u) + \Psi_u + \Theta_{Au} \tag{1}$$

$$\frac{\partial \tilde{h}_u}{\partial t} = -\nabla \cdot (\vec{u} \tilde{h}_u) + \Omega_u + \Theta_{hu} \tag{2}$$

where A_u is the concentration of a given non-deformed ice category, the ice velocity vector is denoted with $\vec{u}$, Ψ_u stands for the change of ice concentration due to deformation, Θ_{Au} denotes thermodynamical changes, $\tilde{h}_u$ is the mean thickness of non-deformed ice per unit area, Ω_u is the change of concentration of non-deformed ice, and Θ_{hu} is thermodynamical change.

To evaluate the deformed ice categories the following equations are applied (Haapala et al., 2005):

$$\frac{\partial A_d}{\partial t} = -\vec{u} \cdot \nabla \cdot A_d + \Psi_d + \Theta_{Ad} \tag{3}$$

$$\frac{\partial \tilde{h}_d}{\partial t} = -\vec{u} \cdot \nabla \cdot \tilde{h}_d + \Omega_d + \Theta_{hd} \tag{4}$$

where Ψ_d and Ω_d are the redistribution terms of deformed ice, describing the growth in concentration and mass of deformed ice due to ridging and rafting.

The HELMI forecasting model takes thermodynamic and dynamic forcing from weather prediction model HIRLAM. The forecast is made every 6 h or after each HIRLAM run. The length of the forecast is 54 h and interval of 3 h. Sea surface temperature (SST), including ice edge information, is prescribed and updated once a day. This is obtained from digital ice and SST charts that are based on daily SAR images, satellite SST data and observations from ships. Ice forecasts have been validated against the observed ice situations and good agreement was found (Lehtiranta et al., 2012).

On the other hand, hindcasts use HIRLAM reanalyzes and are stored at 1-h intervals. Their ice edge is not reinitialized by observations but rely solely on the model physics throughout the ice season. The present set-up of the ice prediction system does not include any dynamical ocean component, thus ocean currents are neglected. Although ocean currents in the Baltic are negligible for ice drift magnitude, they may have effect on the compression magnitude, especially on compression relief when water level gradient induces off-coast currents after a stormy period. This may be one reason for the discrepancies, observed in the validation exercises, between modeled compression and observations close to the fast ice edge.

Table 3
Interpretation of internal friction magnitude in practical compression scale.

Internal friction magnitude obtained from HELMI model (Nm^{-2})	Interpretation	Practical scale (–)
0–1.5	No significant compression	0
1.5–2.5	Mild compression	1
2.5–5.5	Moderate pressure	2
5.5–9	Severe pressure	3
>9	Extreme severe pressure	4

Ice motion is determined by the momentum balance equation, which yields (Haapala et al., 2005):

$$m\left(\frac{D\vec{u}}{Dt} + f\hat{k} \times \vec{u}\right) = A(\vec{\tau}^a + \vec{\tau}^w) - mg\nabla H + \nabla \cdot \sigma \tag{5}$$

where m is the total ice and snow mass, $\vec{u}$ denotes the horizontal ice velocity vector, f is the Coriolis parameter, $\hat{k}$ is the upward unit vector, $\vec{\tau}^a$ is the air stress vector, $\vec{\tau}^w$ stands for the water stress vector, g is the acceleration due to gravity, ∇H is the sea surface tilt, σ is the internal stress tensor.

The divergence of internal stress tensor creates internal friction of ice. The magnitude of the latter is used as the principal model variable to describe compression. It is to be noted that the viscous–plastic rheology does not describe elastic stresses and the internal stress arises from the interactions of moving ice. Forces arising in a static ice field are included by assuming a negligibly slow viscous creep. Roughly, the internal friction term can be interpreted to describe the forces arising when ice floes are pushed and sheared against each other, or broken and heaped into ridges. Thus it is a good descriptor for the interaction between dynamical ice cover and an ice-going ship. This is manifested as ice forces against the ship hull and as the closing of channels, or other phenomena that navigators associate to compressive ice conditions.

The internal friction magnitude has typical values ranging from 0 to 10 N/m^2. The magnitude acts as a proxy for ice compression, scaled to semi-empirical compression numeral 0–4, where 0 means no compression and 4 stands for extreme severe compression, see Table 3. However, to estimate the actual local forces additional scaling arguments must be taken into account such as floe size and other ice cover geometry.

3. Method

3.1. Data processing

The analysis of the convoy operations requires the AIS data and sea ice data to be processed and integrated. Fig. 1 shows a flowchart of the data processing. The steps are briefly outlined below.

Step 1. The AIS data of DB1 is grouped by ship (using the MMSI number) and chronologically sorted. This results in trajectories of each vessel over the considered time period.
Step 2. The AIS data is resampled per ship to obtain the position, speed and course at equal time instances. This step is necessary because the transmission rate of AIS messages depends on the navigational status, the speed and rate of turn of the vessel,

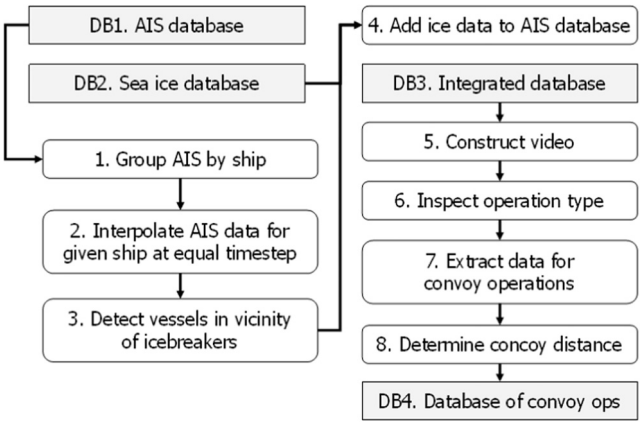

Fig. 1. Flowchart of data processing for constructing a convoy operations database.

see USCG (2012). However, to calculate convoy distances in Step 8, the positions of the vessels at the same time instance are needed.

