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A STUDY OF DYNAMIC DRIFT ICE EVENTS IN A SMALL BAY

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ABSTRACT

In winters 2002 and 2003, two drastic sea ice dynamic events took place in Pärnu Bay, a basin of 15 km across in the Gulf of Riga, Baltic Sea. The ice in the former event was driven into motion by the wind, about half of the basin opened and in the other side heavy rubble formation occurred. The thickness of the fast ice was 20 – 40 cm and pack ice about 5 – 15 cm, and the wind speed was about 20 m/s, unusual combination necessary for the event. As a consequence, the shipping conditions became very difficult for the Pärnu harbour. The ice in the latter event was driven about 45 km southwestward in three days. The ice thickness in this event was about 30 cm, and wind speed ranged 5 and 12 m/s. A fine resolution ice model with parameters similar as in the Baltic Sea modelling in general reproduced the events.

INTRODUCTION

The Gulf of Riga is a brackish water basin in the eastern part of the Baltic Sea, with size of 140 × 110 km and mean depth of 26 m (Fig. 1). It is connected to the Gotland Sea (also known as the Baltic Proper) by Irbe Strait in the west, enclosed by long beaches in the south and east, and bounded by islands in the north. In the northeast corner there is Pärnu Bay, where the main Estonian harbour in the Gulf of Riga, the town Pärnu, is located. Pärnu Bay could be divided into an inner and outer basin. The inner part could be defined as a basin locating north from the Liu-Tahkuranna line (Fig. 1), having approximate measures of 13 × 14 km, an area of about 180 km^2 and the maximal depth of 7.6 m. The outer part extends down to the southern tip of the Kihnu Island, forming an area of about 25 × 25 km, area 500 km^2 and the maximal depth of about 15 m.

Ice forms in the Gulf of Riga annually, and the length of the ice season is 3 – 5 months. In mild winters ice occurs only in the Pärnu Bay region but in normal or severe winters the whole gulf freezes over. Usually the ice thickness in Pärnu Bay is large enough to

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form stable fast ice but in mild winters thin ice may be broken by winds. This happened in 2002 in exceptionally strong manner. A strong storm broke the ice cover and drove it to form compressed rubble fields. The ice situation was then very difficult for shipping to the Pärnu port. In contrast to the event in 2002, the ice in the 2003 event was driven by continuous northerly moderate wind, moving about 45 km southwestward in three days.

