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Ice deformation in the Gulf of Finland in the severe winter of 2002/2003

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Abstract. The Gulf of Finland is one of the heaviest ship traffic areas in the world. The ice-covered period in the gulf lasts up to 140 days in severe winters. Common features are openings in ice (flaw leads) and ice ridges. The winter of 2002/2003 was exceptionally harsh: the entire Gulf of Finland was for a long time covered with thick ice, severe weather conditions caused much ice deformation and numerous ship incidents happened.

We investigated the dependence of ice deformation rate on wind speed and direction, and variation in ice conditions in space and time. The numerical sea ice model HELMI was used to determine relations between wind conditions, ridged ice and ship damages. The occurrence frequency of leads in different regions was analysed by MODIS satellite imagery.

The strongest wind blew from the NE, SW and NW in the winter of 2002/2003. The growth rate of deformed ice was more related to the wind direction than to speed. The ridging was most intensive when the wind blew from the E, SW and NW. Openings were formed almost everywhere during moderate or strong winds. Elongated leads, caused by northerly winds, were more common in the Finnish coastal region.

Key words: Gulf of Finland, sea ice, ice modelling, ice deformation, winter 2002/2003.

INTRODUCTION

The Gulf of Finland is a narrow, shallow and ecologically vulnerable part of the Baltic Sea. The gulf (Fig. 1) is fully covered with ice in normal and severe winters, while only some eastern areas freeze in mild winters. The thickness of ice varies, depending on its age and the nature of ice-forming processes. Sea-ice conditions differ strongly in the east–west direction. Ice forms first in the eastern part of the gulf already at the beginning of December and melts there usually in the middle of April (Jevrejeva et al. 2004). The coastal current from the Baltic Proper and the winds in sector S to SW keep the southern part of the Gulf of Finland relatively ice-free.

On average permanent ice cover in the mouth of the Gulf of Finland forms by 10 February, and ice disappears from the gulf during mid-April (Seinä & Peltola 1991). The coastal morphology causes a wide fast ice zone along the northern fragmented coast with many small islands, creating the asymmetry of ice conditions with the more open southern coast. The ice cover period is longer in the eastern part of the Gulf of Finland and shorter in its entrance area. The average number of ice days varies from ca 20 in the southern part of the open gulf and ca 60 in its northern part to up to 120 in a few coastal bays in the eastern gulf area (Pärn & Haapala

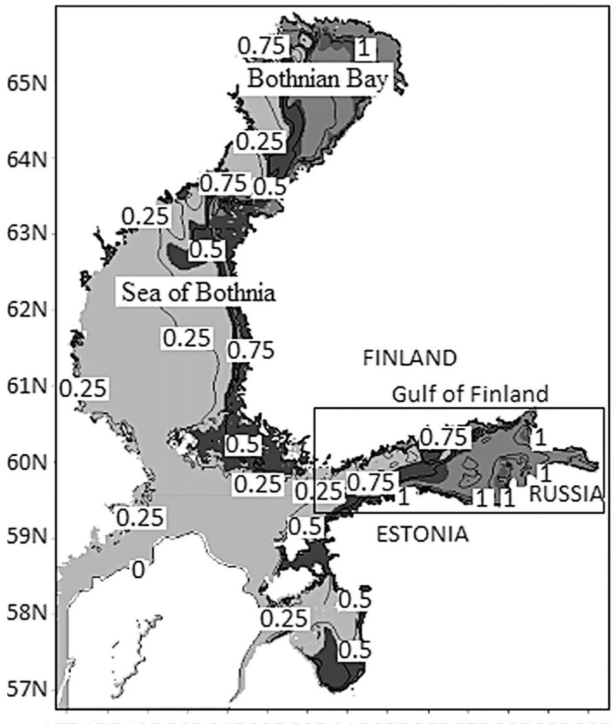

Fig. 1. Baltic Sea. Modelled total ice thickness on 22 February 2003.

2011). Level ice in the Gulf of Finland is typically 30–40 cm thick, but under certain snow-free conditions it may thermally grow up to 90 cm thick (Seinä & Peltola 1991).

Wind control of the deformation process largely determines the distribution of sea-ice thickness. Apparent results of the deformation are drift and ridging events on the ice field, also opening leads in pack ice. Openings in ice are common in the Gulf of Finland. A lead emerging along the gulf axis facilitates navigation through the area. A dynamic drift ice cover forms in the middle of the gulf and elsewhere off the shores, islands and shoals. Drift ice appears as a long narrow field which is dynamically sensitive to compactness and thickness of ice (Soomere et al. 2008).

Pack ice in the gulf tends to raft and ridge frequently – the proportion of ridged ice usually rises to 25% in February (SMHI 1982). Ice thickness measurements in the Baltic Sea (Leppäranta & Hakala 1992) have shown that the amount of deformed ice is significantly larger than reported in routine ice charts and the mean ice thickness (taken over several square kilometres) could exceed consequently 2–3 m in wide areas of the Baltic Sea. The largest observed ridges were 6–8 m thick (Leppäranta & Hakala 1992), but it is probable that larger ones exist, in the eastern part of the gulf, near the fast ice boundary at Kotka–Vyborg longitudes (Leppäranta & Wang 2002).

In the Baltic Sea the visible part of the ridge, the sail, is typically 1–3 m high, while the bulk of the ridge volume is contained in the 5–15 m deep subsurface keel (Lensu 2003). Such ice structures seriously endanger a vessel navigating among the sea ice. The probability of navigation disasters is rising in areas with a high deformed ice growth rate (Palosuo 1975; Pärn et al. 2007).