Step 3. The AIS data of the vessels nearby the icebreakers (identified by the MMSI numbers) is collected for each time step and linked to the respective icebreaker data. An inspection domain of 2 NM is selected.

Step 4. Using the sea ice database (DB2), the ice data is obtained for the location of the icebreaker and added to the AIS database. It is assumed that the ice conditions at the icebreaker position are representative for the entire convoy.

Step 5. The integrated database (DB3) is visualized. Videos are made for each icebreaker, showing the icebreaker, nearby traffic and ice conditions. The design and information content of these videos is discussed in Section 3.2.

Step 6. The videos are viewed and the icebreaker operation types are recorded. The various considered operation types are outlined in Section 3.3.

Step 7. Based on the visual inspection of the icebreaker operation types, the data related to the convoy operations is extracted from the database. This includes the data of the icebreaker, the ships following the icebreaker and the ice conditions. The procedure for this data extraction is outlined in Section 3.4.

Step 8. The convoy distances are calculated and stored, as described in Section 3.5. This leads to the final database of convoy operations (DB4), which contains the convoy distances, speeds and ice conditions. It is this final database which is subsequently analyzed to answer the research questions.

3.2. Data visualization (Step 5)

Fig. 2 shows a screenshot of a video which visualizes the AIS and sea ice data of the icebreaker operations. The various elements of the video are outlined below.

A. Icebreaker. Central in a 2 NM inspection domain, the icebreaker is shown by a contour at its instantaneous position. A speed vector gives an indication of the projected position of the icebreaker in a time window of 1 min.

B. Assisted/nearby vessels. Within the 2 NM inspection domain, the vessels assisted and/or nearby the icebreaker are shown by a contour at their instantaneous positions. Speed vectors give an indication of the projected positions of the vessels in a 1-min time window. It is noted that not all vessels shown in this domain are assisted by the vessel: the icebreaker may pass vessels in a channel or may lead vessels to or from an offshore waiting area.

C. Dynamic icebreaker data. Instantaneous icebreaker data is displayed above the outer inspection domain circle, to the right and left sides. The analyzed icebreaker's velocity, heading, center of gravity, and geographic coordinates are provided. The date and time are shown as well.

D. Data of assisted/nearby vessels. The type, ice class, tonnage and main dimensions (length, width and draft) of the vessels in the closest vicinity of the icebreakers are shown, as well as their distance to the icebreaker and their instantaneous speed. The same note as in point B. applies.

E. Distance to closest harbors. Because no background map or sea chart could be included in the video, an indication of the position of the icebreaker is given through the directions to and distances from the two nearest harbors. Three-letter

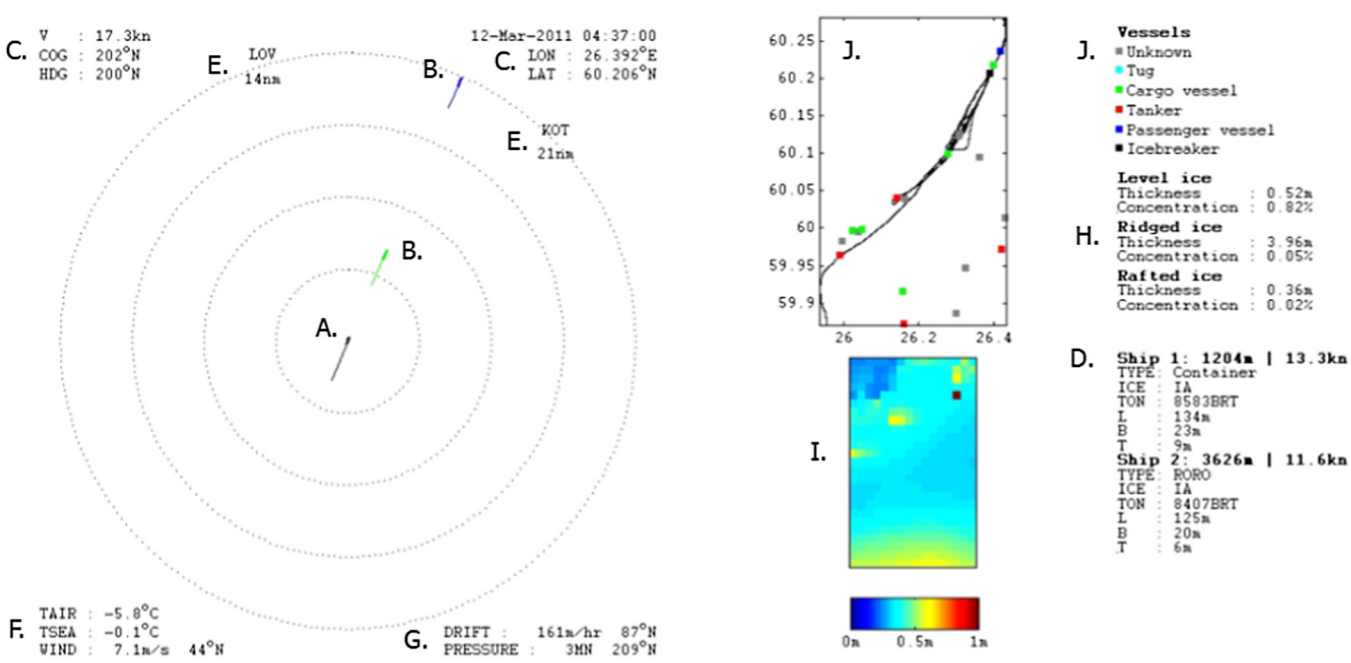

Fig. 2. Snapshot of the video visualizing the icebreaker operations, IB Urho 12.03.2011.

