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Cover picture: The Swedish icebreaker Atle in the Bothnian Bay.
(Photo by Mats Moberg, SMHI.)

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Title (and Subtitle)

A coupled ice-ocean model supporting winter navigation in the Baltic Sea. Part 1. Ice dynamics and water levels.

Abstract

A sea ice forecasting system for the Baltic Sea is presented together with some illustrations. The model is a dynamic coupled model, consisting of both a sea ice and a storm surge model. The model was forced using wind and pressure fields from the HIRLAM system and was introduced in preoperational tests during the winter of 1992/93. In general, the results were most promising, but further work is needed, particularly the inclusion of thermodynamics to the model, a closer coupling between the ice-ocean model and the HIRLAM model, and the development of an automatic method for the generation of initial data to the model.

Key words

Baltic Sea, modelling, forecasting, sea ice dynamics, water levels.

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1. INTRODUCTION

When the ice is moving, pressure ridges which are difficult to force, and leads which are easily navigable, are formed. It is therefore important to forecast the ice drift for a safe and economic shipping. Within the Swedish-Finnish Winter Navigation Research Programme large efforts have been made to increase our knowledge about sea ice in the Baltic Sea. Several results have been achieved which have partly been published by the Winter Navigation Research Board and partly in international journals (e.g. Geophysica, Journal of Geophysical Research and Tellus).

In the present paper we illustrate some results from a sea ice forecasting model. This model is a dynamic, coupled model consisting of both a sea ice and a storm surge model. The ice model is based on the Hibler (1979) model and on an earlier Baltic Sea ice model by Leppäranta (1981). The momentum equation uses a steady state approximation and the ice thickness is described with a three-level approach. The mechanical deformation describing closing and opening of leads and ridging is modelled as in Leppäranta (1981) and the ice constitutive law follows the plastic model of Hibler (1979). The combined ice model was first given by Wu and Leppäranta (1988). First test results from the Baltic Sea were presented by Leppäranta and Zhang (1992) and the model is now named the BOBA model, as it was first applied in the BOhai Sea and the BAltic Sea.

The ocean model is a two-dimensional one-layer model presented by Zhang and Wu (1990). The coupled ice-ocean model was first applied to the Gulf of Bothnia by Zhang and Leppäranta (1992) in a study of sea ice and water levels. In the present application we have extended the model area to the Baltic Sea and applied the model for forecasting ice drift and water levels. The meteorological forcing was taken from the HIRLAM forecasting system (Machenhauer, 1988; Kållberg, 1989; Gustafsson, 1993), which was starting as an operational model at SMHI during the winter of 1992/1993.

In Section 2, the model is discribed. Then, some information on the winter of 1992/ 1993 is given. In Section 4, model illustrations are presented. Finally, a discussion with some recommendations for future work are outlined.

2. THE MODEL

2.1 The sea ice model

The sea ice is treated as two dimensional, with x, y and t as independent variables. In the mass conservation equation only mechanical processes are included, and thus thermodynamic processes are not yet incorporated. In the ice drift equation, we assume steady state. The mass conservation and ice drift read:

$$\frac{\partial m_i}{\partial t} + \nabla \cdot (m_i U_i) = 0 \tag{1}$$

$$\tau_{ai} + \tau_{wi} + C + \nabla \cdot \Sigma = 0 \tag{2}$$

where m_i is the ice mass, U_i the ice drift vector, C the Coriolis force, τ_{ai} and τ_{wi} are the air stress on ice and the ice-water stress respectively, and Σ is the internal ice stress.

The ice mass is connected to ice concentration A_i and ice thickness h_i through the following equation of state:

$$m_i = \rho_i h_i A_i = \rho_i (h_l + h_r) A_i \tag{3}$$

where h_l and h_r are the level and the equivalent thickness of ridged ice, respectively.

The coupling to the atmosphere is through the air stress, which reads:

$$\tau_{ai} = \rho_a C_{ai} |W_a| (W_a \cos \theta_a + k \times W_a \sin \theta_a) \tag{4}$$

where W_a is the wind vector, k the vertical unit vector, ρ_a the air density, C_{ai} the air drag coefficient and θ_a the air-turning angle.

The corresponding coupling between ice and ocean is through the water stress, which reads:

$$\tau_{wi} = \rho_w C_{wi} |U_w - U_i| \left[(U_w - U_i) \cos \theta_w + k \times (U_w - U_i) \sin \theta_w \right] \tag{5}$$

where ρ_w is the water density, U_w the current vector calculated from the ocean model, θ_w the turning angle of water and C_{wi} the water drag coefficient.

