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On the relationship between sea ice deformation and ship damages in the Gulf of Finland in winter 2003

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Abstract. Sea ice ridges and other types of deformed ice are the main obstacles for the winter navigation. During the severe winter 2002/2003, about 60% of the ship hull damages, registered in the Baltic Sea, occurred in the Gulf of Finland. We have analysed ice deformation features, derived from the HELMI sea ice model in relation to two ship damages that occurred in the Gulf of Finland this winter. The damages happened close to the high growth rate area of deformed ice at the interface of different ice conditions with notable ice thickness gradients. It is concluded that the rate of ridged ice production is an indicator of the compression of the ice pack and a potential indicator of ice-induced danger to shipping.

Key words: Gulf of Finland, sea ice, winter navigation, ice deformation, ship damage.

1. INTRODUCTION

The Gulf of Finland is an elongated (in the W–E direction) sub-basin of the Baltic Sea with the total length of 460 km and the width up to 120 km (Fig. 1). It is an important corridor for merchant and passenger shipping for its coastal states Estonia, Finland and Russia. More than 37 000 ships over 300 GRT cross (enter or leave) the entrance line of the Gulf of Finland annually, based on the data from the Automatic Identification System (AIS) for monitoring the maritime traffic in the Baltic Sea area [1,2]. The shipping intensity has an increasing trend due to the strong economic growth in this region, including tanker traffic to the new Russian oil terminals [2,3]. And the number of tanker accidents seems to increase

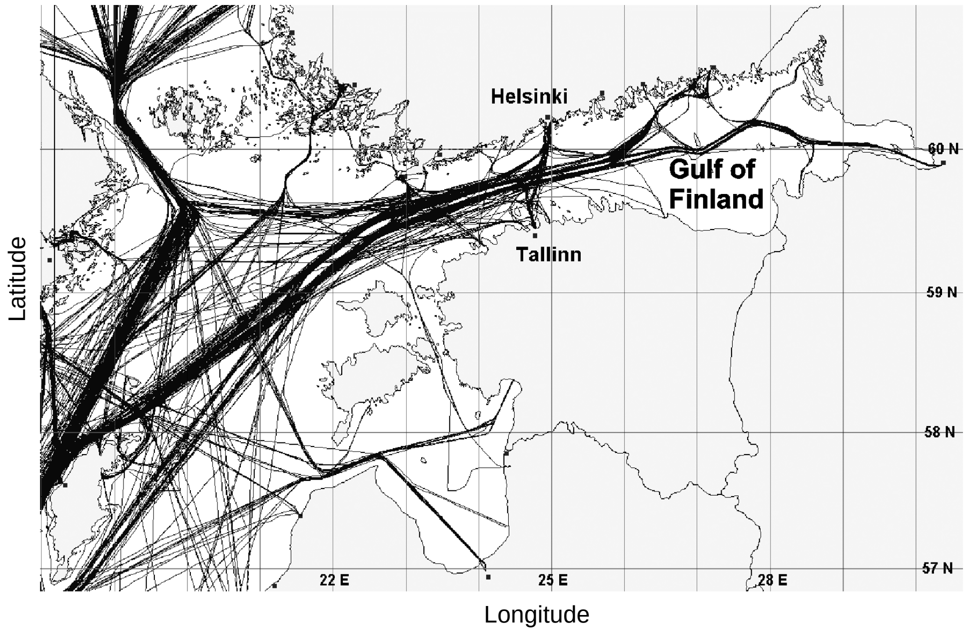

Fig. 1. Map of the Gulf of Finland in the northeastern Baltic Sea. Selected ship routes from the first half of April 2007 are shown by the HIROMB-SeaTrackWeb data (Swedish Meteorological and Hydrological Institute; the routes not necessarily represent the long-term shipping statistics).

when the winter is more severe. In the Baltic Sea shipping regulations, special attention is paid to the most dangerous wintertime navigation period [4,5] when vessels navigate through the ice.

The Gulf of Finland is fully ice-covered in normal and severe winters [6,7]. Even in very mild winters some parts of the Gulf of Finland freeze. Sea ice conditions substantially vary in the east–west direction. The average length of the ice season exceeds 120 days in the eastern part and is only a couple of weeks in the western entrance area of the gulf. The sea ice formation begins first in the eastern part of the Gulf of Finland, usually in the beginning of December. The break-up of ice cover occurs commonly in the middle of April, but in the coastal zone and small bays the land-fast ice may persist even until the beginning of May. The thickness of undeformed level ice is typically 30–40 cm but may reach 80 cm in certain snow-free conditions.