Table 4
Characteristics of icebreaker operations and events in video, for recording.

Operation/event	Characteristic
Towing	The assisted vessel appears closely behind the icebreaker, with same speed and course. Towing is preceded and followed by a period during which the vessels are stationary for connecting/disconnecting the tow
Escorting	The icebreaker navigates with one vessel (disregarding a possibly towed vessel) following the trajectory of the icebreaker in close distance, i.e. within the 2 NM inspection domain
Convoy	The icebreaker navigates with two or more vessels (disregarding a possibly towed vessel) following the trajectory of the icebreaker in close distance, i.e. within the 2 NM inspection domain. Assisted vessels further in the convoy may be outside this domain
Double convoy	Two icebreakers, the second ahead or behind but slightly abeam the first, assist a vessel which typically has a significantly larger width than the icebreakers
Cutting loose	The assisted vessel is stationary and the icebreaker moves back and forth and/or around the vessel in close proximity. This often is accompanied with compressive ice conditions
Meeting	A meeting occurs when vessels (either stationary or moving) are detected within the 2 NM inspection domain, but which are not assisted by the icebreaker
Begin/end assistance	The beginning and end of the assistance of a vessel occurs when the corresponding operation type (convoy, towing, ...) starts/stops
Exchange	An exchange occurs when one icebreaker ends the assistance (typically convoy) while another icebreaker begins the assistance of a certain (group of) vessel(s)
Connect/disconnect tow	A towing operation is preceded and followed by a period during which the icebreaker is stationary closely in front of the bow of the assisted vessel
Not engaged	The icebreaker is not physically assisting another vessel, e.g. when travelling towards/from a vessel in need of assistance or when monitoring the traffic

Table 5
Operations log of IB Urho, 12.03.2011 between 10:00 and 11:30.

Operation	Time (top: hour, below: time interval in minutes)														
	10										11				
	6	12	18	24	30	36	42	48	54	60	6	12	18	24	30
Escorting		x	x	x	x	x	x	x	x	x	x				
Convoy															
Double convoy															
Breaking loose															
Towing	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
Meeting	x	x	x	x							x	x	x	x	x
Begin/end assistance		x									x				
Exchange															
Connect/disconnect tow															x
Not engaged															

abbreviations of the port names are displayed at the edge of the inspection domain, in the direction of their location. The distance between the icebreaker and port is shown below the name abbreviation.

F. Environmental data. Below the inspection domain circle, the instantaneous air temperature, wind temperature, and wind speed and direction are provided.

G. Dynamic sea ice data. Below the inspection domain circle, the ice drift speed and direction and internal ice friction magnitude and direction are shown.

H. Dynamic sea ice data. The level ice, ridged ice and rafted ice thicknesses and concentrations are shown at the position of the icebreaker.

I. Ice chart. An ice chart of the average weighted ice thickness (incorporating level, ridge and rafted ice) shows the instantaneous position of the icebreaker by a dark red marker. It provides insight in the average ice conditions over the trajectory of the icebreaker.

J. Dynamic traffic image. The icebreaker's trajectory is recorded over a 24-h time period, and presented as a black line on the plot. The traffic image also shows the instantaneous positions of all other vessels within the icebreaker's range of travel. Each vessel is represented by a colored marker, indicating its vessel type according to the legend on the right.

3.3. Recording of operation type and events (Step 6)

When the videos of the icebreakers of Table 2 are made for each day in the considered time period, with information as described in Section 3.2, the videos are viewed and a record is made of the operations in which the icebreaker is engaged. The five identified icebreaker operations (towing, escorting, convoy, double convoy and cutting loose) are identified and recorded in 6-min intervals. In addition to these main categories, a number of auxiliary events are recorded to facilitate the further data processing, including meeting, begin/end assistance/convoy, exchange, connect/disconnect tow and not engaged. Table 4 contains a brief description of the characteristics of each of these operations and events. To attain credible results, a selection of videos and records was prepared and presented to crew of icebreakers to get a common understanding of how different operations appear in the developed visualizations, as in Montewka et al. (2015). Based on the experiences gained during this exercise, all videos for the entire period were analyzed.

An example of the records of icebreaker operations is shown in Table 5 for the example of Video 1. The video clearly shows icebreaker Urho on 12 March 2011 starting a towing operation with a cargo vessel near the harbors of Kotka and Loviisa, with one cargo vessel soon following in escort mode. The operations occur mostly under severe ice compression. The escort ends around 11:11, and around 11:23, the tow is disconnected. Various ships are met during the operation.

3.4. Extracting escorting and convoy data (Step 7)

The extraction of the AIS and sea ice data for the escorting and convoy operations is done using the operations log files as in Table 5. The overall procedure for this is shown in Fig. 3.

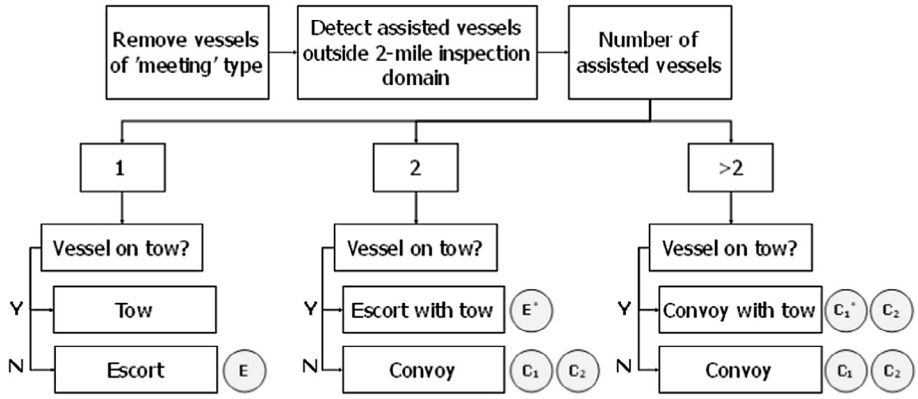

Fig. 3. Classification of operation types and distance calculation methods.

