SEA ICE DYNAMICS IN BALTIC SEA BASINS

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ABSTRACT
The Baltic Sea consists of several sub-basins where the horizontal dimensions are 10–300 km. These basins have own individual ice conditions: the thickness of undeformed ice is 0.1–1 m, deformed ice accounts for 10–50% of the total ice volume, and the degree of homogeneity of the ice varies largely. In a given basin the ice may be stationary or in the free drift state.

INTRODUCTION
The Baltic Sea is a semi-enclosed brackish water basin in the seasonal sea ice zone. Its area is 0.4 million km², mean depth is 56 m, and it is divided into several sub-basins. The Baltic Sea ice dynamics problem has an own regime of scales somewhere between large polar seas with permanent ice circulation systems and small basins where the mobility of the ice is very limited. The size of the basins is 10–300 km, the thickness of undeformed ice goes up to 1 m, and ice ridges are typically 5–15 m thick.

In this presentation the dynamics of Baltic Sea ice is examined particularly in two basins: the Gulf of Riga and the Gulf of Finland. The former is a nearly square basin with sides of 100 km while the latter is rectangular, size $300 \times 100$ km, with a strongly increasing ice thickness toward the end of the basin. The work is based on numerical modelling with scaling analysis by analytical methods.

SEA ICE DYNAMICS MODELLING
The ice cover is here a three-level system, as usually in Baltic Sea ice models, specified by ice compactness $A$ and the thicknesses of undeformed and deformed ice $h_u$ and $h_d$ (Leppäranta, 1981). The conservation laws of ice and momentum (pure dynamics) are (e.g., Leppäranta, 1998)

\[
\frac{\partial}{\partial t} + \boldsymbol{u} \cdot \nabla \{A, h_u, h_d\} = -\{A, 0, h_d\} \nabla \cdot \boldsymbol{u} \\
\rho h(\frac{\partial}{\partial t} + \boldsymbol{u} \cdot \nabla + f \boldsymbol{k} \times \boldsymbol{u}) = \nabla \cdot \boldsymbol{\sigma} + \tau_a + \tau_w - \rho h g \nabla \zeta
\]

where $t$ is time, $\boldsymbol{u}$ is ice velocity, $\rho$ is ice density, $h$ is mean ice thickness, $f$ is Coriolis parameter, $\boldsymbol{k}$ is unit vector vertically upward, $\boldsymbol{\sigma}$ is internal ice stress, $\tau_a$ and $\tau_w$ are the

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tangential air and water stresses on the ice, \( g \) is the acceleration due to gravity, and \( \xi \) is the sea level elevation.

The Hibler (1979) viscous-plastic rheology is used for the ice stress,

\[
\sigma = [\xi \varepsilon - P/2]I + 2\eta \varepsilon
\]

where \( \varepsilon \) is strain rate, \( \xi = P/2\max\{\Delta, \Delta_0\} \), \( \eta = \xi/e^2 \) and \( P = P^*H \exp\{-C(1-A)\} \), \( \Delta = [\varepsilon_I^2 + (\varepsilon_{II}/e)^2]^{1/2} \), \( \Delta_0 \) is maximum creep rate, \( e \) is the aspect ratio of the yield ellipse, \( P^* \) is the compressive strength of ice of unit thickness, and \( C \) the constant for the hardening with compaction. The usual quadratic formulae are used for air and water stresses (e.g., Haapala and Leppäranta, 1996).

Representative basic scales in the Baltic are \( H = 10–50 \text{ cm}, U = 10 \text{ cm/s}, T = 1 \text{ day}, L = 10–300 \text{ km}, P = 10 \text{ kN/m} \) for compact ice or 0 for free drift, \( U_a = 10 \text{ m/s}, \) and \( U_w = 5 \text{ cm/s} \). The magnitudes of the terms of the momentum equation are then (the scale value is the ten-based logarithm of the term in MKSA units)

<table>
<thead>
<tr>
<th>Term</th>
<th>Scale</th>
<th>Scale value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local acceleration</td>
<td>( \rho H U/T )</td>
<td>–4 to –3</td>
</tr>
<tr>
<td>Advective acceleration</td>
<td>( \rho H U^2/L )</td>
<td>&lt; –3</td>
</tr>
<tr>
<td>Coriolis term</td>
<td>( \rho H f U )</td>
<td>–2 to –3</td>
</tr>
<tr>
<td>Internal friction</td>
<td>( P^* H /L )</td>
<td>(-\infty ) for free drift to (-1 ) for compact ice</td>
</tr>
<tr>
<td>Air stress</td>
<td>( \tau_a )</td>
<td>–1</td>
</tr>
<tr>
<td>Water stress</td>
<td>( \tau_w )</td>
<td>–1</td>
</tr>
<tr>
<td>Pressure gradient</td>
<td>( \rho H f U_w )</td>
<td>&lt; –3</td>
</tr>
</tbody>
</table>