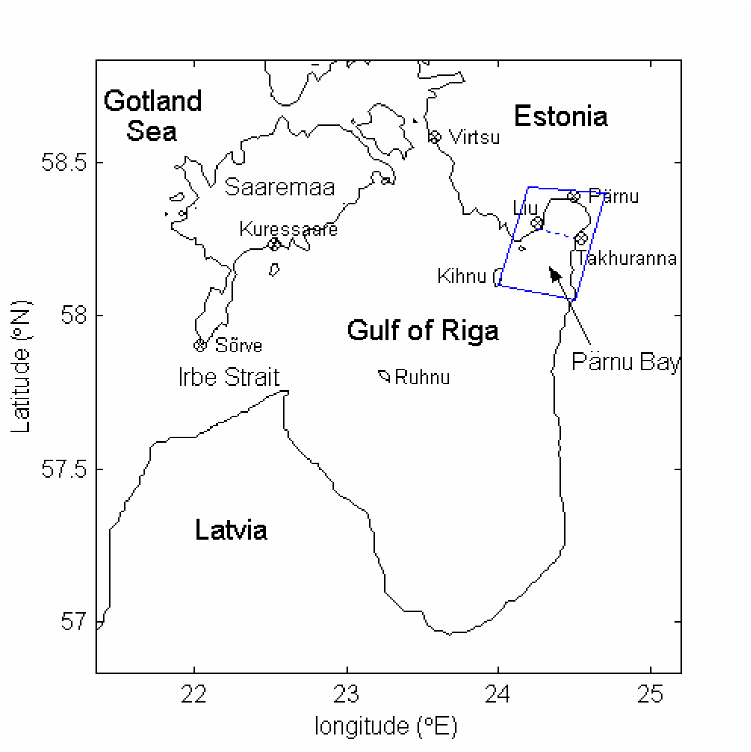


Fig. 1. Topography of the Gulf of Riga and Pärnu Bay

Drift ice is a granular, compressible, two-dimensional medium. The “grains” are individual ice floes, which form drift ice particles, and the resulting medium is approximated by a continuum. The necessary condition is that the length scales d, D and L_G of ice floes, drift ice particles, and gradients of drift ice properties, respectively, satisfy $d << D << L_G$ (Leppäranta, 1998). The motion of drift ice is calculated from the conservation laws of ice and momentum. Winds and currents drive the ice, and the response of the ice to the forcing comes from the internal stress and the adjustment of the ice mass distribution. High-resolution models for the sub-basins in the Baltic Sea, with grid length of 5km and 1.852 km, have produced realistic results down to length scales of L_G about 100 – 200 km (Wang et al., 2003; Zhang, 2000). The purpose of this study is to investigate the applicability of this continuum model in fine resolution for a very small basin such as Pärnu Bay, with L_G of about 15 km and D of less than 500 m. The study shows that when the ice is thin as there and the floe size is small, the continuum approximation is still feasible.

ICE CONDITIONS

Dynamic Event in 2002

The ice condition in the Gulf of Riga in winter 2001/2002 was mild. Ice first appeared on 10 December 2001 in Pärnu Bay. On 1 February 2002 it reached the largest area, covering about one third of the total gulf (Fig. 3a), however the main part of the area was new ice. After that the ice cover began to shrink due to dynamic and thermodynamic effects, and finally disappeared on 5 April. The significant dynamic ice event happened during 1 – 15 February.

The meteorological and hydrological measurements were made every 5 minutes at the Pärnu Station. As can be seen in Fig. 2, wind direction was first from north on 1 February, then it gradually turned to east to south, and after 3 February, it remained in the SW direction until 12 February, with only a very shot period of deviation. During 13 – 14 February, wind again obtained a north direction. The wind speed at this period showed a great variability. The storm happening during 4 – 6 approached almost 20 m/s, and wind speed reached about 10 m/s during 2 – 3, 10 and 12 February, while during the rest of the dates wind speed was generally under 10 m/s.