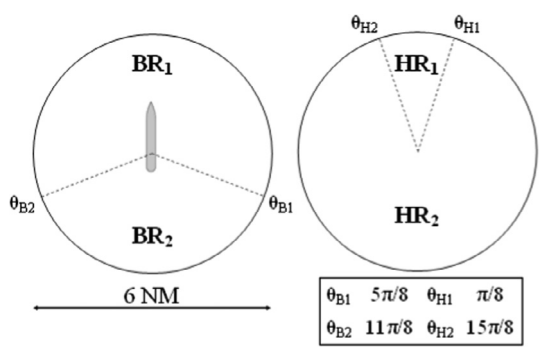

Fig. 4. Classification encounter type for detecting vessels in convoy.

First, for time blocks recorded as escorting or convoy, as well as simultaneously meeting vessels not being assisted by the icebreaker, the data points of the vessels of 'meeting' type are removed from the list of vessels assisted by the icebreaker.

Second, it is checked whether vessels outside the 2 NM inspection domain are part of the convoy as well. This is needed because convoys may stretch outside the inspection domain limits. This is checked as follows, using a simplified encounter classification scheme adapted from Tam and Bucknall (2010), which is illustrated in Fig. 4:

1. Using the data of the assisted vessel in convoy furthest away from the icebreaker, two bearing region domains are drawn for this vessel. The radius of these domains is 3 NM.[1]
2. Vessels in BR_2 with a relative heading to the former vessel within region HR_1, which have a speed difference with this vessel of less than 5 kn, are taken to be part of the convoy. These are added to the set of vessels following the icebreaker.
3. Steps 1 and 2 are repeated until no additional vessels are found to be part of the convoy.

In the third step in Fig. 3, the assisted vessels are counted. Together with the information about the simultaneous occurrence of a towing operation, the operation type is classified and the appropriate distance calculation procedure selected. This is discussed in Section 3.5.

When extracting the data points corresponding to escort and convoy operations from the integrated database, the data in periods marked as "begin/end assistance" is discarded. This is due to the recording method in 6-min intervals[2]: some data points in this period may not represent a convoy operation. Hence, only data points of ongoing escorts/convoys are further analyzed.

3.5. Calculation of convoy distances (Step 8)

In the analysis of the convoy distances, a distinction is made between escorting operations and convoy operations, based on experience from icebreaker crew. In convoy operations, a further distinction is made between the distance between the icebreaker and the first following vessel and the distances between the subsequent vessels in the convoy.

The distinction between the distance between icebreaker and the first independently following vessel (which in a convoy typically is the weakest vessel), and the vessels navigating in the convoy, is needed based on the reasoning that the icebreaker is more powerful and agile in ice conditions than the following vessels. Hence, the criticality of the distance between the first independently following vessel and the icebreaker is not the same as the criticality of the distance between the other following vessels. The icebreaker crew found that the presence of a towed vessel in escort or convoy operations is not relevant in deciding on the distance maintained between the first following vessel and the icebreaker or icebreaker-tow combination.

Naturally, however, the distances are calculated differently depending on whether or a towing operation is simultaneously ongoing, because if a towed vessel is present, its dimensions must be accounted for in the distance calculations. This leads to four possible arrangements: escort, escort with tow, convoy and convoy with tow, see Figs. 5 and 3.

In the analysis of the distances, a distinction is made between three cases: the distance between the icebreaker and the escorted vessel (E and E^* in Fig. 5), the distance between the icebreaker and the first vessel in a convoy (C_1 and C_1^* in Fig. 5) and the distance

[1] The radius of 3 NM corresponds to the best, thus most frequently used, working scale of marine radar in ice covered waters, see for example (CCG, 2012). The working scale of radar determines the size of an area that can be effectively monitored, thus the number of ships that are followed. If a distance between an observing and observed ships falls in that range, these two vessels are considered as part of a convoy, since they are able to see each other, are aware of behavior of the other, and are able to react when needed. The ships which are more than 3 NM apart remain absent on radars, even if they may be able to see each other visually.

[2] 6-min interval is chosen primarily for pragmatic reasons for the data processing. Since the database is processed by humans, the processing time is essential. If the interval is short (say one minute), the processing time gets longer but the obtained results, despite being more detailed, are not more informative, mainly due to relatively low speed of a convoy thus short distances made over the interval. On the other hand, if the interval is too long (say 15 min), the obtained results may be too coarse and we may face a situation where relevant cases are missed for subsequent analysis.

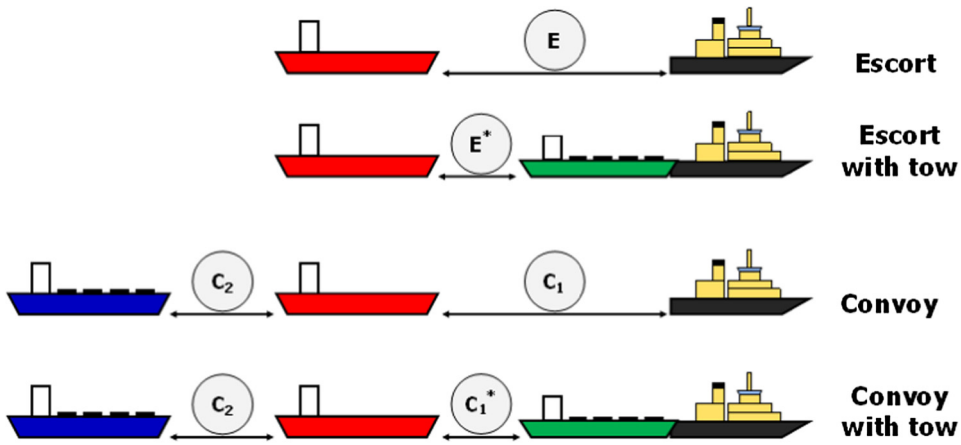

Fig. 5. Definition of analyzed distances in escort and convoy operations.

between the following vessels in a convoy (C_2 in Fig. 5). In all cases, the distances are those between the stern of the first vessel and the bow of the second.

