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A study of sea ice dynamic events in a small bay

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Abstract

In February 2002, a series of interesting sea ice dynamic events took place in Pärnu Bay, a very small basin of 15 km across in the Gulf of Riga, Baltic Sea. The opening of the bay faces SSW. The fast ice sheet was compressed, broken into small floes of typical size of no more than 20 m and moved together with the drift ice on 5 February driven by a strong SSW wind. The ice was then immobile for a week in a SW wind. After that, the wind turned northwestly with mild velocities and part of the ice cover drifted out of Pärnu Bay, so that about half of the basin opened while on the other side heavy rubble formation occurred. The thickness of the ice was from 20 to 40 cm on the coast to 5–15 cm towards the ice edge and the highest wind speed was about 20 ms^{-1}. For this paper, we performed a scale analysis to estimate the strength of the thin fast ice and applied a fine resolution ice model to investigate the sea ice dynamics. The compressive strength of the fast ice is found to be within 30 and 60 kPa, and the breakage of the thin fast ice fits into the drift ice theory. The standard strength parameter of the dynamic ice model, $P^* = 30$ kPa, is found to be a reasonable estimate of the compressive strength for the drift ice in these events. The severe fast ice breaking process produced drift ice composed of small blocks, mostly of no more than 20 m. Such drift ice keeps the standard compressive strength but seems to have noticeably less shear strength.

Keywords: Pärnu Bay; Scale analysis; Fine resolution sea ice dynamic model; Ice strength

1. Introduction

The Gulf of Riga is a brackish water basin in the eastern part of the Baltic Sea, 140 × 110 km in area with a 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. Pärnu Bay, where the main Estonian harbour in the Gulf of Riga, the town Pärnu, is located, is in the northeast corner. Pärnu Bay can be divided into an inner and outer basin. The inner part is located north of the Liu-Tahkuranna line (Fig. 1), with an approximate measure of 13 × 14 km and a maximal depth of 7.6 m. The outer part extends down to the southern tip of Kihnu Island, forming an area of about 25 × 25 km with a maximal depth of about 15 m.

Ice forms in the Gulf of Riga annually, the length of the ice season being 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 sufficient to form stable fast ice, but in mild winters thin fast ice may be broken

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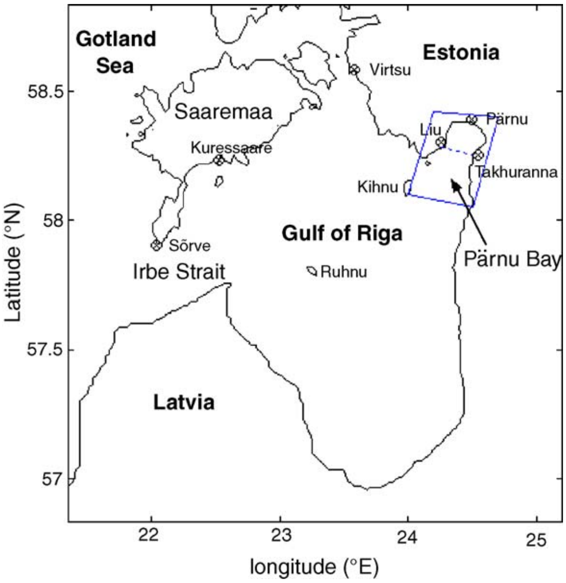

Fig. 1. Topography of the Gulf of Riga and Pärnu Bay.

up by strong winds. However, such events are extremely rare in mid-winter.

One such event happened in February 2002 in a dramatic manner. From 1 to 4 February, the ice cover was immobile under moderate SE and SW winds. On 5 February, a powerful storm broke the fast ice sheet and the drift ice floes, driving them into a compressed rubble field. Despite the widespread breaking of the fast ice sheet and the drift ice floes, the mean thickness did not change much, but the typical size of the resulting floes were mostly no more than 20 m. This compressed rubble field was immobile for a week under a moderate SW wind. The wind then became a light northwestly and part of the ice cover drifted out of the basin. About half of the basin opened while heavy rubble formation occurred on the other side.

We performed a scale analysis to estimate the strength of the thin fast ice sheet and applied a fine resolution dynamic model to investigate the detailed processes of the drift ice. The model is based on a three-level ice state (open water, undeformed ice and deformed ice) and the viscous-plastic rheology of Hibler (1979). This model has been successfully employed in studying the sea ice dynamics in the Bohai Sea (Wu and Leppäranta, 1990; Wu et al., 1997) and the Baltic Sea (Zhang and Leppäranta, 1995; Wang et al., 2003), with grid sizes of 2–10 km. The entire domain of the present study is about 30×50 km and the grid size is down to 463 m. The results show that even in such a small basin the ice model works well and can reproduce a realistic representation of the ice conditions.

2. Model description

The Pärnu Bay events are analysed here using the general drift ice theory and models (e.g., Leppäranta, 2005). This theory takes drift ice as a granular, compressible, two-dimensional medium. The "grains" are individual ice floes, the ensembles of which form drift ice particles, and the resulting medium is approximated by a continuum. The continuum approximation holds when the length scales of ice floes, drift ice particles (usually spatial grids) and the gradients of drift ice properties d, D and L_G satisfy $d \ll D \ll L_G$ (Leppäranta, 2005). Thus, strictly speaking, the breakage of the fast ice sheet is not explained by the theory, but serves as the initial condition. In the Baltic Sea, ice models have produced realistic results for grid size D down to 2–5 km (e.g., Wang et al., 2003; Zhang, 2000). Such models have not yet been used for a detailed study of a very small basin such as Pärnu Bay. Since the ice is thin (less than 30 cm) and the floe size is small (≤50 m), the continuum approximation is feasible down to a grid size of 500 m.

An ice state J is defined as including the relevant material properties of drift ice particles. In the present model, a three-level ice state, $J = \{A, \overline{h}_u, \overline{h}_d\}$, is used, where A is the total ice compactness, and $\overline{h}_u = h_u A_u / A$ and $\overline{h}_d = h_d A_d / A$ the mean thickness of undeformed and deformed ice in the ice-covered region. The actual thickness and compactness of undeformed and deformed ice, h_u, h_d, A_u, A_d, are not explicitly utilized in the model. The total mass per unit area is therefore $m = \rho_i(\overline{h}_u + \overline{h}_d)A$, where ρ_i is the ice density. The basic equations for sea ice dynamics are the conservation laws of momentum and ice (e.g., Leppäranta, 2005):

$$m\frac{\mathrm{d}\boldsymbol{V}}{\mathrm{d}t} = -mf\boldsymbol{k}\times\boldsymbol{V} + \boldsymbol{\tau}_a + \boldsymbol{\tau}_w - mg\nabla\xi + \nabla\cdot\boldsymbol{\sigma}, \quad (1)$$

$$\frac{\partial}{\partial t}\{A, \overline{h}_u, \overline{h}_d\} = -\boldsymbol{V}\cdot\nabla\{A, \overline{h}_u, \overline{h}_d\} + \{\psi_A, \psi_u, \psi_d\}, \quad (2)$$

where d/dt is the substantial time derivative, $\boldsymbol{V}$ the ice velocity, f the Coriolis parameter, $\boldsymbol{k}$ the unit upward vector normal to the surface, $\boldsymbol{\tau}_a$ and $\boldsymbol{\tau}_w$ the air and water stresses, g the gravity acceleration, ξ the sea surface elevation, $\boldsymbol{\sigma}$ the internal ice stress, and ψ_A, ψ_u, ψ_d the ice redistribution functions due to mechanical deformation. Here short-term dynamic events are examined and thermodynamic effects are neglected.