The most significant obstacles for the winter navigation in the Baltic Sea are pressure ridges and brash ice. They are particular forms of deformed (compressed) ice that develops under variable wind stress. Outside the land-fast ice region (depths down to 5–15 m) [8], the deformation of the pack ice is a key process determining the evolution of the distribution of the sea ice thickness. The dominant deformation processes are pressure ridging (piling of smaller ice blocks broken from interacting ice sheets) and rafting (overriding of one ice sheet by another). Recent ice thickness measurements in the Baltic Sea [9] have shown that the amount of deformed ice is significantly larger than reported in the routine ice charts. Consequently, the mean ice thickness could exceed 1–2 m in large areas of the Baltic Sea. Sea ice ridges are the thickest ice forms. The visible part of the ridge, called sail, is typically 1–3 m high while the most of the ridge volume is contained in the subsurface part of the ridge, the depth of which may reach up to about 25 m in the Baltic Sea [10,11].

Modelling of the Baltic Sea ice dynamics started more than twenty years ago [12]. It has provided valuable results both in research and in operational applications. Among a number of ice model variables, observational validation and detailed analysis are usually done for the ice thickness and concentration, for different types of ice [13,14]. The progress in simulating the above "standard output" variables and ice drift velocity has increased the interest in the deformation-related model variables like the ridge height, the fraction of deformed ice and the rate of ice compression.

High pressure in the ice field causes ice deformation and can be dangerous to the vessels. In a severe winter 2002/2003, about 62% of ship hull damages, registered over the entire Baltic Sea, occurred in the Gulf of Finland, whereas 30% of damages were caused by ship–ice interaction and 15% of hull damages occurred in the ice field under compression [15].

In the present paper we perform an analysis of sea ice deformation fields in the Gulf of Finland in relation to ship damage events in winter 2003, based on the results from the HELMI sea ice model that is used also in the Finnish ice service. The analysis is a step towards the determination of actual ice loads on ships in operational situations, contributing to a better management of winter navigation. A brief presentation of the sea ice model used is given first, followed by a description of observed and modelled ice conditions in the particular winter. Finally, we focus on the analysis of modelled ice features during two events of ship damage.

2. DESCRIPTION OF THE HELMI MODEL

The HELMI (HELsinki Multicategory Ice (model)) model describes the spatial and temporal evolution of sea ice thickness distribution. It tracks ice concentrations of different thickness categories, the redistribution of ice categories due to deformations, the horizontal components of ice velocity and the internal stress of the ice pack and accounts for the thermodynamics of sea ice. The physics of the model with some applications to the climate studies is described in detail in [16,17]. In the Baltic Sea, the HELMI model has been applied for the regional sea ice forecasting (http://polarview.fimr.fi). The only differences between the operational and climate applications are in the horizontal resolution and in the scheme of atmospheric forcing.

The equations for the ice concentration and thickness for each ice category read

$$\partial A_i / \partial t = -\mathbf{u} \cdot \nabla A_i + \Psi_i^A + \Phi_i^A, \tag{1}$$

$$\partial h_i / \partial t = -\mathbf{u} \cdot \nabla h_i + \Psi_i^h + \Phi_i^h, \tag{2}$$

where A_i and h_i are the concentrations of the ice cover area per sea surface area and the mean (in terms of the ice volume per unit area) thickness of the ice category i, $\mathbf{u}$ is the vector of ice drift velocity, Φ_i are the thermodynamical growth or decay rates and Ψ_i are the thickness redistribution functions due to mechanical deformations, describing open water changes, rafting and ridging.

The redistribution functions Ψ_i depend on the ice thickness, concentration and strain rates [18,19]. Continuum scale sea ice models resolve an average behaviour of the pack ice and the subgrid scale processes are either neglected or taken into account in a simplified manner. Presently the HELMI model approximates the complex nature of sea ice forms by seven thickness categories. For the undeformed ice (level ice), we use five categories. The first undeformed ice category is typically the oldest and thickest ice due to the thermodynamical growth. The fifth undeformed ice category describes the growth of new ice in the leads. The deformed ice is separated into two ice thickness categories, one for rafted ice and the other one for the ridged ice. Ice categories are not bounded by the minimum and maximum ice thickness, except the thinnest category that is not allowed to exceed 10 cm in thickness.