The ice thickness is calculated from a three-level approach. The levels are: open water ($1 - A_i$), level ice thickness (h_l) and ridged ice thickness (h_r). They are calculated according to:

$$\frac{\partial}{\partial t}(A_i, h_l, h_r) = -U_i \cdot \nabla (A_i, h_l, h_r) + (\psi_A, \psi_l, \psi_r) \tag{6}$$

where ψ_A, ψ_l and ψ_r are the mechanical deformation functions describing open water changes, rafting and ridging and must satisfy the following mass conservation condition:

$$h_i \psi_A + A_i(\psi_l + \psi_r) = -h_i A_i \nabla \cdot U_i \tag{7}$$

The calculations of the deformation functions follow Leppäranta (1981) according to:

1) for ice concentrations less than one or divergence in the ice pack, the deformation functions read:

$$\psi_l = \psi_r = 0 \tag{8}$$

$$\psi_A = -h_i \nabla \cdot U_i \tag{9}$$

2) For ice concentrations equal to one and converging ice drift, where the ice thickness is below a critical thickness (h_{cr} equal to 0.1 m), the deformation functions read:

$$\psi_A = \psi_r = 0 \tag{10}$$

$$\psi_l = -h_i \nabla \cdot U_i \qquad \text{(rafting)} \tag{11}$$

3) As in case 2 but with ice thicknesses above the critical thickness (h_{cr}), the deformation functions read:

$$\psi_A = \psi_l = 0 \tag{12}$$

$$\psi_r = -h_i \nabla \cdot U_i \qquad \text{(ridging)} \tag{13}$$

In the internal ice friction term it is necessary to take the plastic nature of sea ice into account. This is done by applying the non-linear viscous-plastic constitutive law of Hibler (1979):

$$\Sigma = 2\eta\dot{\varepsilon} + (\xi - \eta) tr\dot{\varepsilon} I - PI/2 \qquad (14)$$

where ξ and η are non-linear shear and bulk viscosities, $\dot{\varepsilon}$ is the strain-rate tensor, I is the unit tensor, tr is the trace operator and P is the ice strength. The ice strength is related to the ice thickness and concentration according to:

$$P = P_{*}\, h_i \exp\left(-C(1 - A_i)\right) \qquad (15)$$

where P_* and C are empirical constants. The viscosities describe linear behaviour for small strain rates and plastic behaviour for larger strain rates. Constants applied in the present study are listed in Table 1, where the drag coefficients are according to an earlier study in the Baltic Sea by Leppäranta and Omstedt (1990).

Table 1. The parameters in the model.

Parameter	Symbol	Value
Density of air	ρ_a	1.3 kgm^{-3}
Density of ice	ρ_i	910 kgm^{-3}
Density of water	ρ_w	10^3 kgm^{-3}
Drag coefficient of air	C_{ai}	1.8×10^{-3}
Drag coefficient of water	C_{wi}	3.5×10^{-3}
Boundary layer angle in air	θ_a	0°
Boundary layer angle in water	θ_w	17°
Strength constant of ice	P_*	10^4 Nm^{-2}
Reduction constant for opening	C	20
Maximum thickness of rafting	h_{cr}	0.1 m
Coriolis parameter	f	1.26×10^{-4} s^{-1}

2.2 The ocean model

The ocean model starts from a vertical, integrated form of the Navier-Stokes equation. The equation reads:

$$\frac{dU_w}{dt} = -f\, k \times U_w - g\, \nabla\zeta - \nabla P_a / \rho_w + \left[(1 - A_i)\tau_{aw} + A_i \tau_{ai} - \tau_{bw}\right] / \rho_w (D + \zeta) \qquad (16)$$

where f is the Coriolis parameter, g is the gravity constant, ζ the sea level, P_a the air pressure, τ_{aw} the air stress on water, τ_{bw} the bottom friction stress and D the water depth. The corresponding continuity equation reads:

$$\frac{\partial \zeta}{\partial t} + \nabla \cdot \left[(D + \zeta) U_w \right] = 0 \tag{17}$$

The bottom friction stress reads:

$$\tau_{bw} = \rho_w \, g \, C_b^{-2} |U_w| U_w \tag{18}$$

where C_b is the Chezy coefficient expressed by an empirical formula. For further details about the ocean model, see Zhang and Wu (1990).

2.3 Numerical procedure

The numerical procedure was made by applying finite-difference technique to the equations. When integrating the ocean part, the ice variables were kept fixed and vice versa. In the ice model the spatial discretization was made according to Arakawa's B-type grid with a grid size of 10 nautical miles (Figure 1), and a time-step of 3 hours.