The governing terms are the wind and water stresses and the internal friction. For high velocities the wind and water stresses are dominant; for low velocities the internal friction is dominant in compact ice while the Coriolis term together with the wind and water stresses are dominant if the compactness is smaller. In free drift the length scales of ice motion are those in the wind and currents. In wind-driven drift of compact ice, a natural ice length scale is \( L = P/\tau_a \); if \( P = 10 \text{ kN/m} \) and \( \tau_a = 0.1 \text{ N/m}^2 \) we have \( L = 100 \text{ km} \).

**NUMERICAL EXPERIMENTS**

A series of model experiments has been performed for the ice dynamics in the Baltic basins. The model is similar to those of Zhang and Leppäranta (1995) and Haapala and Leppäranta (1996). The key parameters are: air drag coefficient = \( 1.2 \times 10^{-3} \) (geostrophic wind), water drag coefficient = \( 3.5 \times 10^{-3} \) (geostrophic current), and ice strength constants as \( P^* = 25 \text{ kPa}, e = 2, C = 20 \) and \( \Delta_0 = 2 \times 10^{-9} \text{ s}^{-1} \).

**Gulf of Riga**

The initial ice compactness was 0.99 and the initial ice thickness 0.2 m or 0.5 m. Geostrophic wind speed was 10 m/s and simulations were made for different wind directions while geostrophic water flow was assumed zero. Results for two seven-day model runs are shown in Fig. 1; the wind direction was from southwest, exact vector direction being 35 degrees to right from north. In both cases the ice is drifting. A lead
Figure 1a: Result from 7-day model run for the Gulf of Riga with initial ice thickness of 0.5 m.

Figure 1b: Result from 7-day model run for the Gulf of Riga with initial ice thickness of 0.2 m.
Figure 2a: Result from 7-day model run for the Gulf of Finland with initial ice thickness of 0.5 m.

Figure 2b: Result from 7-day model run for the Gulf of Finland with initial ice thickness of 0.2 m.
opens on the west coast, and its width is more for thinner ice. Ridging takes place on the
northeast corner of the basin. Scaled with the thickness of ice, twice as much deformed
ice is produced in the thin ice case and the ridging zone is found in the very same
location. In the center of the basin there is a small (10 km) island. It is seen that thin ice
passes it quite well but a deformed ice spot appears for the thicker ice.

**Gulf of Finland**

The initial ice compactness was 0.99 and the initial ice thickness 0.2 m or 0.5 m. Geo-
ostrophic wind speed was 10 m/s and its direction was eastward toward the end of the
basin (exact vector direction being 75 degrees to right from north). The geostrophic
water flow was assumed zero. Results for two seven-day model runs are shown in
Fig. 2. In both cases the ice is drifting. Ice edge moves east on the west, more for
thinner ice. Ridging takes place in the eastern basin. Scaled with the thickness of ice,
twice as much deformed ice is produced in the thin ice case. The ridging zone is stuck
between islands at 27 °E in the thick ice case but extends much further east up to the
coast in the thin ice case.

**REMARKS**

This work is a progress report on our research of the effects of scale and shape of basins
in sea ice dynamics. The sub-basins of the Baltic Sea provide excellent cases for
modelling, with good field data existing for the validation. The dimensions of these sub-
basins are 10–300 m while the thickness of undeformed ice is 0.1–1 m. Linear
dimensions of the Baltic ice morphology scale with the Central Arctic by about 1:5 but
the models work well with essentially the same parameterisation schemes and parameter
ranges.

The mobility of the ice is highly sensitive to the ice thickness in the Baltic. For compact
ice field to drift, one must have \( \tau_a L > P^* h \), which condition turns on and off several
times during the course of the winter. While drifting, the length scale of becomes
\( L = P^* h / \tau_a \), and therefore islands and coastal forms form larger size barriers to the drift the
thicker the ice is. Also because thinner ice forms ridges more easily, the amount of
ridged ice becomes a complicated function of wind and ice conditions.

**ACKNOWLEDGEMENT**

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