The following assumptions are made regarding the deformation processes: 1) the deformed ice is generated only from undeformed ice categories, 2) the cross-over thickness determines whether the undeformed ice is rafted or ridged. These assumptions are based on the Parmeter law [20] and field observations [21]. It is also assumed that the thinnest 15% of the ice categories experience deformation [18]. Further assumptions are that the shear deformations are not taken into account and the shape and porosity of the ridges are constant. These assumptions are based on the results of field observations [10,22].

Ice motion is determined by the momentum balance equation

$$m(\mathrm{d}\mathbf{u}/\mathrm{d}t + f\,\mathbf{k} \times \mathbf{u}) = A(\boldsymbol{\tau}_a + \boldsymbol{\tau}_w) - mg\nabla\xi + \nabla \cdot \boldsymbol{\sigma}, \tag{3}$$

where m is the total ice and snow mass per unit area, $\mathbf{u}$ is the horizontal ice velocity vector, f is the Coriolis parameter, $\mathbf{k}$ is the upward unit vector, A is the overall mean ice concentration, $\boldsymbol{\tau}_a$ and $\boldsymbol{\tau}_w$ are the air (wind) and water stress vectors, $\nabla\xi$ is the sea surface tilt, g is the acceleration due to gravity and $\boldsymbol{\sigma}$ is the internal stress tensor. The internal stress of pack ice is calculated according to the viscous-plastic rheology [23]. This formulation also relates the consumption of kinetic energy to the ice pack deformations [24].

The HELMI sea ice model employs curvilinear coordinates. The variables are spatially discretized on the Arakawa C-grid. The advective part of the ice thickness and the concentration equations are solved by an upwind method. The momentum balance equation is solved by the line successive relaxation procedure, proposed by Zhang and Hibler [25].

In the present study we use the horizontal grid step of 1 nautical mile (1852 m). The model domain covers the whole Baltic Sea. The results are mainly analysed for the Gulf of Finland, but for comparison purposes also for the Gulf of Riga. For atmospheric forcing we used the data from the NCEP/NCAR reanalysis project (http://dss.ucar.edu/pub/reanalysis/).

3. OBSERVED AND MODELLED ICE CONDITIONS IN THE GULF OF FINLAND DURING WINTER 2002/2003

The air temperature time series given in Fig. 2 show that the cold season 2002/2003 began rather early. The temperatures were below the long-term average during most of the November and in December. Also the first half of January was relatively cold. The end of January was warmer than the average. February was again colder than the average. The entire winter 2002/2003 was the coldest over the last 34 years.

The Baltic Sea ice season 2002/2003 started already in early November with rapid ice formation in the northern Bothnian Bay, in the eastern part of the Gulf of Finland and in the coastal areas of the Gulf of Riga. By the end of December the entire Gulf of Finland was ice-covered. The ice thickness ranged from 15 cm in its western part to 50 cm in the eastern area [26]. Already in January vessels had to navigate through the ice along the longest way in 40 years. The icebound sailing distance reached up to 200 nautical miles instead of average 50 nautical miles.

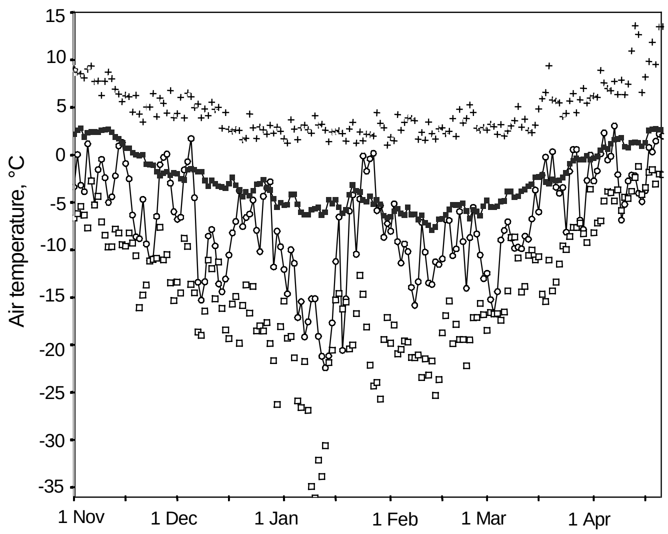

Fig. 2. Daily averages of the air temperature (circles) in the Gulf of Finland during winter 2002/2003. Filled squares show the average air temperature for the period of 1971–2005; unfilled squares and crosses represent the daily minimal and maximal air temperature for 1971–2005 from the NCEP/NCAR reanalysis data, respectively.