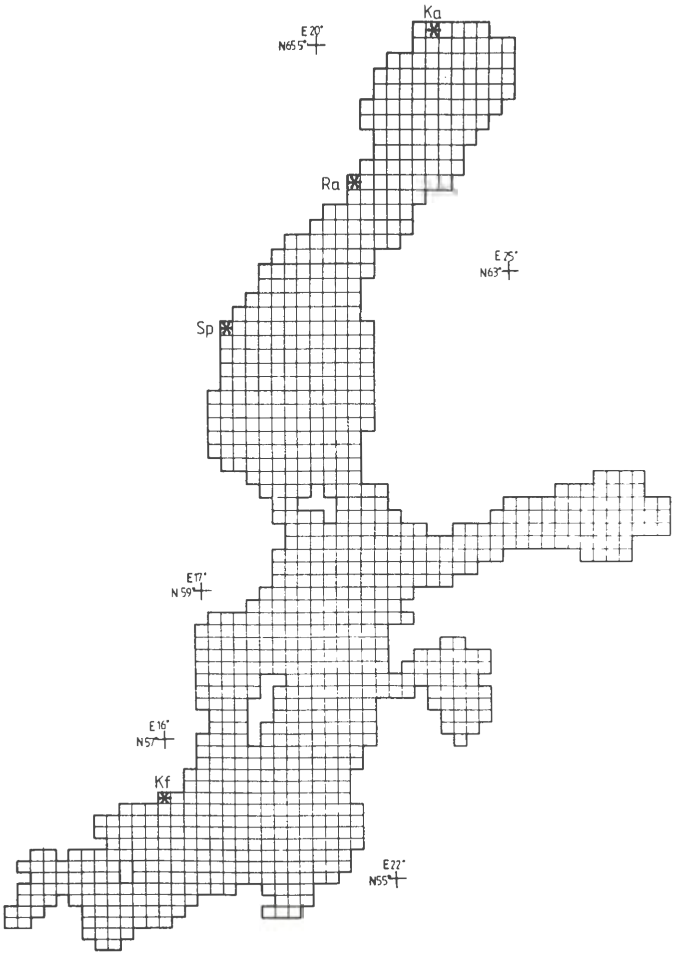

Figure 1.
Grid for the ocean model. The stars indicate the sea level stations mentioned in the text.

The velocity of fast ice was put to zero and its concentration equal to 1. The main simplification was that the ice momentum equation was treated time-independently. The numerical solution was obtained with successive over relaxation schemes. The solution of the ocean model was derived by the numerical integration method of the ADI procedure (Zhang and Wu, 1990). The grid size was the same as that in the sea ice model, but the time step was put equal to half an hour. For further details of the numerical procedure; see Zhang and Wu (1990) and Zhang and Leppäranta (1992).

2.4 Operational procedure

The operational procedures were developed during the winter of 1992/93 and are outlined in Figure 2. The initial data (ice concentration, mean ice thickness and water levels) were taken from NOAA satellite and ice chart information and from water level observations, and they were manually gridded. Only the mean sea level in the Baltic Sea was given. On the basis of the HIRLAM forecasting system, weather forecasts up to 48 hours were extracted and used as input data to the ice-ocean model. The ice-ocean forecast at 24 hours was then after subjective control used as the initial data for the next day. To take in- and outflows to the Baltic Sea into account, the mean sea level in the model was adjusted to observation from the water level station at Landsort in the central part of the Baltic Sea. In Section 5 we will further discuss the operational procedure.