A number of authors have studied historical ice conditions in the Gulf of Finland, focusing on climatological aspects of fast ice (Leppäranta & Seinä 1985; Jevrejeva et al. 2004; Jaagus 2006). The mechanical behaviour of pack ice fields is studied by Leppäranta (2005). An overview of the related issues can be found in Leppäranta & Myrberg (2009). In the Gulf of Finland weather-dependent synoptic flaw leads are often observed on routine ice charts and remote sensing images. Haas (2004) carried out detailed ice thickness measurements along the Finnish coast in February 2003 by using the helicopter-borne electromagnetic-inductive (HEM) method. The lead detected in the Gulf of Finland was surrounded by thick deformed ice (up to 5 m) between Helsinki and Tallinn.

In the present paper the results of an ice model and Moderate Resolution Imaging Spectrometer (MODIS) images are co-analysed. We examine the characteristics of the ice deformation in the Gulf of Finland, specifically, lead formation by wind forcing. We show how the increase in deformed ice is related to wind speed and direction and how the ice conditions vary in space and time. Likewise the effect of high ice deformation on the frequency of ship damages in the winter of 2002/2003 is studied.

MODELLING OF SEA ICE DYNAMICS

The HELMI model is a multicategory sea ice model originally developed for climate research (Haapala et al. 2005). The model physics and numerics are the same in operational and climate simulations. The only differences are in the horizontal resolution and atmospheric forcing used. The model resolves ice thickness distribution, i.e. ice concentration of variable thickness categories, redistribution of ice categories due to deformations, thermodynamics of sea ice, horizontal components of ice velocity and internal stress of the ice pack. Deformed ice growth rate is defined as the change of mean thickness of ridged and rafted ice during unit time.

The redistribution function depends on ice thickness, concentration and the strain rates (Thorndike et al. 1975; Hibler 1986). Continuum-scale sea ice models resolve the average behaviour of pack ice and either neglect the subgrid processes or take them into account in a simplified manner. In the HELMI model the following assumptions of the deformation processes have been made: (i) deformed ice is generated only from undeformed ice categories, i.e. rafted ice is not deformed further in the model; (ii) cross-over thickness determines whether the undeformed ice is rafted or ridged. This assumption is based on the Parmeter (1975) law and field observations (cf. Rothrock 1979). It is also assumed that the thinnest 15% of the ice categories experience deformations (Thorndike et at. 1975). Shear deformations are not taken into account and the shape and porosity of the ridges are assumed to be constant. These assumptions are based on field observations (Kankaanpää 1997; Timco & Burden 1997).

Ice motion is determined by the time-dependent momentum balance equation, which takes into account the Coriolis force, wind and water stresses, sea surface tilt and internal stresses. The internal stress of pack ice is calculated according to the viscous-plastic rheology (Hibler 1979) but it also relates the consumption of kinetic energy to ice pack deformations (Rothrock 1975).

The sea ice model employs curvilinear coordinates. The governing equations are discretized in space using the Arakawa C-grid. The advective part of the ice thickness and concentration evolution equation is solved by an upwind method. Momentum balance is solved by the line successive relaxation procedure proposed by Zhang & Hibler (1997).

The present set-up of the model predicts evolution of five undeformed and two deformed ice categories. Ice categories are advected in the thickness space without any limits, except that the thinnest category is not allowed to exceed 10 cm. Deformed ice is divided into separate categories of rafted and ridged ice.

The horizontal resolution of the model is 1 nm (nautical mile). The model was forced by six-hourly wind data from a reanalysis by National Centers for Environmental Prediction and Atmospheric Research (NCEP/NCAR). The NCEP/NCAR data are from the global atmospheric model of 2.5° × 2.5° resolution. In order to assess the utility of the NCEP/NCAR data (25°E, 59.8°N) in regional studies, these were compared with meteorological observations. These high-resolution wind data originate from the Tallinna madal Lighthouse (59°42.7′N, 24°43.9′E). The wind speed and direction were recorded every 5 min. Figure 2 shows good correlation between the reanalysed and measured wind data. The correlation coefficient is 0.91 and 0.88 for meridional and zonal components, respectively.

WEATHER CONDITIONS

The winter season of 2002/2003 started very early and its beginning was the coldest over the last 40 years (Fig. 3). The temperatures were below the long-term average during most of 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. In comparison with the average, the ice cover period lasted longer by one month.

The sum of negative degree days indicates how mild or severe the ice season was. It shows the thermodynamic ice thickness growth and the extent of ice by summarizing negative degree days (daily average) under the melting point in a period (Leppäranta 2005). When this number is over 300, the Gulf of Finland is fully ice-covered. The number of negative degree days increased faster than usual in the late autumn of 2002 (Fig. 3). The cumulated sum in an average winter is 400 °C. The winter of 2002/2003 exceeded this level already at the beginning of January. The whole ice season was more severe than in a mean winter; the sum of negative degree days was over 800 °C.

The wind conditions during the winter of 2002/2003 are shown in Figs 4 and 5. Six episodes were recorded when wind speed was over 8 m s^{-1}: (1) NE wind on 16–19 January, (2) SW wind on 26 January, (3) NE wind on 29–30 January, (4) S wind on 2 February and SW wind on 3–4 February, (5) S and N winds dominating on 10–13 March, (6) N wind on 20 March.