A specific feature of the winter 2002/2003 was the exceptionally thick ice. The level ice thickness was up to 80 cm on the Finnish coast. The ice thickness in the drift ice was even larger. According to the airborne electromagnetic measurements the mean ice thickness exceeded 1.5 m in several areas in late February [27]. Navigational conditions in the northern regions of the Baltic Sea were difficult and restrictions were valid 117–149 days during the whole winter. Typically, merchant ships need ice breaker assistance in the Gulf of Finland beginning with January; however during the winter season 2002/2003 icebreakers were needed already beginning with December. The maximum ice extent for the whole Baltic Sea was observed on March 5, when the ice-covered area was up to 232 000 km^2 [7]. According to this, the winter 2002/2003 is classified as an average ice winter [6], but certainly ice conditions in the Gulf of Finland were harder than on the average [7]. The length of the Gulf of Finland ice season in winter 2002/2003 exceeded the long-term average by more than a month.

The evolution of ice conditions during the entire winter was studied applying the HELMI model in the hindcast mode. Already in the beginning of January the total ice extent reached the maximum for a normal winter and the mean ice concentration was more than 90% over the Gulf of Finland area (Fig. 3). During the first half of January, the ice concentration decreased remarkably due to wind-induced deformation processes. From the mid-January the mean ice concentration decreased from 95 to 70% in the Gulf of Finland. The concentration is compared with the neighbouring Gulf of Riga with similar atmospheric conditions: 1) initial ice extent growth was delayed by about two weeks, 2) in the second half of January the mean ice concentration was reduced more drastically – from about 90 to 20–40%, 3) in February the concentration increased to about 60%, but remained

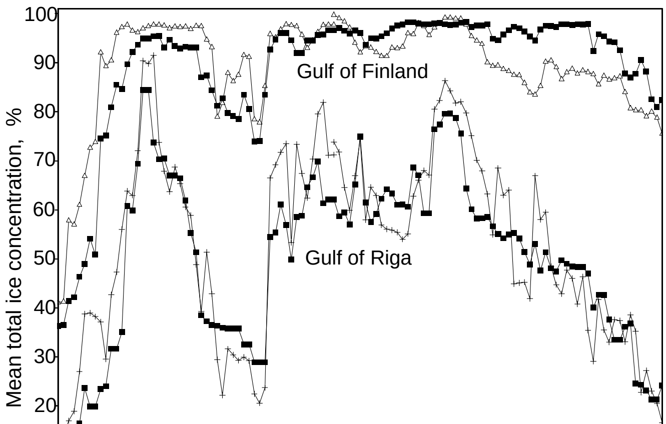

Fig. 3. Modelled (crosses and triangles) and observed (filled squares) mean total ice concentration (all ice categories) over the gulfs of Finland and Riga during winter 2002/2003.

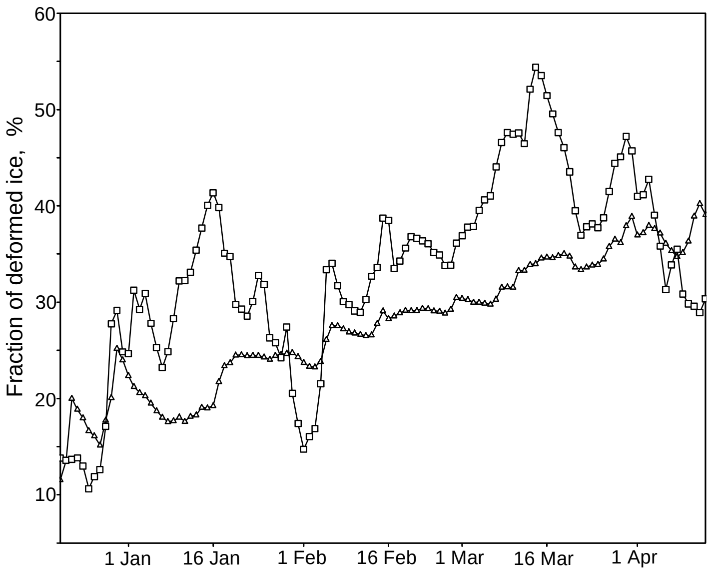

Fig. 4. Modelled time series of the average deformed ice fraction as part of the total ice concentration in the Gulf of Finland (triangles) and the Gulf of Riga (squares) during winter 2002/2003.

until the break-up by more than 30% lower than in the Gulf of Finland. The simulated mean ice concentrations in both of the gulfs are in a good agreement with the observed values.