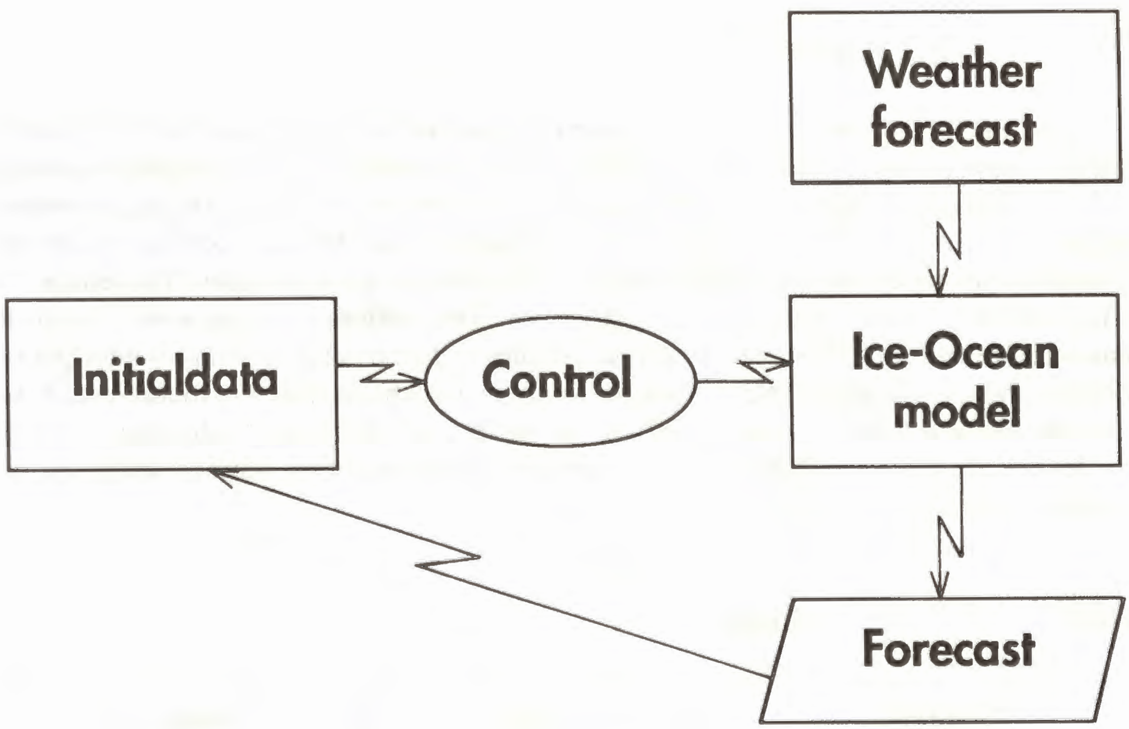

Figure 2. Schematic presentation of the operational model structure.

3. THE WINTER 1992/93

The ice winter of 1992/93 was a mild winter with very easy ice conditions. The air temperatures were mild with relatively high wind speeds. The first ice started to form in the end of October. In December, mild periods with westerly winds started to dominate. In late January new ice was forming, but the ice formation was interrupted by milder periods. The maximum ice extent for this winter was reached on February 23 - 24. Due to strong southerly winds rafted and ridged ice formed along the Swedish coast in the Bothnian Bay. In the middle of April the ice started to melt and the Bothnian Bay was ice free in the middle of May.

The first ice-ocean forecast was made on January 27. From then to April 30, 1993, almost daily forecasts of ice drift and water levels were performed, using HIRLAM wind and pressure forecasts. During the winter several problems with the HIRLAM system were detected. The HIRLAM area was too small, which made the data assimilation of rapid changes difficult, the land-ocean friction parametrizations were bad and the input of ice and sea surface temperatures to HIRLAM was poor. Some of these features were corrected during the winter and a new, better version of HIRLAM was introduced on April 7, 1993.

4. ILLUSTRATIONS

4.1 Water levels

The sea level variations during ice-covered periods in the Baltic Sea have been earlier analysed by Omstedt and Nyberg (1991). The sea levels showed larger amplitudes during autumn and early winter, whereas the amplitudes were reduced during midwinter, spring and summer. When the data were collected into different ice classes, it was observed that the amplitudes were reduced during severe ice conditions. The reason was partly meteorological conditions and partly ice. The reduction of sea levels due to ice has also been studied by using the present model and analysing different winter periods (Zhang and Leppäranta, 1992). From the study it was shown that the model could well describe the reduction in water level variations due to ice. Some further tests with the model are illustrated in Figure 3. The positions of the sea level stations are given in Figure 1 and Table 2.

Table 2. The sea level stations.

Stations	Latitude	Longitude
Kungsholmsfort (Kf)	56° 06'	15° 35'
Spikarna (Sp)	62° 22'	17° 32'
Ratan (Ra)	64° 00'	20° 55'
Kalix (Ka)	65° 42'	23° 06'

Starting from assuming a constant sea level, the model adjusts to the atmospheric conditions quite rapidly. In general the sea levels were well predicted in the Baltic Sea, but showed larger amplitudes than those observed in the Gulf of Finland (not illustrated in Figure 3), which probably was due to the parametrization of the bottom friction.