In the distance calculation, an assumption is needed as to the location of the AIS transponder, as this is not retained in the available data. This position is needed to estimate the position of each vessel's stern and bow. For icebreakers, it is assumed that this transponder is located amidships, whereas for cargo vessels and passenger ships, its position is assumed at respectively 0.1L and 0.9L ahead of the stern, with L the ship's length.

4. Results

In this chapter, the empirical analysis results for the escort distances (types E and type E* in Fig. 5), convoy distances (types C_1, C_1^* and C_2 in Fig. 5) and escort and convoy speeds are presented. This is done using a series of Tukey-boxplots (McGill et al., 1978) and tables containing a series of summary statistics of the empirical data. The distribution mean and median give insight in the central measures of the distribution. The standard deviation, skewness and kurtosis are higher-order moments of the distribution. These contain information about the degree of variation, the level of asymmetry and the peakedness of the data with respect to the mean value. The 0.25 and 0.75 quantiles show the values for which 25% and 75% of the data has a smaller value. Further details about the calculation of these parameters and their interpretation can be found in e.g. Sheskin (2011).

These relatively simple methods are deemed sufficient to address the stated research questions of Section 1, i.e. to provide qualitative and quantitative insight in the influence of ice conditions on the escort/convoy distances and speeds.

4.1. Escort and convoy distances

In Fig. 6, the distances in escort (type E and E*) and convoy operations (type C_1, C_1^* and C_2), as defined in Fig. 5, are shown for different ice conditions. Table 6 shows a number of summary statistics of the distributions of the distances for the same ice condition classes.

It is seen that in level ice thickness, the distributions of distances E and E* and C_1 and C_1^* are very similar. In contrast, distances C_2 and C_2^* show a larger mean and variation. All distributions are positively skewed and have high kurtosis values, indicating that much of the data is clustered around the central measures and that outliers are comparatively infrequent. The influence of the ice thickness is rather limited for E, E*, C_1 and C_1^*, while being somewhat more outspoken for C_2 and C_2^*. For the ridge and raft ice thickness, the distributions have similar features as for

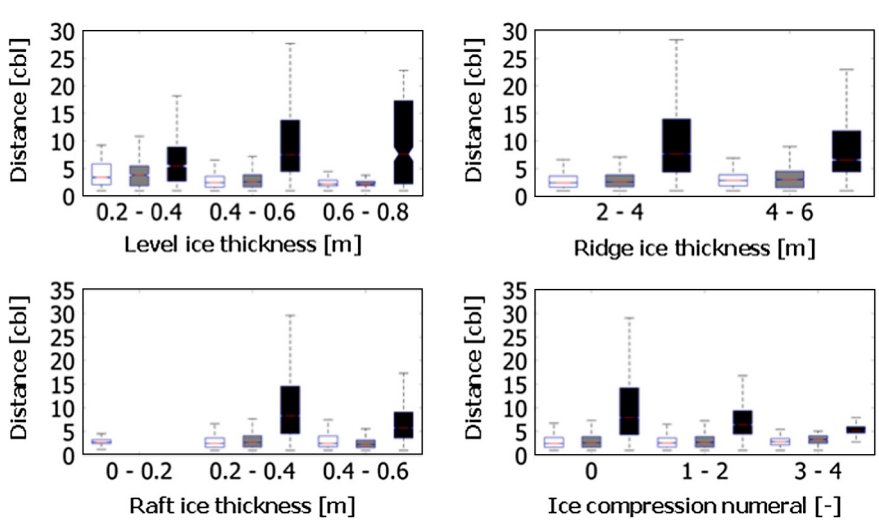

Fig. 6. Tukey-boxplots for distances [cbl] in escort (E and E*, white) and convoy (C_1 and C_1^*, gray; C_2, black) operations, for different ice conditions.

Table 6
Summary statistics of distances [cbl] in escort and convoy operations, for different ice conditions.