The ice extent is in correlation with the North Atlantic Oscillation (NAO) index values in severe and mild winters (Vihma & Haapala 2009). In mild and average winters SW winds dominate in the Gulf of Finland (Table 1), but in severe winters strong winds are blowing from the N and NE. As seen from Fig. 5, the strongest winds in the winter of 2003 blew from the NE (from 10–70°), SSW (180–225°) and NW (280–360°).

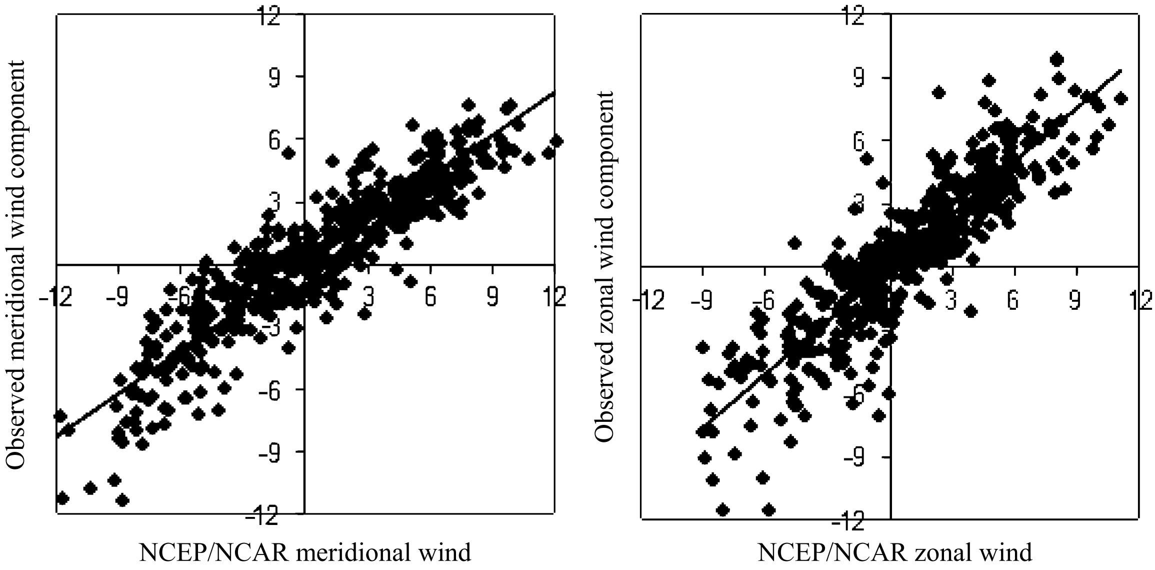

Fig. 2. Wind data from the NCEP/NCAR reanalysis and observed data from Tallinn.

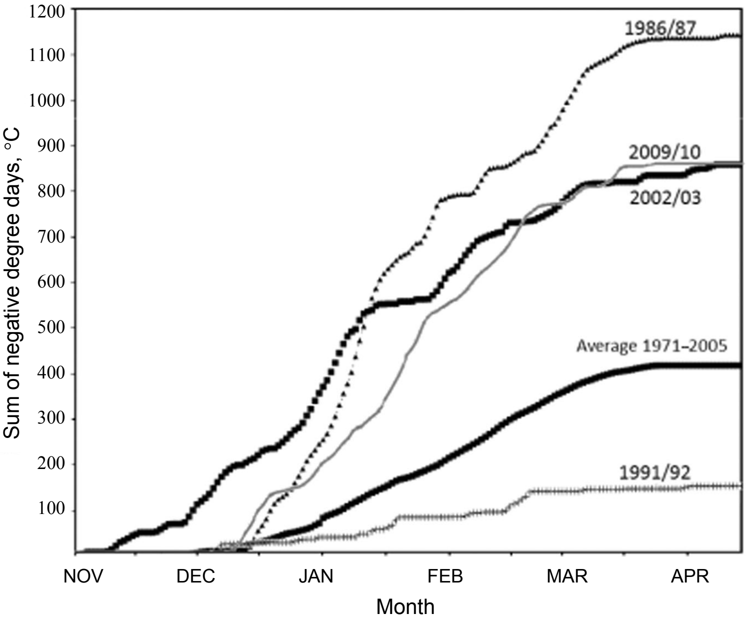

Fig. 3. The sum of negative degree days in the central Gulf of Finland. A very severe winter (1986/87), a mild winter (1991/92), a severe winter (2002/03), the winter of 2009/2010 and the average for the winters of 1971–2005 are shown.