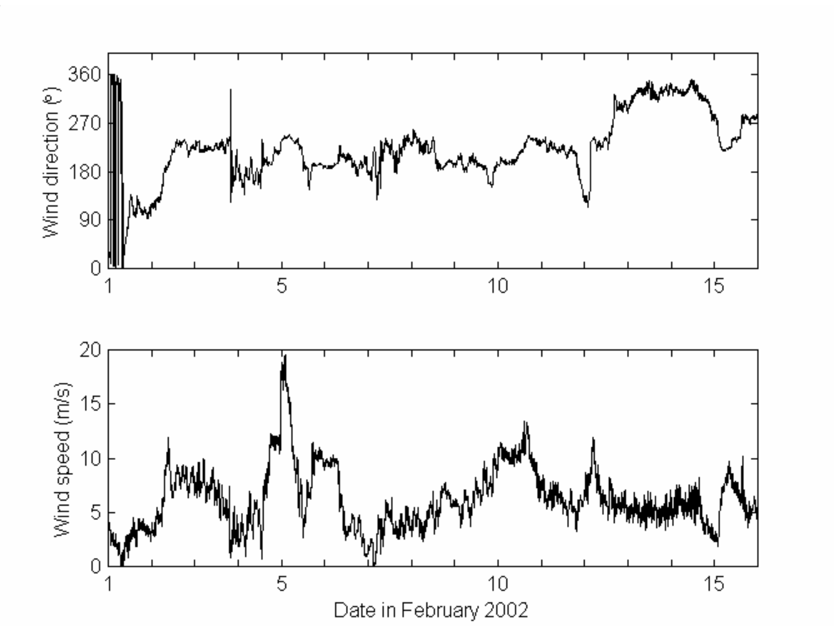
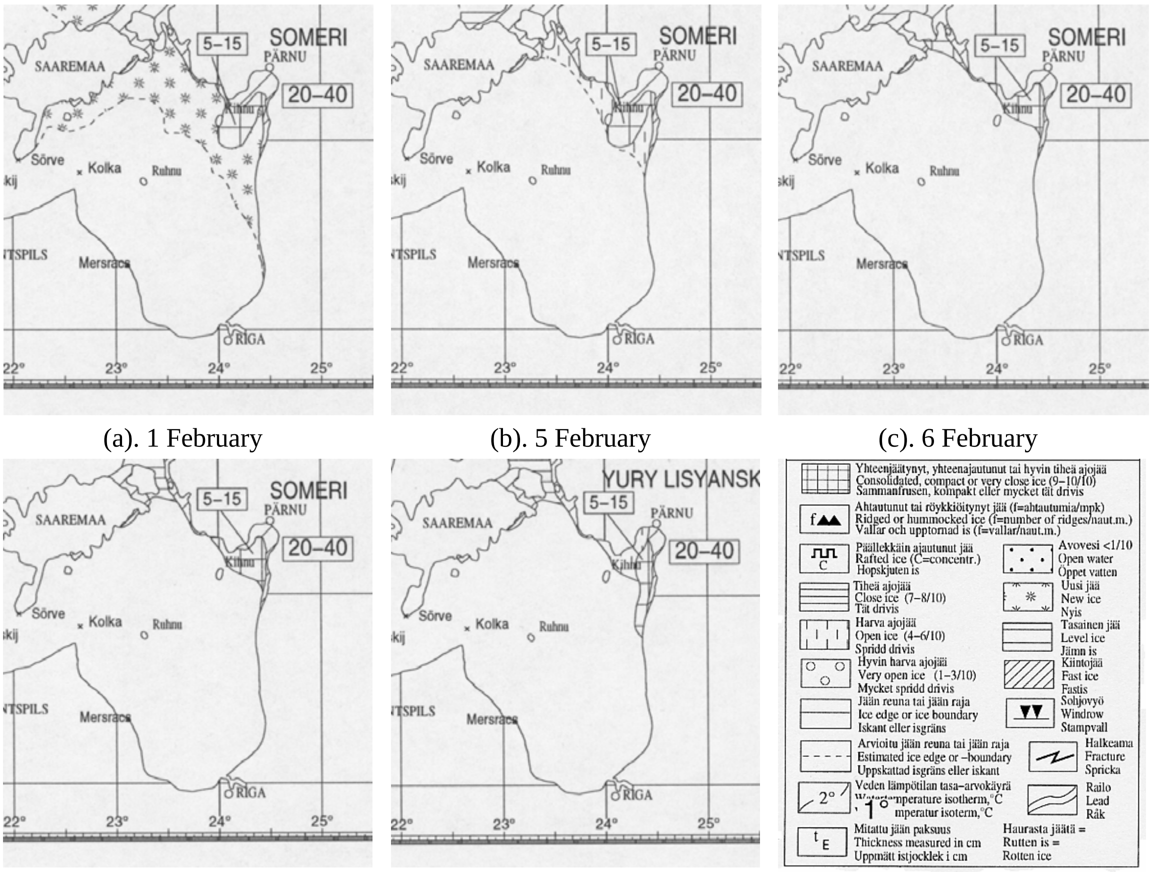


Fig. 2. Wind velocity in February 2002 at Pärnu, the wind direction is clockwise from north

Figure 3 showed the selected ice charts from the Finnish Ice Service during this period. The ice chart was published about 12:00 every day, based on all possible data collected after previous chart. One source for the Gulf of Riga information was Latvian ice service's ice report, which came to the Finnish Ice Service every afternoon (and probably based on data collected during the last 24 hours), the other sources were satellite images and good guesses (Jouni Vainio, Finnish Ice Service, personal communication). As can be seen, there were two remarkable alterations of ice state. The first one happened during 4 – 6 February (Figs. 3b and 3c), when the compacted ice previously protruded out of Kihnu Island on 5 February was all pushed into the Pärnu Bay under the strong storm forcing (see Fig. 2). While during most of the time (1 – 5 and 6 – 13 February) the ice remained immobile. The new ice was not accounted in here since it dynamically has no strength. This result implies there must be a threshold to start the dynamic ridging process. The second one happened during 13 – 14 February (Figs. 3d and 3e), when the ice flowed out from Pärnu Bay under the north wind forcing (see Fig. 2). The open boundary on the south gives little resistance against the ice drifting in this situation.