	Escort			Convoy: icebreaker-1st vessel			Convoy: other vessels		
Level ice (m)	0.2–0.4	0.4–0.6	0.6–0.8	0.2–0.4	0.4–0.6	0.6–0.8	0.2–0.4	0.4–0.6	0.6–0.8
Mean	3.8	3.0	3.6	4.0	3.1	2.3	6.4	9.5	9.4
Median	3.4	2.5	2.2	3.8	2.6	2.1	5.5	7.5	7.6
Std. dev.	1.9	1.9	3.5	2.4	1.9	0.9	4.5	6.4	7.0
Skewness	0.4	2.3	1.7	0.8	1.5	1.6	1.4	0.9	0.2
Kurtosis	2.1	10.6	4.4	3.4	5.3	6.9	5.7	2.9	1.4
0.25 quantile	2.1	1.7	1.8	1.9	1.7	1.9	2.7	4.5	2.2
0.75 quantile	3.4	3.6	2.9	5.5	3.9	2.7	8.9	13.8	17.3
Cases	3003	44,030	798	714	19,799	85	1382	26,118	342
Ridge ice (m)	2–4	4–6		2–4	4–6		2–4	4–6	
Mean	3.0	3.2		3.1	3.6		9.5	8.5	
Median	2.4	2.9		2.6	3.0		7.7	6.6	
Std. dev.	2.0	2.1		1.9	2.4		6.4	5.8	
Skewness	2.1	2.5		1.6	1.0		0.8	1.2	
Kurtosis	9.3	12.0		5.8	3.0		2.9	4.1	
0.25 quantile	1.6	1.9		1.7	1.6		4.4	4.4	
0.75 quantile	3.6	3.9		3.9	4.5		14.0	11.8	
Cases	40,863	6968		17,538	3060		23,618	4224	
Raft ice (m)	0–0.2	0.2–0.4	0.4–0.6	0–0.2	0.2–0.4	0.4–0.6	0–0.2	0.2–0.4	0.4–0.6
Mean	3.2	3.0	3.3	–	3.2	2.7	–	10.0	7.2
Median	2.8	2.5	2.5	–	2.7	2.3	–	8.3	5.7
Std. dev.	1.5	1.9	2.3	–	2.0	1.7	–	6.6	4.9
Skewness	1.7	2.3	1.7	–	1.4	2.3	–	0.7	1.4
Kurtosis	5.4	10.9	5.9	–	4.7	9.6	–	2.7	5.0
0.25 quantile	2.4	1.6	1.8	–	1.7	1.6	–	4.5	3.6
0.75 quantile	3.3	3.6	4.1	–	4.1	3.2	–	14.6	9.1
Cases	727	39,966	7138	0	17,019	3579	0	21,367	6475
Compression (–)	0	1–2	3–4	0	1–2	3–4	0	1–2	3–4
Mean	3.0	3.1	3.2	3.2	3.0	3.3	9.7	7.6	7.0
Median	2.4	2.6	2.8	2.6	2.7	3.3	7.9	6.4	5.1
Std. dev.	2.0	2.2	2.2	2.0	1.6	1.1	6.5	4.9	4.7
Skewness	2.0	2.4	4.0	1.5	1.2	1.2	0.8	1.5	2.0
Kurtosis	8.8	10.1	20.8	5.0	4.9	11.6	2.8	5.8	6.4
0.25 quantile	1.7	1.7	2.1	1.7	1.7	2.5	4.3	4.4	4.7
0.75 quantile	3.7	3.6	3.5	3.9	3.9	4.1	14.2	9.4	6.0
Cases	39,772	6552	1507	18,380	1654	564	23,600	3650	592

Notes: Cases: number of data points in given category, distances as calculated in Section 3.5, compression levels as defined in Table 3.

the level ice cases, with differences existing to some extent between E, E^*, C_1 and C_1^* on the one hand, and C_2 and C_2^* on the other. The influence of the ice thickness is limited also in these cases. These findings may be explained by the fact that once the icebreaker has created an ice channel or cleared an existing one, the assisted vessels do not, or not extensively, come in contact with ice. Thus, the characteristics of the ice may be less important.

When considering the compressive ice cases, it is seen that the distributions have similar shape and characteristic parameters as in the other ice cases. However, it is significant to observe that with increasing ice compression, the means, medians and variation of distances C_2 and C_2^* decrease remarkably. In other words, the convoys become more compact with increasing ice pressure. This can be explained by the fact that the ice channel edges more significantly affect the ship resistance under more severe compression, as the channel closes faster.

Overall, it seems that a target distance of ca. 3 cbl is a reasonable approximation for distances E, E^*, C_1 and C_1^*. For C_2 and C_2^*, target distances of 8 cbl, 6 cbl and 5 cbl are reasonable compression-free ice, moderate compressive ice and severely compressive ice.

4.2. Escort and convoy speeds

In Fig. 7, the transit speeds in escort and convoy operations are shown for different ice conditions. Table 7 shows a number of summary statistics of the distributions of the speeds for the same ice condition classes. The analyzed speeds are the speed over ground of each ship in the analyzed operation, i.e. the assisted vessel(s) as well as the icebreaker. This dataset thus describes the absolute (i.e. with reference to an inertial reference frame) speed performance of all the ships in the given operation, for the considered time period.

It is seen that in level ice thickness, the distributions of the escort and convoy speeds have similar characteristics, with a negative skew and a moderate kurtosis. For escort operations, the means and standard deviations are not much affected by the ice thickness. In convoys, higher ice thicknesses lead to moderately to significantly lower average transit speeds compared to conditions of smaller ice thicknesses.

In ridge ice conditions, the empirical speed distributions have similar characteristics as in the level ice cases, with lower (near-normal) kurtosis. The ridge thickness has no significant effect on escort or convoy speeds, but it is seen that convoys proceed ca. 1 kn slower than singly escorted vessels. Raft ice conditions are somewhat surprising in that higher raft ice thicknesses correspond to higher escort and convoy speeds. The distributions are negatively skewed and escort operations have higher kurtosis than convoys.

Finally, the effect of compressive ice is perhaps surprising in that there is no significant effect on the escort or convoy transit speeds. It could be expected that conditions of higher ice compression are more challenging to transit for both the icebreaker and the assisted vessels, but this is not observed. It may be the case that the transit speeds are maintained so that the channel closing due to ice

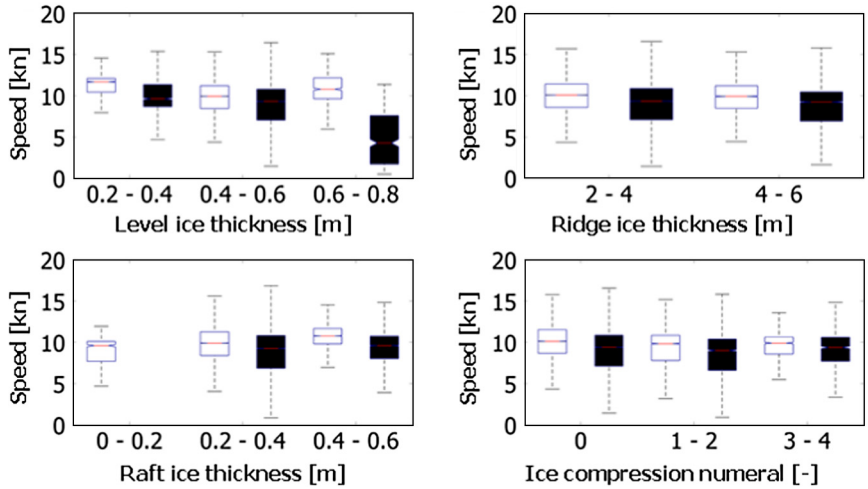

Fig. 7. Tukey-boxplots of speeds [kn] in escort (white) and convoy (black) operations, for different ice conditions.