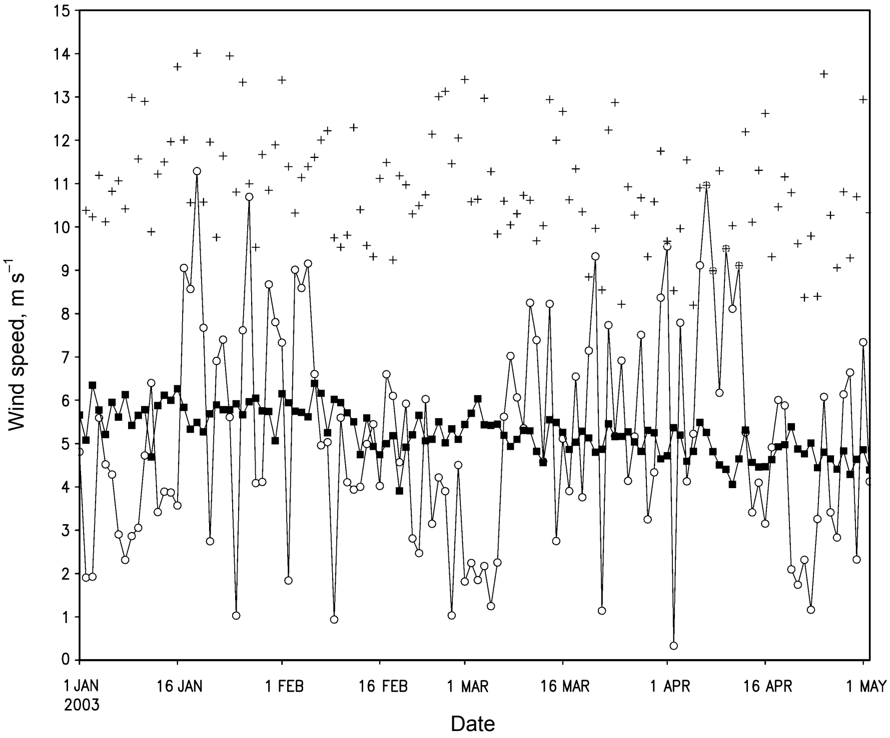

Fig. 4. Daily wind speed from NCEP/NCAR reanalysis for winter 2002/03 (circles), and mean (squares) and maximum (crosses) daily wind speeds during 1971–2005.

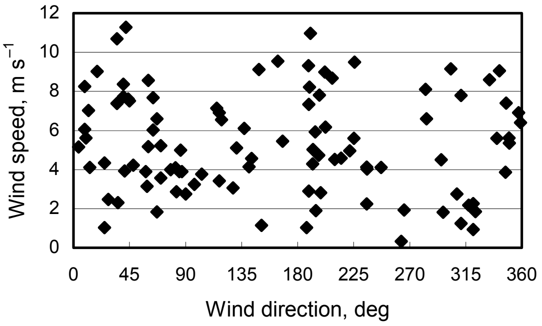

Fig. 5. Wind speed and direction in winter 2003.

Table 1. Percentage of winds from different directions on the Gulf of Finland in winters of 1971–2005 (1 Jan to 1 May) from the NCEP/NCAR reanalysis data

Direction	%
NE (0°–89°)	16
SE (90°–179°)	26
SW (180°–269°)	37
NW (270°–359°)	21

ICE CONDITIONS

The ice season of 2002/2003 in the Baltic Sea began with rapid ice formation. In early November 2002 ice cover started to develop in the Bothnian Bay, 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. Ice thickness ranged from 0.15 m in its western part to 0.5 m in the eastern area (Pastukhov & Talijev 2003). The length of the sea lane that ships go through ice in the Gulf of Finland is usually about 100 km, but in the winter of 2002/2003 it reached up to 400 km. The ice-breaking period was then significantly longer than during an average winter. In 2003 the ice was very thick and deformed, navigation was difficult and navigational restrictions were valid for 117–149 days (Hänninen 2003). Ice breaking in the Gulf of Finland is usually first needed in January, but during that winter it started already in December.

The maximum thickness of fast ice was 0.7–0.9 m in the north of the Bothnian Bay, 0.6–0.75 m in the Sea of Bothnia, 0.5–0.65 m in the western Gulf of Finland and 0.65–0.8 m in the eastern Gulf of Finland. The maximum ice thickness in open sea was 0.4–0.6 m in the Bothnian Bay, 0.2–0.4 m in the Sea of Bothnia, 0.2–0.5 m in the northern Baltic Sea and 0.4–0.75 m in the Gulf of Finland. The ice season was over one month longer than the long-term average in the Gulf of Finland and about two weeks longer in the Bothnian Bay (see http://www.itameriportaali.fi/en/tietoa/jaa/jaatalvi/en_GB/2003/)

Ice conditions during a typical severe winter (2002/2003) in the Gulf of Finland are depicted in Fig. 6. Ridged ice covers large offshore areas of the gulf and ice thickens towards its eastern part. Ice is ridging