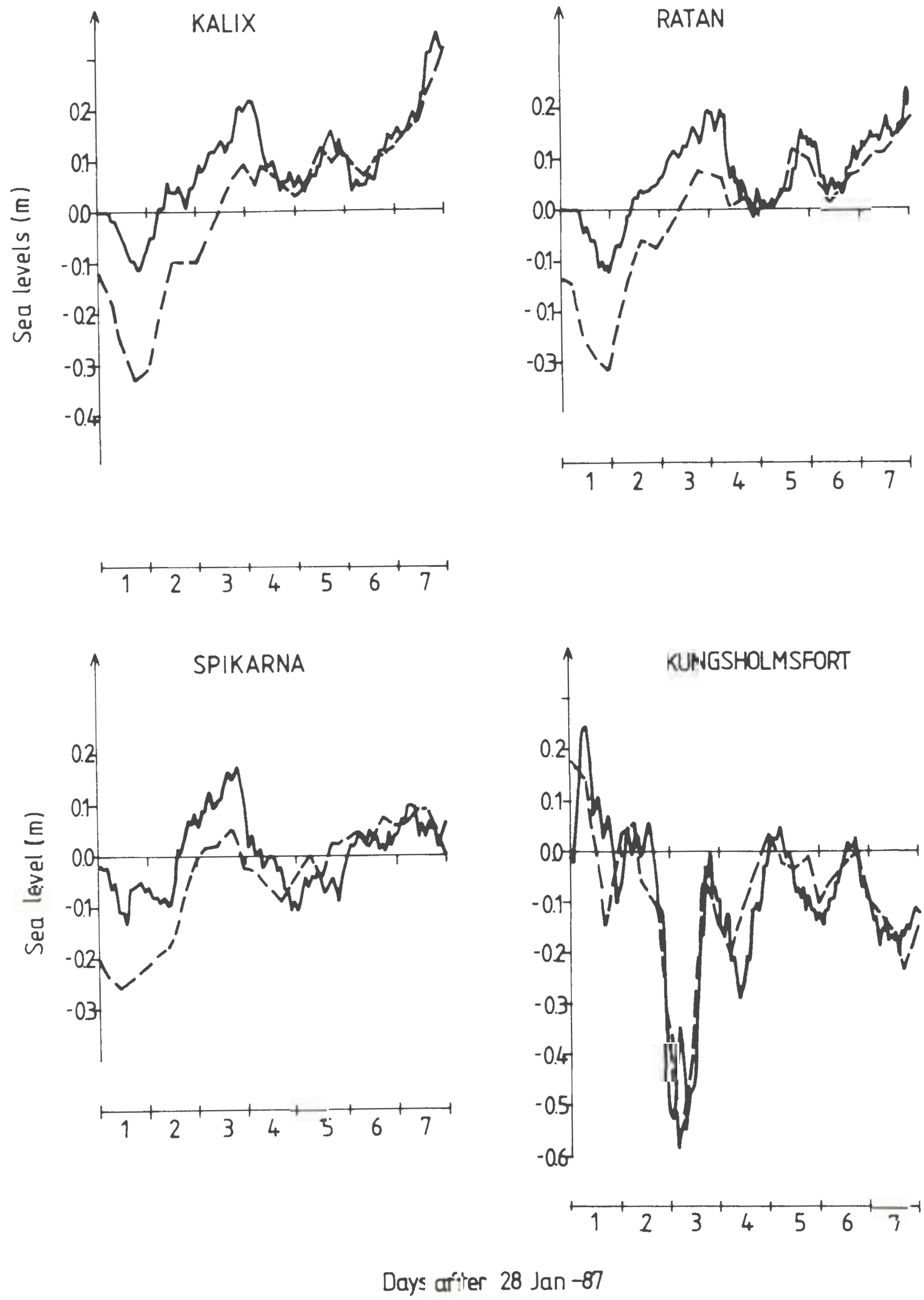

Figure 3. *Calculated (fully drawn lines) and measured (dashed lines) water levels during the period January 28 - February 4, 1987. The positions of the sea level stations are given in Figure 1 and Table 2.*

4.2 Ice drift

To illustrate the model we first present an example of calculated winds, ice drift and currents (Figures 4 - 6). The wind field is from the HIRLAM system and interpolated to the ice-ocean model grid. From the figures one can, for example, notice: mesoscale variability in the wind field, ice drift in almost the same direction but variable in speed, and a quite complex current field. Basic features from one-layer ocean models are that the currents flow along the winds in the shallow coastal areas and in the opposite direction in the central parts of the basins. Also due to variable topography eddy-like structures in the current field are often generated. The main quality control of one-layer ocean models are, however, whether they predict the water levels realistically or not. As this was the case with the present model, one can expect that particularly currents through straits were realistically simulated by the model.

In the winter of 1992/93 daily forecasts were performed during about three months. In the beginning of the winter, thermodynamic processes as ice formation and melting were active, which was not dealt with in the present model. However, by manual updating of the initial fields several successful forecasts were made. We have not made any objective evaluation of the model, instead only one situation is discussed below.