Table 7
Summary statistics of speed [kn] in escort and convoy operations, conditional to ice conditions as per HELMI hindcasts.

	Escort			Convoy		
Level ice (m)	0.2–0.4	0.4–0.6	0.6–0.8	0.2–0.4	0.4–0.6	0.6–0.8
Mean	11.1	9.7	10.8	9.8	8.8	4.7
Median	11.7	10.0	10.8	9.7	9.3	4.3
Std. dev.	1.8	2.4	2.6	3.1	3.2	3.1
Skewness	−2.2	−0.8	−1.1	−0.3	−0.5	0.2
Kurtosis	10.1	4.2	5.7	4.2	3.2	1.7
0.25 quantile	10.5	8.5	9.6	8.7	7.1	1.7
0.75 quantile	12.1	11.2	12.2	11.4	10.8	7.6
Cases	3003	44,023	798	2107	46,061	427
Ridge ice (m)	2–4	4–6		2–4	4–6	
Mean	9.8	9.5		8.8	8.7	
Median	10.1	9.9		9.4	9.3	
Std. dev.	2.4	2.5		3.2	3.2	
Skewness	−0.8	−1.1		−0.5	−0.4	
Kurtosis	4.2	4.4		3.2	3.2	
0.25 quantile	8.6	8.5		7.1	6.9	
0.75 quantile	11.4	11.2		10.9	10.5	
Cases	40,863	6961		41,333	7262	
Raft ice (m)	0–0.2	0.2–0.4	0.4–0.6	0–0.2	0.2–0.4	0.4–0.6
Mean	9.0	9.6	10.7	–	8.7	9.1
Median	9.6	9.9	10.8	–	9.3	9.6
Std. dev.	2.2	2.4	2.1	–	3.3	2.7
Skewness	−0.8	−0.9	−0.8	–	−0.5	−0.9
Kurtosis	4.8	4.0	6.1	–	3.0	4.4
0.25 quantile	7.7	8.4	9.8	–	6.9	8.0
0.75 quantile	10.1	11.3	11.7	–	10.9	10.8
Cases	727	39,959	7138	0	38,593	10,002
Compression (–)	0	1–2	3–4	0	1–2	3–4
Mean	9.9	9.1	9.4	8.9	8.3	8.8
Median	10.1	9.8	9.9	9.4	9.0	9.4
Std. dev.	2.3	2.8	2.3	3.3	3.0	2.5
Skewness	−0.8	−0.9	−1.0	−0.5	−0.8	−1.1
Kurtosis	4.2	3.5	4.5	3.1	3.2	4.1
0.25 quantile	8.7	7.8	8.6	7.1	6.6	7.7
0.75 quantile	11.6	10.9	10.7	10.9	10.4	10.6
Cases	39,765	6552	1507	42,178	5261	1156

Notes: Cases: number of data points in given category, compression levels as defined in Table 3.

compression occurs when the ships have already proceeded further.

Overall, it seems that a transit speed ca. 10 kn is a reasonable approximation for escort operations, whereas for convoys, a speed of 9 kn can be adopted. However, in level ice thicknesses over 0.6 m, a convoy transit speed of 5 kn is a good rule-of-thumb value for operational planning purposes.

5. Discussion

5.1. Uncertainties

In scientific work, it is important to consider the importance of uncertainties on the conclusions of an inquiry (Douglas, 2009). Inaccuracies in data, assumptions and modeling procedures are conditions or choices which may affect the results. Various uncertainty assessment methods have been proposed, e.g. Flage and Aven (2009), Kloprogge et al. (2011) and Goerlandt and Montewka (2015). For the present purposes, the simple approach suggested by Flage and Aven (2009) is applied. First, various key elements of the analysis are listed. Then, their associated uncertainties are judged and their sensitivities for the results assessed. A brief justification of the ratings is provided. The qualitative scales for assessing the uncertainty and sensitivity are shown in Table 8. All assessments are subjective, with main purpose to communicate the robustness of the analysis with respect to its particularities, enhancing transparency and improving discussion among peers. The assessment can furthermore act as a guide for further research and methodological refinement.

Table 9 shows the uncertainty and sensitivity ratings of the various elements of the analysis. It is seen that there is generally low uncertainty related to the data sources and data processing procedures. Sensitivities are also expected to be rather low. The uncertainties regarding the influence of other contextual factors on the ice convoy operations are moderate, and the conclusions of the analysis may change to some extent change due to this. This is addressed further in Section 5.2, where directions for future work are discussed.

5.2. Future work

Given that the presented analysis is the first research where the ship safety domain concept has been investigated for convoy operations in ice conditions, it is evident that the current work has some limitations and that future research efforts can provide further insight in this phenomenon.

First, the analysis can be performed for other ice seasons and different operations areas. The current analysis is limited to data

Table 8
Interpretation of uncertainty and sensitivity ratings.

Aspect	Rating	Interpretation
Uncertainty U	L	All of the following conditions apply: • The assumptions made are seen as very reasonable • Much reliable data are available • There is broad agreement/consensus among experts • The phenomena involved are well understood, models are known to give predictions with the required accuracy
	M	Conditions between those characterizing low and high uncertainty
	H	Conditions opposite to those characterizing low uncertainty
Sensitivity S	L	Large changes in base values needed to bring about altered conclusions
	M	Relatively large changes in base values needed to bring about altered conclusions
	H	Relatively small changes in base values needed to bring about altered conclusions

Table 9
Uncertainty–sensitivity assessment for convoy analyses.