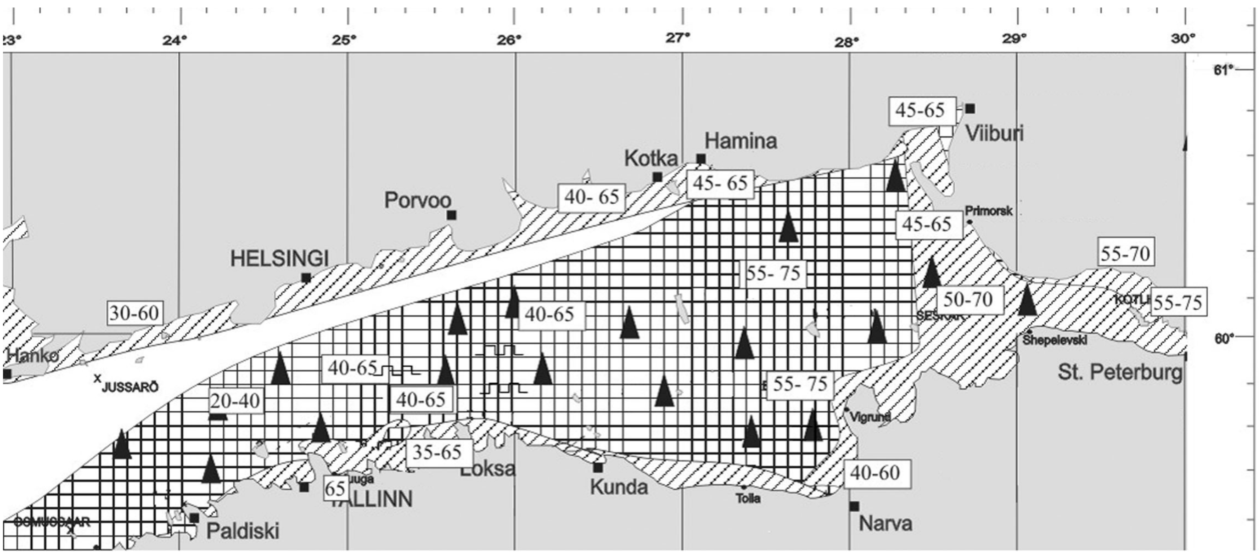

Fig. 6. Ice chart of the typical severe winter (1 April) in the ice season 2002/03. In the previous few days the strongest winds blew from the N to NW sector. The diagonal lines indicate fast ice and squares consolidated ice, ▲ is ridging ice and ⎍⎍ rafting. The ice chart (in Estonian) was provided by the Estonian Meteorological and Hydrological Institute.

and rafting more severely in the narrowest part of the gulf between 25°E and 26.2°E and in its widest part between 27°E and 28°E. North–south differences in ice properties are noteworthy. As the strongest winds blew from the N, NW before 1 April, the ice drifted southwards, generating a lead about 10–20 km offshore from the northern (Finnish) coast of the gulf. At the boundary of landfast ice, ridges were formed in the compressive region on the southern and eastern sides, respectively.

The total extent of ice during the winter of 2002/2003 was very large already at the beginning of January (Fig. 7). On 16 January undeformed ice concentration decreased quickly from 90% to 70% mainly due to ice deformation. At that time ice deformed sharply. Deformed ice concentration increased all over the period (Fig. 7). The mean total concentration of deformed ice ranged from 12% in the area of the Gulf of Finland to 40% in the total ice area. The mean total ice concentration is well described by the model. The root mean square deviation of the observed values was 5.8% during 1 January–1 April 2003.

DEFORMED ICE BUILDING AND DISTRIBUTION

In a large restricted basin like the Gulf of Finland, wind-driven sea ice drift has large horizontal gradients due to the vicinity of landlocked fast ice, causing sea-ice ridging in the compressive regions and opening of pack ice in the divergent regions. The wind modifies ice conditions essentially by raising stress in an ice field, resulting in compressive deformation of ice.

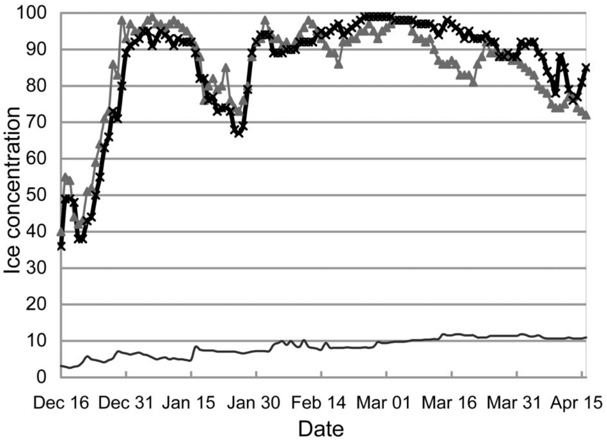

Fig. 7. Simulated and observed mean total ice concentrations, marked respectively by triangles and crosses. The smooth line is deformed ice concentration.

Model experiments, performed to study the growth rate of deformed ice in the Gulf of Finland, showed that the deformation of ice depends on wind speed to some extent but is much more influenced by changes in wind direction (Fig. 8). For example, low winds (speed about 4 m s^{-1}) with variable direction are able to cause strong ice deformation, but stronger steady winds (about 9 m s^{-1}) may result in a lower deformation rate. However, the wind speed impacts the ice floe to move. When the ice motion is restricted, the ice cover starts to compact, the floes are tightly compressed together and deformation of ice begins. But resistance effect is different for different wind directions. In the Gulf of Finland the most intensive ridging generally takes place when the wind blows from around the E (from 80–120°), SW (180–225°) and NW (320–360°).

We analysed also the cumulative deformation phenomena to characterize ridged and rafted ice distribution. Deformation events are distributed over the ice season. We estimated the mean deformed ice thickness over the latitudes (59.15–60.5°N) or longitudes (23.5–29°E). Figure 9 depicts the variation in the mean deformed ice thickness in space and formation of ice over time. The amount of deformed ice was the largest between 27.5 and 28°E (Fig. 9A). In the middle of March, when the wind was blowing mainly from the SW, W and NW, ice deformed strongly also at 26.6–27.2°E. We can see that ice deformation in that area began already at the beginning of the year and increased through the whole season. The most deformed ice area was in the eastern gateway of Narva Bay. In the middle of March the area extended to the north and covered the entire Narva Bay. Comparatively less deformed ice was produced at 24.7–25.7°E and 26.2–26.8°E.