The portion of deformed ice in total ice thickness is a good measure of the significance of the deformation process in the total ice balance. The time series of the fraction of deformed ice over the whole Gulf of Finland and the Gulf of Riga were calculated from the model outputs. The results of this calculation (Fig. 4) show that the bulk intensity of deformation processes is higher in the Gulf of Riga. Generally, the fraction of deformed ice increases from 15–20% of the whole ice cover in the beginning of winter up to 30–35% before the break-up. The highest fractions of deformed ice were up to 35% in the Gulf of Finland and up to 55% in the Gulf of Riga.

4. CASE STUDY OF ICE COMPRESSION EVENTS IN THE GULF OF FINLAND

In the ice-covered sea, most of merchant ships are able to proceed only along the artificial ice channels and natural leads and openings. An artificial ice channel is broken by an icebreaker or another powerful ship. An ice channel in the open sea is not in a stable state since it is exposed to external (mainly to wind) forcing. If wind is strong enough to bring the ice fields into motion, a compression in the ice cover frequently occurs. In some cases, the ice pack remains stationary although strong winds are acting. Horizontal differences in the field of ice motions cause compression and compacting (an increase of the ice concentration), but also decompression (a decrease of the concentration or even formation of openings) in the ice cover. Navigation in compressive ice is very difficult and sets special demands to ships.

We have performed two case studies to analyse the situations where ships were sailing along the leads or a ship channel and stuck in compressive ice. Compressive ice situations were identified with the use of the daily growth rate of deformed ice categories (that is, changes owing to rafting and ridging) extracted from the HELMI model.

Model experiments, performed earlier to study the deformed ice growth rate in the Gulf of Finland, showed that the deformation of ice depends on the wind speed to some extent but is much more influenced by changes in the wind direction. For example, low winds (speed about 4 m/s) with variable direction are able to cause strong ice deformation, but stronger steady winds (about 9 m/s) may result in a lower deformation rate. In the Gulf of Finland the most intensive ridging generally takes place when wind blows from SW, SE or NW [28].

4.1. Ship damage on January 11, 2003

Wind conditions in January are given in Fig. 5 as measured at the Tallinn Harbour. Wind speed was only 3 m/s in the morning of January 11, but in the evening reached 8 m/s. The wind direction gradually turned from N to SW during the day.

A 95 000 DWT Oil tanker, ice class IC with cargo was on her way from Russia to Denmark when she got stuck in the compressive ice near Suursaar (27.5°E, 60.0°N) on January 11, 2003, and ice blocks piled up at side shells of the ship [15].

The damaged ship came from NE and incidentally entered into the compressive ice area. The exact time of the ship accident is not known to the authors. According to the observations, on the day before the ship accident the whole sea area was ice covered. The ice concentration was over 95% and the thickness of level ice ranged from 15 to 35 cm. The model simulations show a compression and production of the new ridged ice around the damage place during the time of the accident (Fig. 6). The largest ridge production rates (up to 1.4 m/day in the middle of the Gulf of Finland) were modelled westward from the location of the accident, around longitudes 25.5–26.0°E. The daily growth rate of deformed ice (that is the increase of the mean thickness of ridged and rafted ice during a 24 h period) was only from 0.1 to 0.3 m/day in the region of the accident. The occurrence of compression areas can be partly explained by the ice drift pattern (not shown) due to changing wind conditions. The ice pack was nearly immobile around the ship damage location in the morning of 11 January, but a fast SSE drift (more than 30 cm/s) was apparent westwards from the accident place. This situation caused intense ridged ice production in the middle of the Gulf of Finland and presumable high compressive forces around the accident place. By the evening of the day, changed wind direction (Fig. 5) induced a nearly uniform northward drift with a speed of 10–12 cm/s all over the damage area.