(a). 1 February (b). 5 February (c). 6 February

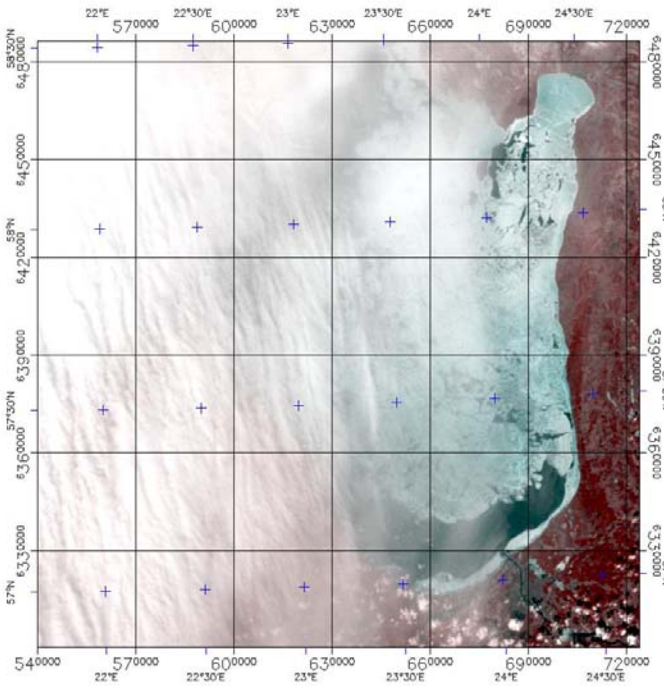
(d). 13 February (e). 14 February (f). Legend in the ice chart

Fig. 3. Ice conditions in February 2002

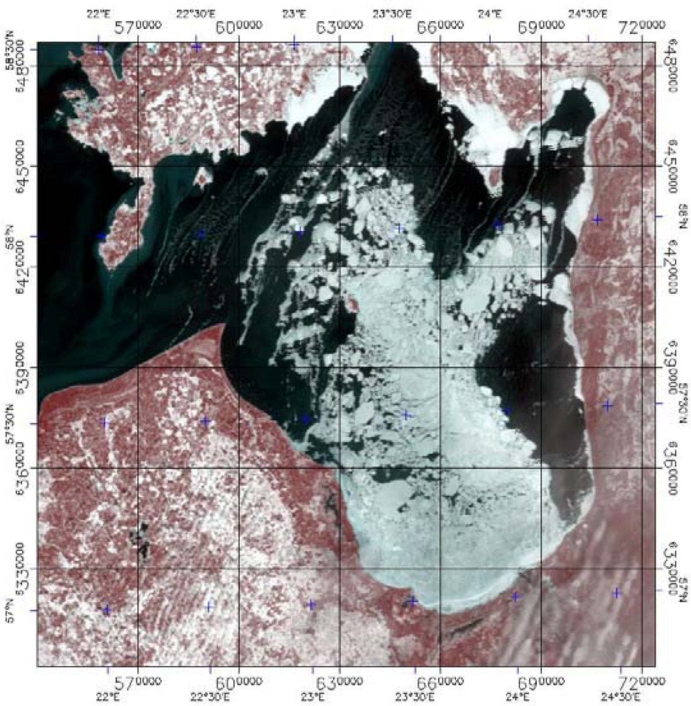
Dynamical event in 2003

The ice condition in winter 2002/2003 for the overall Baltic Sea is normal when referred to the maximum ice extent. However, very special situation for this winter is that it had a longer ice period and a larger ice thickness. Sea ice first appeared in the Gulf of Riga on 4 December 2002, and it covered the all gulf as early as on 3 January 2003. The drift ice thickness in the gulf was generally 10 – 40 cm, with coastal fast ice about 30 – 50 cm. The remarkable ice drift case occurred during 4 – 7 April 2003.