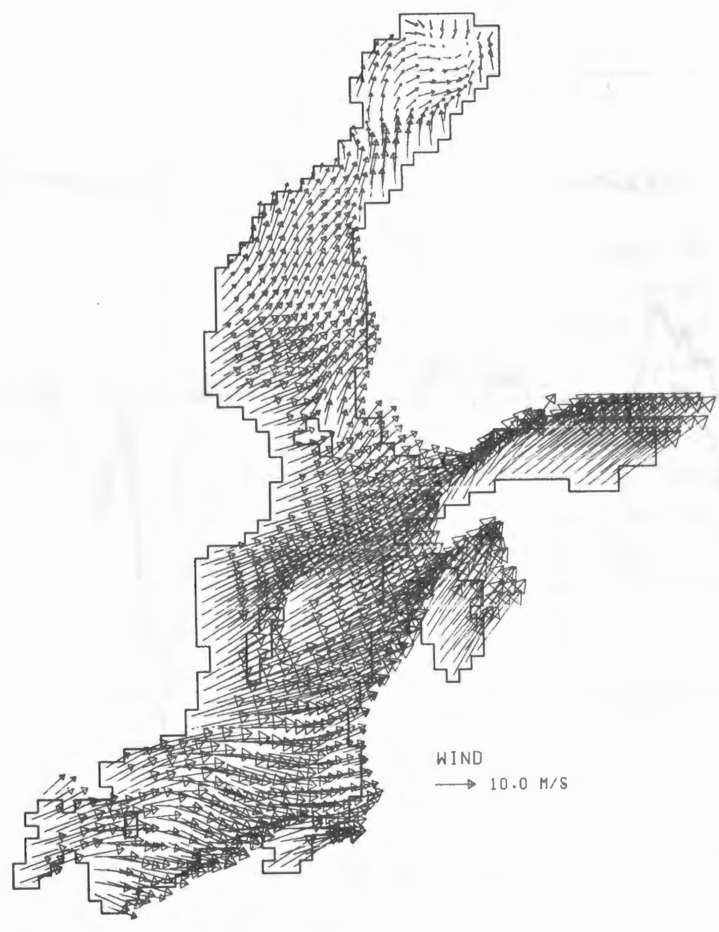

Figure 4. An example of HIRLAM-calculated winds interpolated to the ice-ocean model grid.

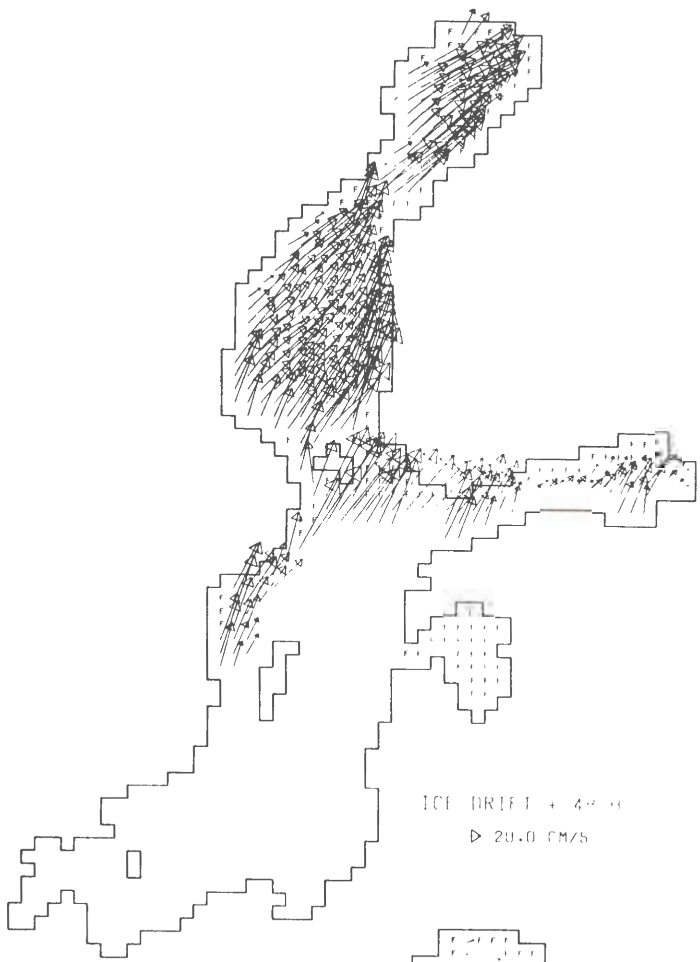

Figure 5.
An example of ice drift calculations.