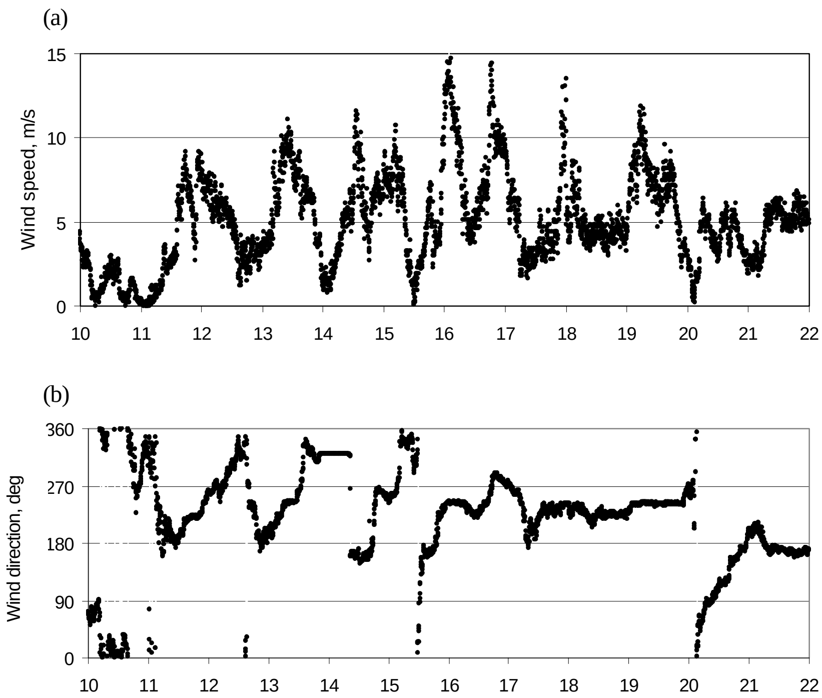

Fig. 5. Wind speed (a) and direction (b), measured at Tallinn Harbour during January 2003.

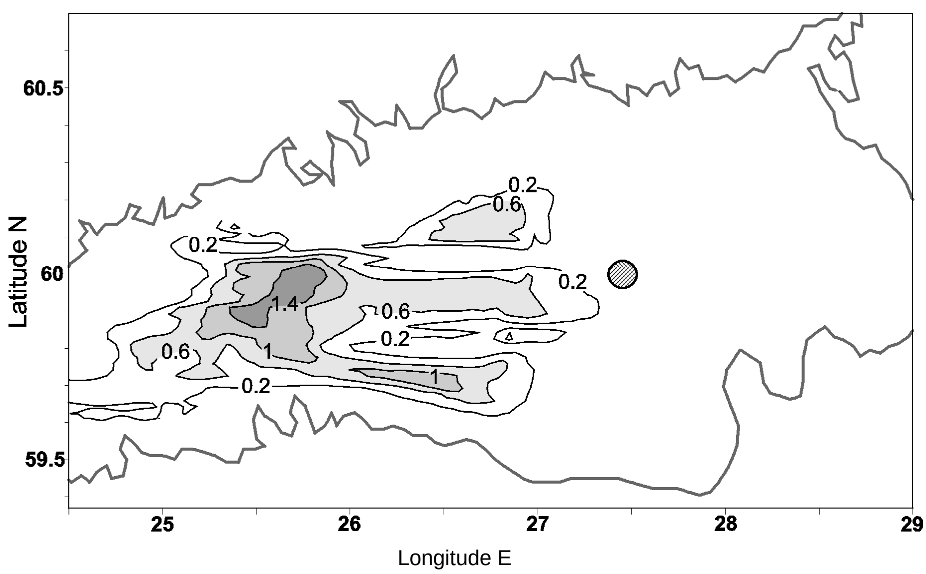

Fig. 6. Simulated daily growth rate of deformed ice in the Gulf of Finland on January 11, 2003. The unit at the contour interval is m/day. The circle denotes the location, where the ship damage occurred.

4.2. Ship damage on January 21, 2003

A tugboat 240 DWT, ice class IA, was damaged in the Gulf of Finland on January 21, 2003 due to the moving compressive ice field. The accident took place at the end of the lead, at the beginning of an ice field (about 60.15°N and 25.2°E). The ship stuck in ice field and started to drift along the ice masses with a speed of 2–3 knots. Ice pieces piled up against the ships side shell. The pile-up process and drifting lasted for about 20 min, then the compression ceased and ice pieces started to slide below the ship bottom; yet the ship had to wait for the icebreaker assistance [[15]].