The ice images on 4 and 7 April from MODIS are illustrated in Fig. 4. Although the western part of the image on 4 April is shaded by cloud, the eastern part, particularly Pärnu Bay, can be clearly seen covered by ice. After three days, the ice moved out of Pärnu Bay about 45 km southwestward. When comparing the two images, we can see the ice field entirely drifted southward. The open area in the south of the gulf on 4 was full of ice on 7, while the ice near the east Latvian coast on 4 appeared to be open water on 7.



(a)



(b)

Fig. 4. Ice conditions (a) on 4 and (b) on 7 April 2003

The measured wind speed and direction at Pärnu during this period is shown in Fig. 5, the data were again recorded for every 5 minutes. A considerable characteristic of the wind is that it seldom exceeded 10 m/s, and during 6 – 7, it was generally about 5 m/s. When closely look at the ice image on 4 April (Fig. 4a), we can see the ice in Pärnu Bay was partly separated by icebreaker.

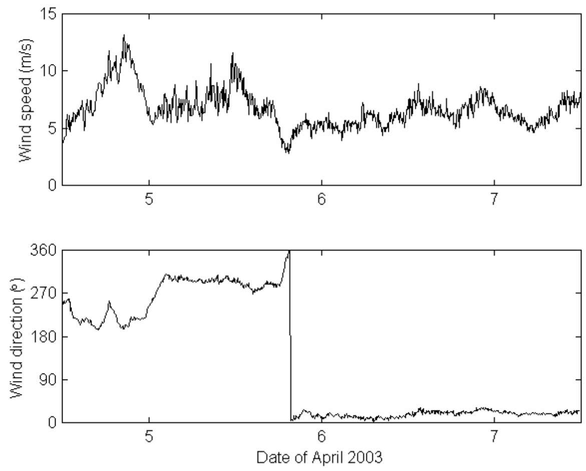


Fig. 5. Wind velocity in April 2003 at Pärnu, the wind direction is clockwise from north

This is probably the main reason why the fast ice was broken under mild wind during this event. The wind was northerly, being consistent with the ice movement.

Dynamical Characteristics

The principal scales of the present ice dynamics events in the Pärnu Bay are: basin size L = 15 km, ice thickness H = 10 cm, and wind speed U_a = 20 m/s. Then condition for unstable ice cover is (Leppäranta, 1998)

$$\tau_a L > P^* H \ . \quad (1)$$

Knowing that this was true in the present dynamic events, we have $P^* < \tau_a L/H \sim 100$ kPa. Earlier strength estimates in the Baltic Sea are in the range 10 kPa $< P^* <$ 100 kPa (Zhang and Leppäranta, 1995; Leppäranta et al., 1998), and therefore the breakage of the thin fast ice fits in the drift ice theory. The free drift ice speed scale becomes 50 cm/s from the wind and the drag parameters. Because of the small thickness of the ice, inertial time scale is a few minutes and the Coriolis term, momentum advection and surface pressure gradient are more than one order of magnitude below the surface stresses. Consequently, the wind stress, water stress and the internal friction dominate the momentum equation. After the breakage of ice by the wind, the ice accelerates in a few minutes to ~ 50 cm/s, which leads to a 10-km displacement in about six hours. Due to the ridging the ice velocity slows down and at the steady state the ice has accumulated strong enough to resist the wind force and be immobile.

Note that, as a characteristic of a plastic rheology, the internal friction is independent of the ice velocity while wind and water stresses are quadratic in air and ice velocities, respectively: and that internal friction is proportional to ice thickness while wind and water stresses are independent on that. As a result, the ice moves easily when it is thin or strongly forced, in way that relative motion increases with forcing.