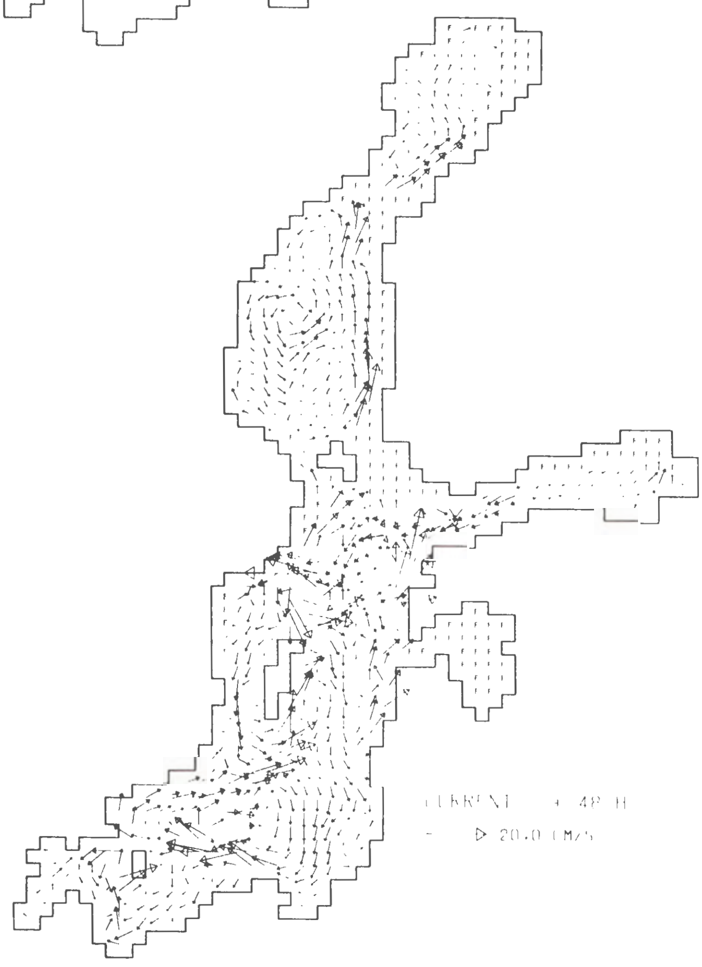

Figure 6.
An example of vertical, integrated currents.

The Bothnian Bay was partly ice covered during March, 1993. During the end of March, the wind direction changed, and the ice was drifting offshore the Swedish coast, forming a navigable lead along the Swedish coast (Figure 7). The model forecast from March 24 is given in Figure 8. By analysing the changes in ice concentration during the forecast (Figure 9) it is easy to see that minor changes in ice concentrations were predicted in the 24 hour forecast, but larger changes were predicted on the 48 hour forecast. The forecast from the next day, March 25, supported the prediction of a lead forming along the Swedish coast (Figure 10). The opening of a lead along the Swedish coast was thus predicted to be between March 25 and 26. By comparing the forecasts with satellite data (Figure 7) it is clear that the model predictions were reasonably correct and could support winter navigation with useful information.

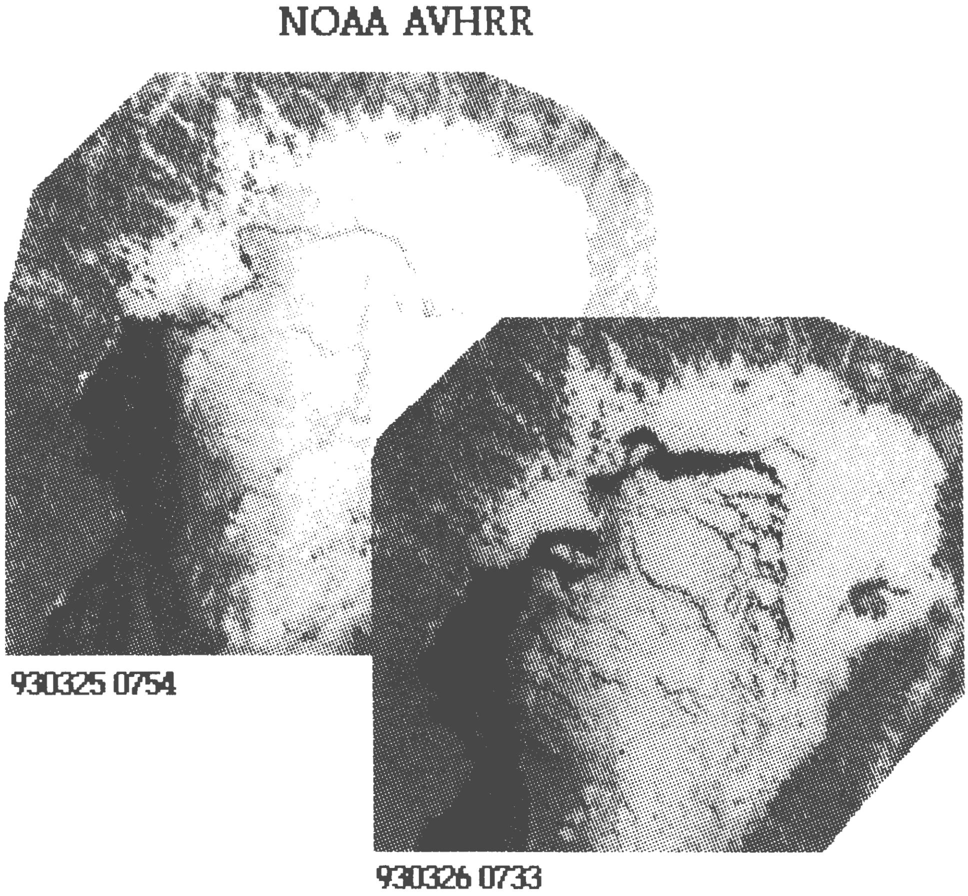

Figure 7. NOAA/AVHRR satellite scenes from March 25 and 26, 1993, illustrating a decrease in the concentrations along the Swedish coast.