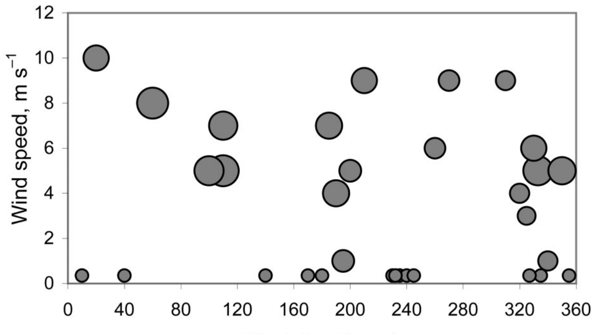

Fig. 8. Growth rate of deformed ice related to wind direction and speed in winter 2002/03. The circles denote the average (over the Gulf of Finland) growth rate from 0.007 m day^{-1} to 0.018 m day^{-1}, as shown by the circle diameter.

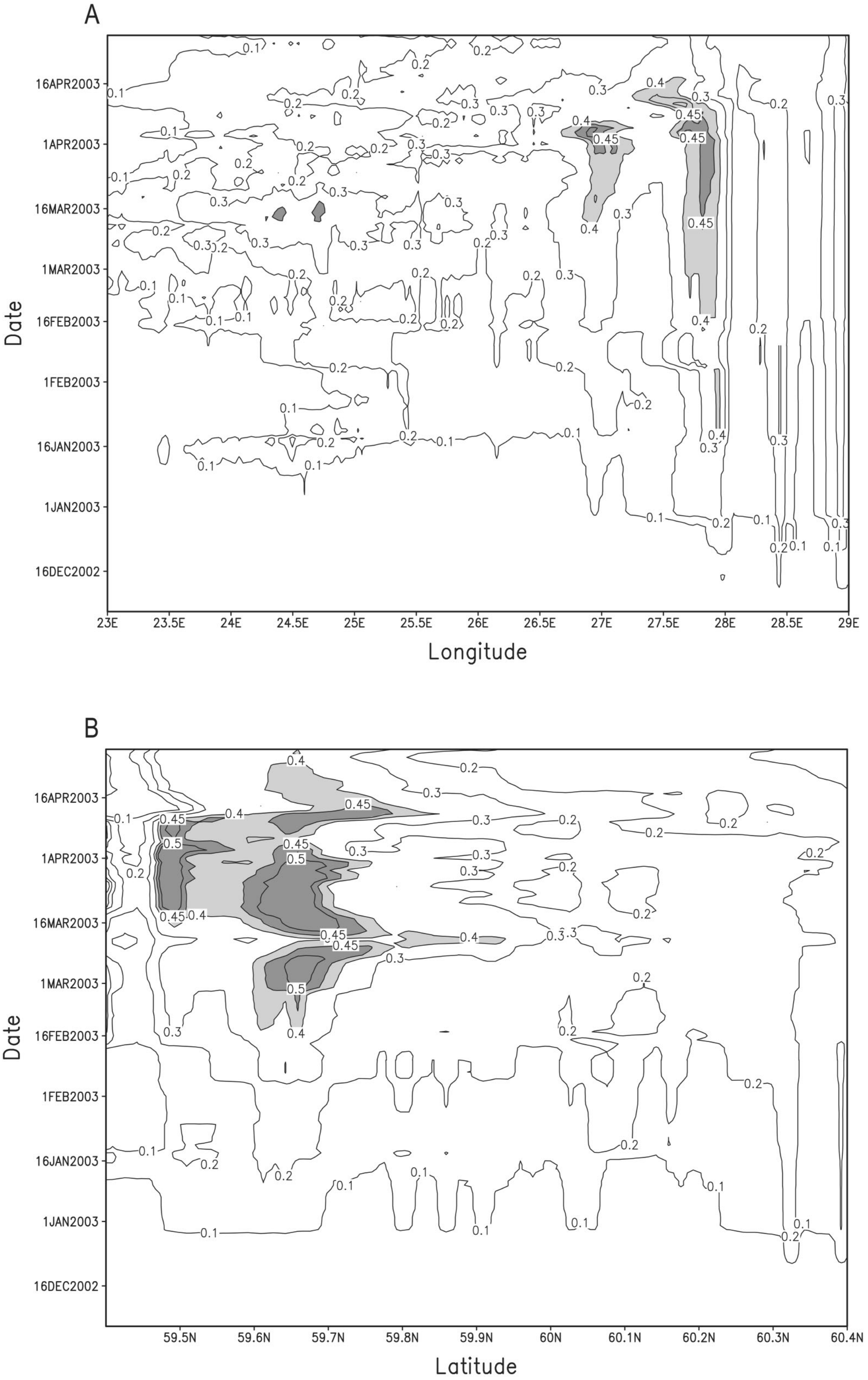

Fig. 9. Mean deformed ice thickness (m) over the latitudes (**A**) or longitudes (**B**). The extremes area (ice thickness >0.4; 0.45) is grey.

The deformed ice was thicker on the south shore. According to the model calculations, more than 60% of the ice deformation events took place in the southern part of the Gulf of Finland. Also, the mass of deformed ice was greater in the southern part and the deformation on the southern coast was twice as strong as on the northern coast (Fig. 9B).

To illustrate the relevance of the mechanical thickening of ice, we can make the following simple comparison of the deformed ice growth rates with the thermodynamic growth rate of ice. Deformed ice growth rate is defined as the change in the mean thickness of ridged and rafted ice during unit time. If the air temperature is −10 °C, 0.35 m thick ice grows daily by about 0.01 m. Thus the thermodynamic growth rate of the undeformed ice is small compared to that of deformed ice. In the same conditions, the new ice in the leads is thickening about 0.05 m day^{-1}.