MODEL SIMULATIONS

For winter 2002, the initial ice thickness and ice concentration were obtained from the ice charts as shown in Fig. 3. Short-range (3 – 5 days) simulations were performed using each ice chart as an initial field. Since ice was immobile during most of the time, our attention was focused on identifying the critical point when ice began to move and ridge. Typical values of the drift ice thickness were chosen as follows: 10 cm for the compacted ice and 30 cm for the fast ice region following the ice charts (Fig. 3). The ice concentration was taken as 1 during 1 – 6, and 0.8 during 12 – 15 February. The new ice and open ice were ignored. For wind forcing the surface wind at Pärnu was used, with time interval of 5 minutes. The current velocity beneath the layer of frictional influence of the ice was set to zero. The grid size is 463 m, and the time step is 5 minutes. The other parameters used in the standard simulation are the same as those in Wang et al. (2003).

For winter 2003, since the ice movement exceeded the range of Pärnu Bay, we used a coarser grid covering the all Gulf of Riga, where the model parameters is the same as Wang et al. (2003), except that the time step here is 5 min. The drift ice thickness was chosen 30 cm and ice concentration 0.8, and fast ice thickness was set to 50 cm and ice concentration 1. The fast ice does not move in the model.

Simulated Results of 2002 Event

Two cases were selected from this event according to the ice state change. The first case covers the period of 1 – 6 February. Referring to the wind history (Fig. 2) and ice conditions (Fig. 3), we can see that sea ice remained immobile under the wind of about 10 m/s during 2 – 3, while deformed severely under the wind of about 20 m/s during 5 – 6. There was very little difference in the wind direction. A standard simulation was performed for 120 hours from 12:00 of 1 February (Fig. 6). We can see that the ice cover remains immobile till the noon of 4 February, while on 5 February ice cover experiences severe deformation, and on 6 February ice extent remains very similar to that on 5 February, but has a noticeable difference thickness distribution. The ice in the northeast corner becomes thicker, but most ice cover with initial thickness of 30 cm does not change much. When comparing this simulation with the ice charts, we can see they match quite well according to the ice extent and ice thickness distribution.

The second case covers 10 – 13 February 2002. A standard simulation of 3 days from 10 February 2002 is shown in Fig. 7. As can be seen, ice cover in Pärnu Bay was half open and half severely deformed after 3 days simulation. A lower ice strength, for instance $P^* = 1.0 \times 10^4$ N m^{-2}, provides a bigger open water and more southward movement of the ice cover. However, zero ice strength seems not appropriate for the ice movement (Fig. 8). The simulated result for this situation illustrates that ice almost totally deforms and leans against the boundary, with ice thickness up to 5 m. This result does not match the observation and the ice charts.

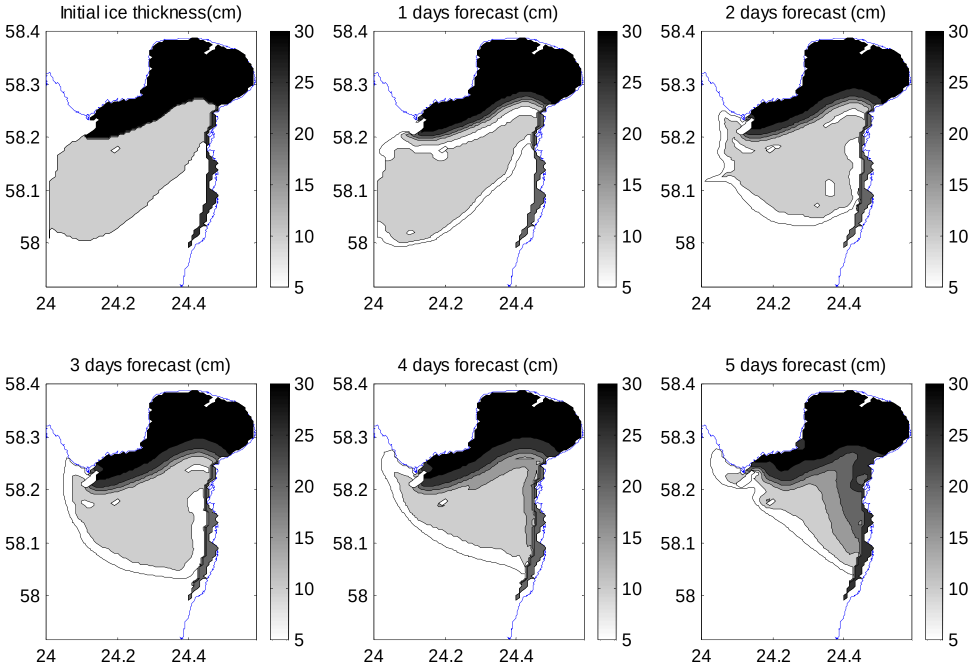


Fig. 6. Standard simulation of ice thickness from 12:00 1 February 2002 (5 days forecast)