Wind speed (Fig. 5) fluctuated from 2 to 7 m/s on 20–22 January. Higher speeds up to 10 m/s were observed earlier on 19 January. On 20 January, a day before the accident, wind turned from N to SW and then stayed in the southerly direction.

The observed ice thickness and concentration revealed large gradients in space on those days (Fig. 7). An ice lead extended from the western entrance in the northern part of the Gulf of Finland, with the ice thickness below 10 cm and concentration below 20%. In the eastern part of the central Gulf of Finland, the level ice thickness increased above 30 cm and the ice concentration above 90%.

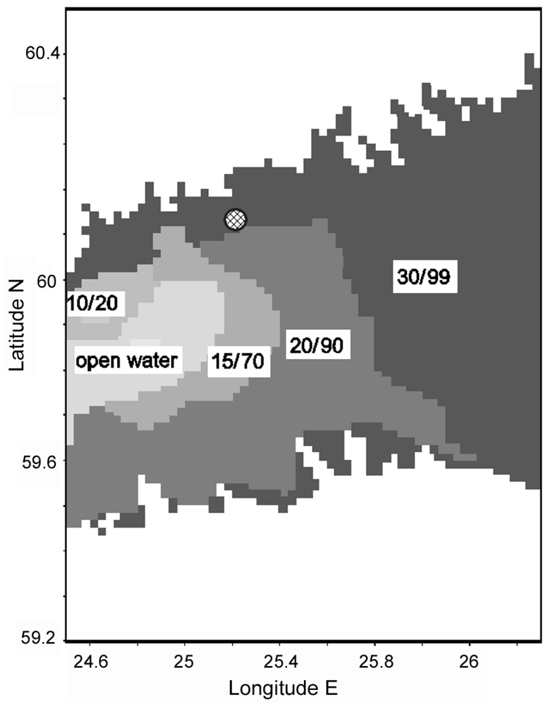

Fig. 7. Observed level ice thickness and concentration in the Gulf of Finland on January 21, 2003 (Finnish Institute of Marine Research, Ice Service). The circle denotes the location, where the ship damage occurred.

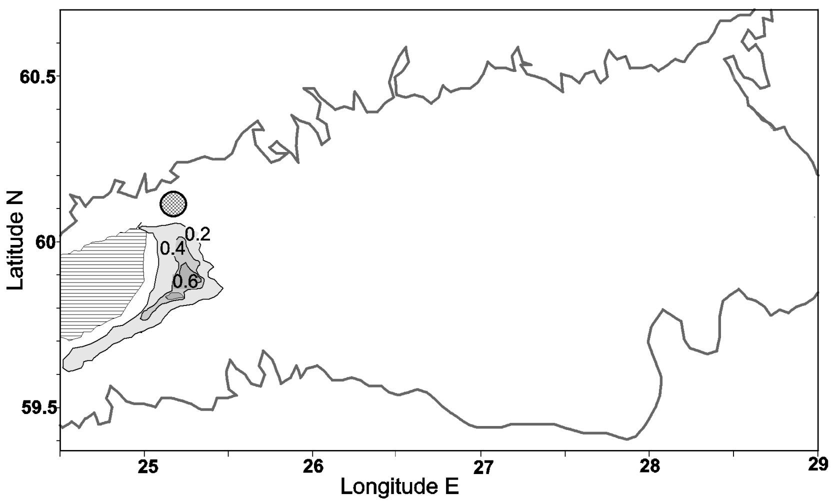

Fig. 8. Simulated growth rate of deformed ice in the Gulf of Finland on January 21, 2003. The unit at the contour interval is m/day. The hatched area denotes free water with ice concentration less than 10%. The circle denotes the location, where the ship damage occurred.

In the area, where ship damage occurred, the total ice concentration was about 70–99%. According to the model results, this area contained mostly deformed ice. The mean total ice thickness in the region was over 70 cm, whereas the mean ridged ice fraction was 60–80%.

Modelling results (Fig. 8) show that a strong deformation took place only in a small area to the south from the location of ship damage, at the edge of the ice margin. The northward drift of ice was the highest (14 cm/s) in the area with a low ice concentration, but at the northern border of the lead, the ice pack was almost motionless. This differential ice drift probably contributed to a high compressive stress in the ice pack. Like in the case of 11 January, the model simulations show only moderate (about 0.1 m/day) ridged ice production in the location of the accident, but much larger (0.6 m/day) ridging offshore.