The analysis of model results and shipping damage reports showed that the high ice deformation growth rate is related to the vessel damages in the Gulf of Finland (Fig. 10). An ice deformation growth rate over 0.004 m day^{-1} occurred during 25% (28 days) of the winter season. Forty-nine ship damage events were registered in the examined period. Most of the damages (80%) took place in days when the average deformation rate exceeded 0.004 m day^{-1}. The deformation growth rates were the highest for the winter on 15–18 January 2003, when the growth rate was up 0.018 m day^{-1}, and on 27–28 February 2003 when the rate was up to 0.016 m day^{-1}. We note that eight accidents took place in the first period in four days and five accidents occurred in the second interval in two days when the ship hull was damaged by ice. In other periods ship damage events were not so frequent.

OBSERVED ICE DEFORMATIONS

Openings in ice are common in the Gulf of Finland. An open water area can sometimes extend over several hundred kilometres. If a lead lies along the axis of the Gulf of Finland, navigation through the area is easier.

The predominant winds in the Gulf of Finland are from the SW (Soomere et al. 2008). A logical presumption would be that ice ridges occur mostly at the northern coast and wind generates openings in the south. The observations made in the winter of 2003 revealed the opposite.

Due to the shape of the gulf, the N and NW winds produce mostly openings elongated along the gulf axis. The N and S winds also create conditions for the formation of leads facilitating shipping through the Gulf of Finland. The S and SE winds create leads near the southern coast.

To investigate the occurrence of leads, we studied MODIS satellite images from the year 2003 (Fig. 11). Altogether 51 images were analysed (Table 2).

The distribution of images was uneven in winter 2003. On the days for which satellite data are missing the wind was 16 times from the SW and 12 times from the N. The modelling study (Pärn & Haapala 2011) shows that SW winds create a few irregular unconnected open water areas which do not facilitate shipping when the Gulf of Finland is ice-covered.

The NW and N winds generate elongated leads that are wide enough for a vessel to navigate. Therefore on the days for which satellite data are missing the leads probably occurred mostly at the northern coast because SW winds do not generate elongated leads (Pärn & Haapala 2011).

In total, 14 irregular openings were identified. Most of the leads (in 22 cases) emerged near the north coast and only two leads near the south coast.

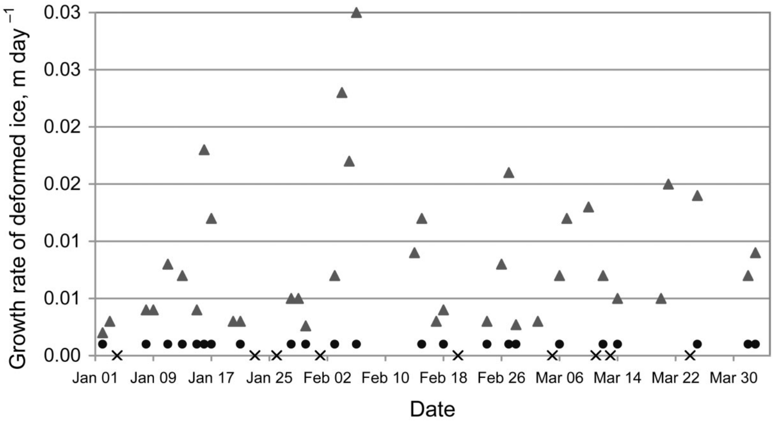

Fig. 10. Time series of the deformed ice growth rate (triangles) and the events of ship damage. Ship damages that occurred during high deformation or in calm ice conditions are marked with circles and crosses, respectively.

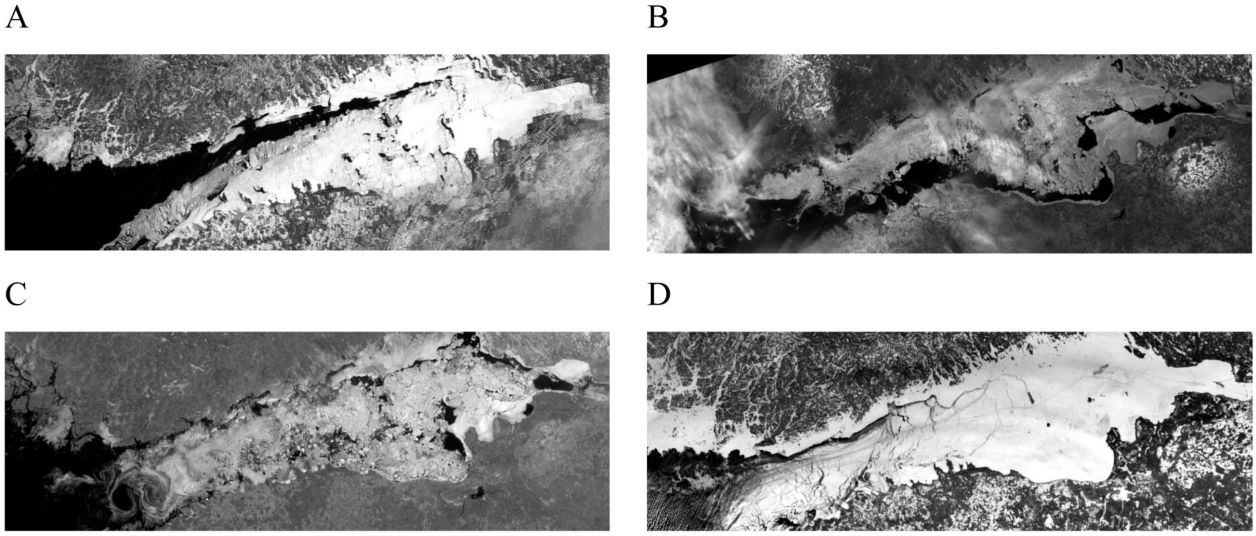

Fig. 11. Ice situation in the Gulf of Finland in 2003. Moderate Resolution Imaging Spectrometer (MODIS) images. **A**, lead at the northern coast; **B**, lead at the southern coast; **C**, irregular openings of arbitrary shape; **D**, fully ice-covered.