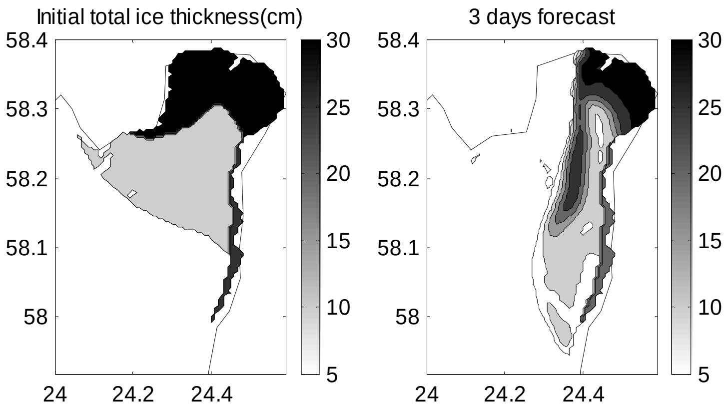


Fig. 7. Standard simulation of ice thickness from 12:00 10 February 2002 (3 days forecast)

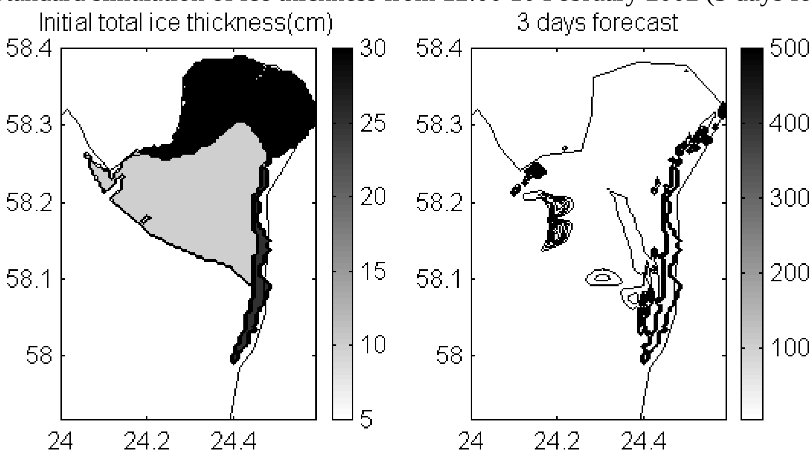


Fig. 8. Simulated ice thickness from 12:00 10 February 2002, $P^* = 0$

Simulated Results of 2003 Event

The ice drift event during 4 – 7 April 2003 is a drastically fast moving process. Because of the large displacement of the ice cover in Pärnu Bay, the whole Gulf of Riga is selected for simulation. The simulated result is shown in Fig. 9, showing the ice thickness field change as well as the ice concentration field. Although the initial ice concentration is 0.8 for the drift ice, it reaches 1 in the southern part of the Gulf of Riga after 3 days. However, ice thickness remains 30 cm in most of the area, and only a very limited area on the southern boundary experiences ridging. When comparing with the satellite images, we can see the simulated results agree pretty well with the observation.