Model element	U	S	Justification
AIS data	L	L	• AIS data accuracy is known to have improved over recent years (Felski and Jaskolski, 2013), with position data accuracy around 10 m. The data was checked and cleaned of data errors (e.g. ship positions on land, unrealistic ship speeds, ...), resulting in ca. 5% data deleted • Position inaccuracies could have minor effects on the calculated distances, but remain small in comparison with the distances between ships as calculated in Section 4. The amount of missing or erroneous data is small in comparison, so the effect of this is expected to be small
HELMI hindcast data	L	L–M	• The hindcast data used here has developed by updating the prior parameters of numerical HELMI ice forecast once they have been observed. Subsequently, the hindcasted parameters including the ice compression were compared with the onsite measurement and icebreakers observations. This allows concluding that the uncertainty associated with such obtained dataset can be considered low (Lehtiranta et al., 2012) • However, in certain sea areas, close to the shore, the quality of the hindcast is deteriorated especially when it comes to the ice compression level (Lehtiranta et al., 2012). However, as the studied areas concern mostly the open sea areas, effects of these possible unreliable data instances are expected to be rather low • Despite the high accuracy of the HELMI model, there are other unknown parameters, related to the ice field, which may affect speed of a leading icebreaker or the distance between her and a ship that follow. These are the presence of ice channel and its condition (whether it is open, frozen after it has closed, or it is filled with growlers and then has frozen), ice leads, the location and distribution of ice ridges. All these affect the performance of a leading IB. However we cannot learn anything about these from the dataset which we have established, because the currently best available ice model does not model these parameters. Therefore, they can be seen as the largest source of epistemic uncertainty for the analysis conducted
Identification of operations	L	L–M	• Rosenblad (2007) describes the characteristics of different operations in sufficient detail to know what to look for in the videos • Shared experiences with icebreaker crew on judging the operations confirms knowledge from literature • If misclassified, resulting dataset may contain different values. Due to high number of points, the effect of this would be rather limited
AIS transponder location	L–M	L	• Assumptions of Section 3.5 are reasonable for common ship types • Effect of inaccuracy is limited: errors up to ca. 30 m may occur for larger ships, considering the distances of interest (typical mean of ca. 600 m), this would result in an error of ca. 5%
Existence of subclusters in data	M	M–H	• The analysis is based on the assumption that convoy distances and speeds are mainly dependent on ice conditions. Other factors, such as vessel sizes, ice classes and other environmental conditions (visibility, daylight, ...) may affect operational conditions as well • If subclusters exist in the data, these may be important to consider for further enhancing the understanding of convoy operations

of one month in a severe winter in the Finnish area of the Gulf of Finland. It would be interesting to compare the results with milder winters and operations in different areas. Empirical characteristics of other navigational operations in ice conditions, e.g. towing and cutting loose operations and ships engaged in independent navigation, can also be derived from an analysis similar as the one presented here.

Second, additional contextual contributes such as vessel sizes, ice classes, environmental factors such as visibility and time of day could be added to the dataset. The relation between these factors and the convoy distances and speeds could be studied e.g. using visual data mining techniques or probabilistic methods.

Considering this last point, it is noted that the state-of-the art in empirical analyses of ship domains in ice-free water conditions, as presented e.g. by van Iperen (2015, 2012), Hansen et al. (2013) and Rawson et al. (2014), do not account for environmental conditions. Given that the results of Section 4 indicate that these can affect domain sizes and navigation speeds, it may be interesting to apply visual or probabilistic data mining techniques to better understand domain sizes for various environmental conditions also in open sea conditions. Such empirical knowledge of ship domains could also be beneficial to reduce uncertainties in maritime transportation risk models. Many models apply ship domains to determine the exposure of collision accidents, see e.g. Li et al. (2012), while the modeled domain shapes involve high uncertainty (Sormunen et al., 2015) and the choice of domain has important effects on the analysis results (Goerlandt and Kujala, 2014).

Third, there are unknown parameters related to the ice field, which may affect speed of a leading icebreaker or the distance between her and a following ship. These are the presence of ice channel and its condition during the operation (whether the ice channel is open or refrozen), ice leads, the location and distribution

of ice ridges. Since the HELMI ice model does not include these parameters, we cannot learn anything about their effect on the analyzed variables. To reduce this uncertainty a new data source could be introduced, like satellite images, and the relevant information incorporated into the existing database. This is left for future research.

6. Conclusion

In this paper, escort and convoy operations in ice conditions have been investigated using AIS and sea ice data. The integration of ship traffic data with contextual data has enabled insight in these modes of icebreaker assistance. The ship domain, which is widely applied in maritime safety and risk research, has been empirically studied. Focus has been on the relations between the domain size (i.e. the distances between ships in convoys) and the prevailing ice conditions. Also the escort and convoy speeds have been studied.

The analysis shows that contextualizing AIS data with environmental data can provide further insights in the contextual dependency of ship domains and operational characteristics. This has not been exploited in earlier empirical domain analysis, while the presented analysis and the applied uncertainty assessment method indicate that this may be a feasible direction of future research.

Acknowledgements

This work presented in this paper is primarily carried out within the WINOIL project in association with the Kotka Maritime Research Centre. This project is co-funded by the European Union, the Russian Federation and the Republic of Finland. The contributions of the first author have been made through the BONUS STORMWINDS project, supported by funding received from BONUS, the joint Baltic Sea research and development programme (Art 185), funded jointly from the European Union's Seventh Programme for research, technological development and demonstration and from the Academy of Finland. The financial support is acknowledged. The authors also thank Hannah Ploskonka and Dannielle Lodge for their help in constructing the database of convoy operations.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ssci.2016.01.004. This concerns in particular Video 1, showing the example described in Section 3.3.

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