5. DISCUSSION AND CONCLUSIONS

The Baltic Sea ice services are increasingly using operational ice models to support a safe and cost-efficient navigation. Among the ice-covered regions, the Gulf of Finland is of highest traffic intensity and unfortunately it has also the highest number of ship damages.

To the knowledge of the authors, this study is a first attempt to investigate if ship damage events are related to the ice field properties that can be simulated and forecast by the contemporary sea ice models. There are several generic sources of uncertainties in the process of constructing such models. Even with the regional sea ice models, the model grid cells are significantly larger than the dimensions of ships, introducing the need to properly transfer the large-scale (1–2 km) ice field stresses into the forces that act on the hull of the ship. Stresses in the ice model are about 0.01 MPa (or with 1/3 m ice thickness 0.03 MPa), but on the much smaller scale in ship–ice impacts the stresses are of the order 1 MPa, in localized parts of hull even up to 70 MPa [29].

The study highlights the need of validation of the modelling of deformation events. In principle, an analysis of subsequent remote sensing images, results from a dense network of the ice drifters or measurements of the distribution of ice thickness could provide detailed enough information on the ice deformation for the model validation or data assimilation in order to improve the reliability of the model. However, retrieval algorithms of the motion and deformations of ice are still under development and all the regular ice monitoring observations are done in the fast ice region. As yet, neither the observed sea ice properties nor the modelled results can be applied to particular disasters with certainty. It is even unclear, which modelled parameters give an adequate forecast of the dangereous sea areas.

Our study showed that both the fraction of deformed ice (Fig. 4) and deformed ice thickness growth rate in the Gulf of Finland are smaller than in the Gulf of Riga. One might speculate that per unit of the icebound ship route (say 10^6 ship-km in ice) there could be more ice-related ship damages in the Gulf of Riga than in the Gulf of Finland. Scarce available data do not allow to make a reliable comparison. Comparison of data from different years allows to make some very rough estimates of the probability of damage. For example, 49 ice-related ship incidents [15] were reported in winter 2002/2003 and about 37 000 annual entrance crossings [1] in 2005/2006 in the Gulf of Finland. These numbers are 10 and 9000 for the Gulf of Riga. Therefore, about 1 incident per 200 ships entering or leaving each gulf occurs in the icebound conditions (that is, during 3 severe winter months).

We have selected two ship damage cases from the severe winter 2002/2003, when altogether 49 ice-related ship incidents occurred in the Gulf of Finland [15]. Unfortunately, in most of the cases (except the two under consideration), exact location and time of the damage event were missing. Therefore statistical analysis was not possible.

In both cases the ship damages happened close to the high growth rate area of deformed ice (Figs. 6 and 8) at the interface of different ice conditions with notable ice thickness gradients. Damages occurred when the ships were sailing in a region between the fast ice and intensive deformation areas in the open sea. The ridged ice production is an obvious indicator of the high compression of the ice pack. The areas, where ridging and rafting ice take place, may thus be considered as major risk regions for the wintertime navigation. The analysis suggests that quite large compressive forces occurred locally in areas relatively far from the intense compression regions. One may speculate that inhomogeneities in the ice (such as small leads or navigation channels) serve as favourable locations of initiating of ridging even in relatively low overall compression rates. In the considered cases, ice deformations were additionally favoured by rapidly changing wind direction that apparently led to the formation of non-uniform patterns of ice drift.

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Soome lahe jäädeformatsiooni ja laevavigastuste vahelisest seosest 2003. aasta talvel

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Rüsijää ahelikud ja ladejää on talvisel meresõidul peamisteks takistusteks. Tuulte põhjustatud jäätriiv tekitab pinged jääkattes, mis kutsub esile suuri jää moondeid. Soome laht on Läänemere ohurikkamaid piirkondi, kus 2002/2003. aasta talvel toimus ligikaudu 60% laevavigastustest. Artiklis on analüüsitud numbrilise jäämudeli (HELMI) väljundandmeid, seostades deformeerunud jää paksuse kasvu kiiruse kahe sel talvel juhtunud laevavigastusega. Mõlemad avariid juhtusid erinevate jääliikide üleminekualal, kus esines märkimisväärne deformeerunud jää paksuse kasv.