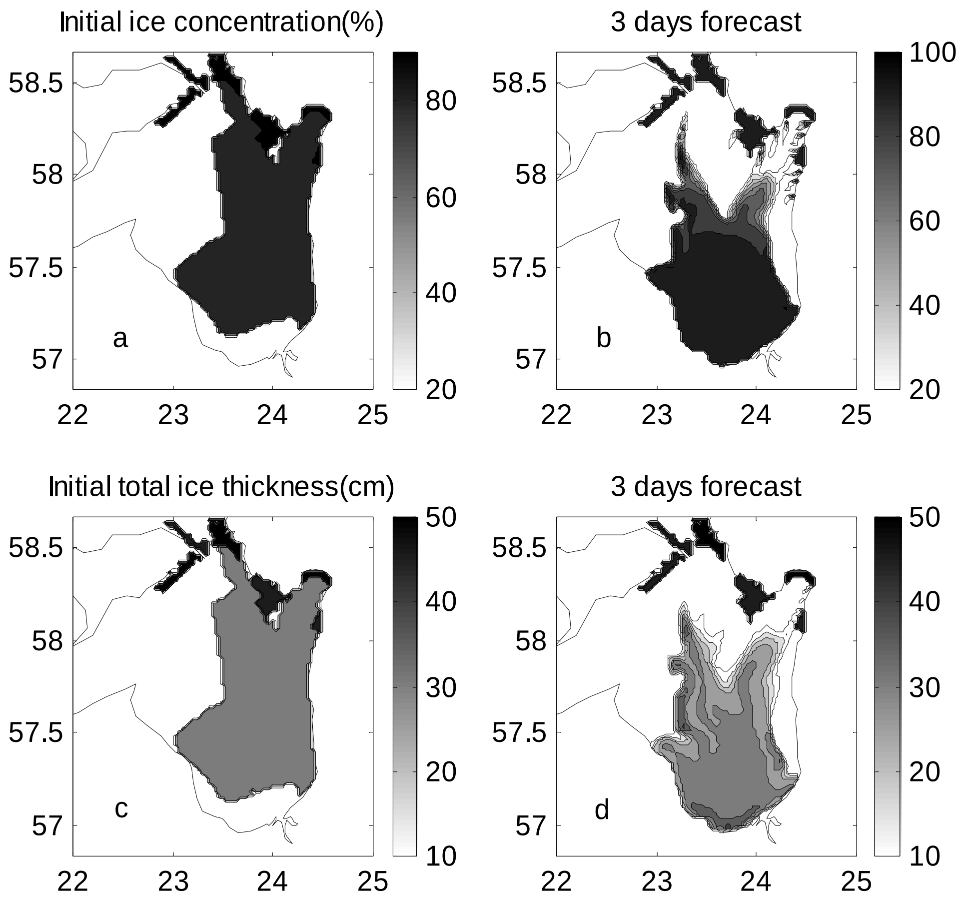


Fig. 9. Standard simulation of ice field from 4 April 2003: (a) Initial ice concentration, (b) 3 days forecast of ice concentration, (c) Initial ice thickness, and (d) 3 days forecast of ice thickness

CONCLUSIONS

In winters 2002 and 2003, two drastic sea ice dynamic events took place in the Pärnu Bay, a basin of 15 km across in the Gulf of Riga, Baltic Sea. The ice in the former event was driven into motion by the wind, about half of the basin opened and in the other side heavy rubble formation occurred. The ice in the latter event was driven about 45 km southwestward in three days. On contrast to the strong storm process in the former event when wind speed reached up to 20 m/s, wind speed ranged 5 and 12 m/s in the latter event despite the significant movement.

A high-resolution model is presented to investigate these dynamic events. The model is based on the conservation laws of ice mass and momentum with a three-level ice state (open water, undeformed ice, and deformed ice) and a viscous-plastic rheology. For the event in 2002, since ice basically moved within Pärnu Bay, the model grid size is 463 m and time step 5 min. While for the event in 2003, since the ice in Pärnu Bay experienced considerable movement, the whole Gulf of Riga is set as the studying area and the model grid size is chosen 1.852 km and time step 5 min. This model is capable to reproduce the main characteristics of these two dynamic drift ice events. It is surprising to find that the ice strength parameter P^* again optimised as $P^* = 3.0 \times 10^5$ N m^{-2}, which is very close to those for the Gulf of Riga (Wang et al., 2003), the whole Baltic Sea (Haapala and Leppäranta, 1996), and the polar oceans (Hibler and Walsh, 1982; Hibler and Ackley, 1983).

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