Table 2. Occurrence of natural leads in the Gulf of Finland in the winter of 2003 from MODIS images

Ice events from MODIS images	Frequency	Dominating winds
Elongated leads near the north coast	22 times	N, NNE and NW winds
Elongated leads near the south coast	2 times	S and SE winds
Fully ice-covered	13 times	No strong winds
Irregular openings of arbitrary shape	14 times	NE, E and SW winds

DISCUSSION AND CONCLUSIONS

The winter of 2002/2003 was average in the Baltic Sea but severe in the Gulf of Finland, judging from the extent of the ice cover. The season was exceptional – the winter arrived earlier and lasted longer. In terms of ice conditions (ice thickness, concentration, formation of ridges and openings), it was a typical severe winter. The ice cover caused considerable damage to vessels navigating in the Gulf of Finland.

The high ice deformation rate is related to the vessel damages in the Gulf of Finland where 49 ship damages (Hänninen 2003) occurred during the winter season. On about 25% of the days during this period the ice deformation growth rate was between 0.004 and 0.027 m day^{-1}. About 80% of the ship damages took place on days when the average deformed ice growth rate was over 0.004 m day^{-1}.

The analysis of relations between the wind direction, wind speed and deformed ice growth rate revealed that the strongest winds blew from the SW and NNE. The most intensive ridging events occurred during wind blowing from the E, SW and NW. The growth rate of deformed ice was less dependent on wind speed than wind direction. The mean concentration of deformed ice covered up to 12% of the area of the Gulf of Finland and 40% of the total ice area. The modelled largest fraction of deformed ice was located between 26.6–27.2°E and 27.5–28°E. Comparatively less deformed ice was produced at 25.5–26.5°E.

Large quantities of ridged ice, which is generally more harmful to shipping than level ice, lie near the southern coast of the gulf. In April the cumulative mean thickness of deformed ice was 0.45 m at the southern side and 0.2 m at the northern side. The deformed ice thickness at the southern side was more than twice as thick as at the opposite side. According to the model results, over 60% of the deformed ice mass was generated in the southern part of the gulf.

Natural leads and open water suitable for shipping were more common in the northern coastal region. Due to the shape of the Gulf of Finland, the dominating SW winds do not create elongated leads, but irregular unconnected open water areas (Fig. 11B) are formed in ice. As northern winds blew frequently this winter, elongated leads (Fig. 11A) repeatedly appeared near the northern coast – at least on 22 days, thus substantially more often than at the southern coast.

Further constructive studies are needed to identify the natural conditions under which vessels get stuck in ice and ship hull damages occur.

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Merejää deformatsioonid Soome lahel jäärikkal talvel 2002/2003

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Soome laht on üks tihedaima laevaliiklusega paiku maailmas ja samas Läänemere ohurikkamaid piirkondi. Talvel 2002/2003 Läänemerel toimunud laevakere vigastustest ligikaudu 60% oli Soome lahel. Merejää püsib kuni 140 päeva, mil tuuled põhjustavad jää ümberpaiknemist; sageli tekivad vabavee avaused ja lahvandused. Teisalt tekivad pinged jääkattes, moodustades kuni 15 m paksusi rüsi- ja ladejää moodustisi. Numbrilise jäämudeli HELMI abil on välja selgitatud deformeerunud jääpaksuse kasvu kiiruse seos tuule suuna ja kiirusega, uuritud rüsi- ning ladejää ajalist arengut ja ruumilist ümberpaiknemist Soome lahes talvel 2002/2003 ning laevakere kahjustuste seost deformatsioonisündmustega. Laevadele soodsate lahvanduste tekkimise looduslike tingimuste analüüsis kaasati MODIS-e satelliidiandmestik. Ligikaudu 60% deformeerunud jää massist ilmnes lahe lõunapoolses osas. Deformeerunud jää kasvumäär sõltub teatud määral tuule kiirusest, kuid on rohkem mõjutatud tuule suunast. Kõige intensiivsemalt deformeerub jää ida-, edela- ja loodetuulte mõjul. Näidati, et deformeerunud jää kasvu määr on seotud laevakahjustustega Soome lahel. Talvel 2002/2003 oli Soome lahel 49 laevakere kahjustust, millest 80% toimus siis, kui kõnesolev määr oli üle 0,004 m ööpäevas. Vastav kasvukiirus oli talvel 2002/2003 25% päevadest. Lääne-, loode-, põhja- ja lõunatuuled tekitasid talvel 2002/2003 jäässe laevaliikluseks sobivaid lahvandusi peamiselt Soome lahe põhjapoolses osas. Soome lahel tavaliselt domineerivad edelatuuled põhjustasid ebaregulaarseid ja mitteseotud jäävabasid alasid, mis ei sobi laevaliikluse jaoks.