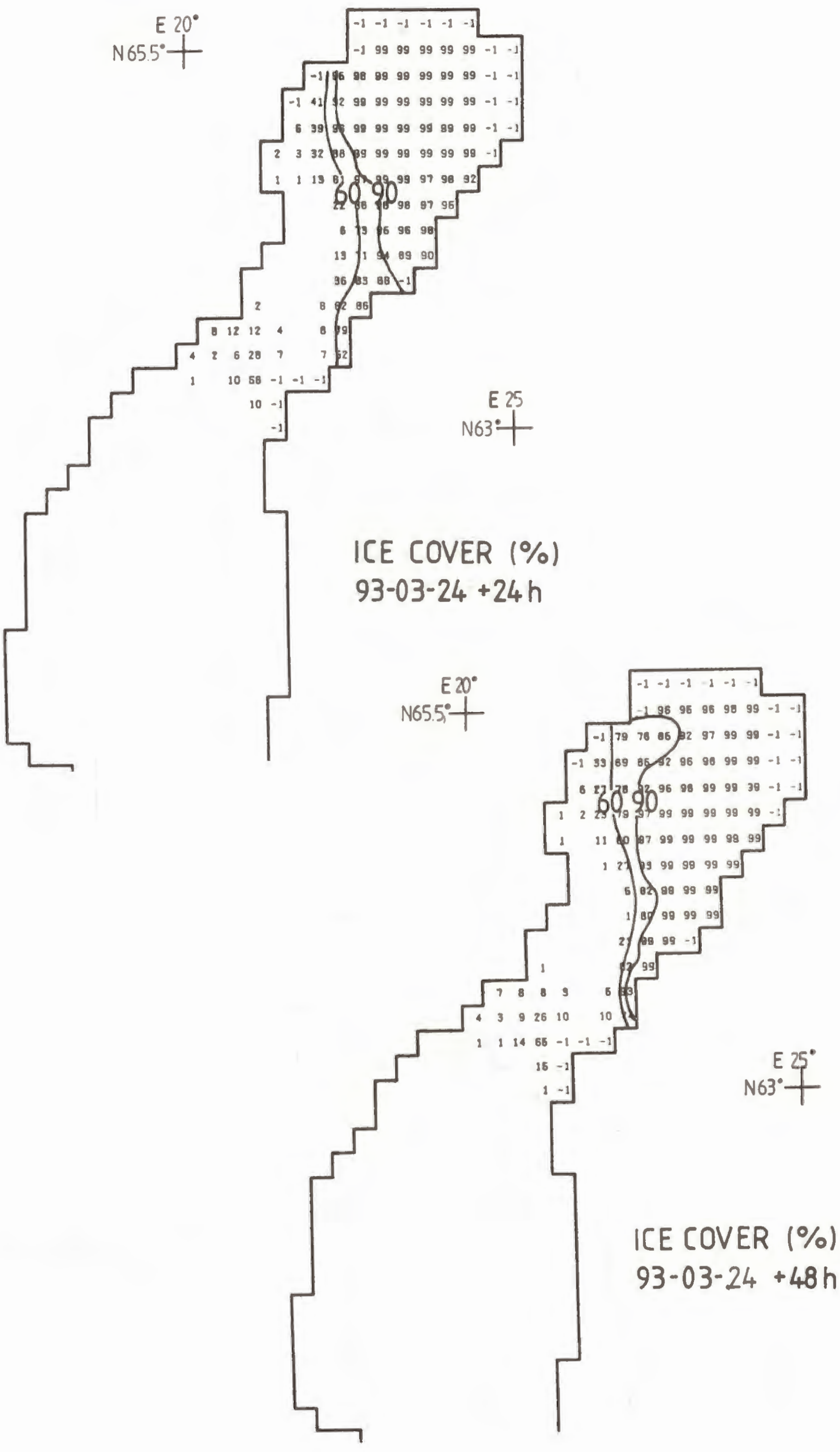

Figure 8. *An operational forecast of ice concentrations in the Bothnian Bay from March 24, 1993. The maps show forecasted ice concentration on March 24 and 26, respectively. Fast ice is denoted by -1.*

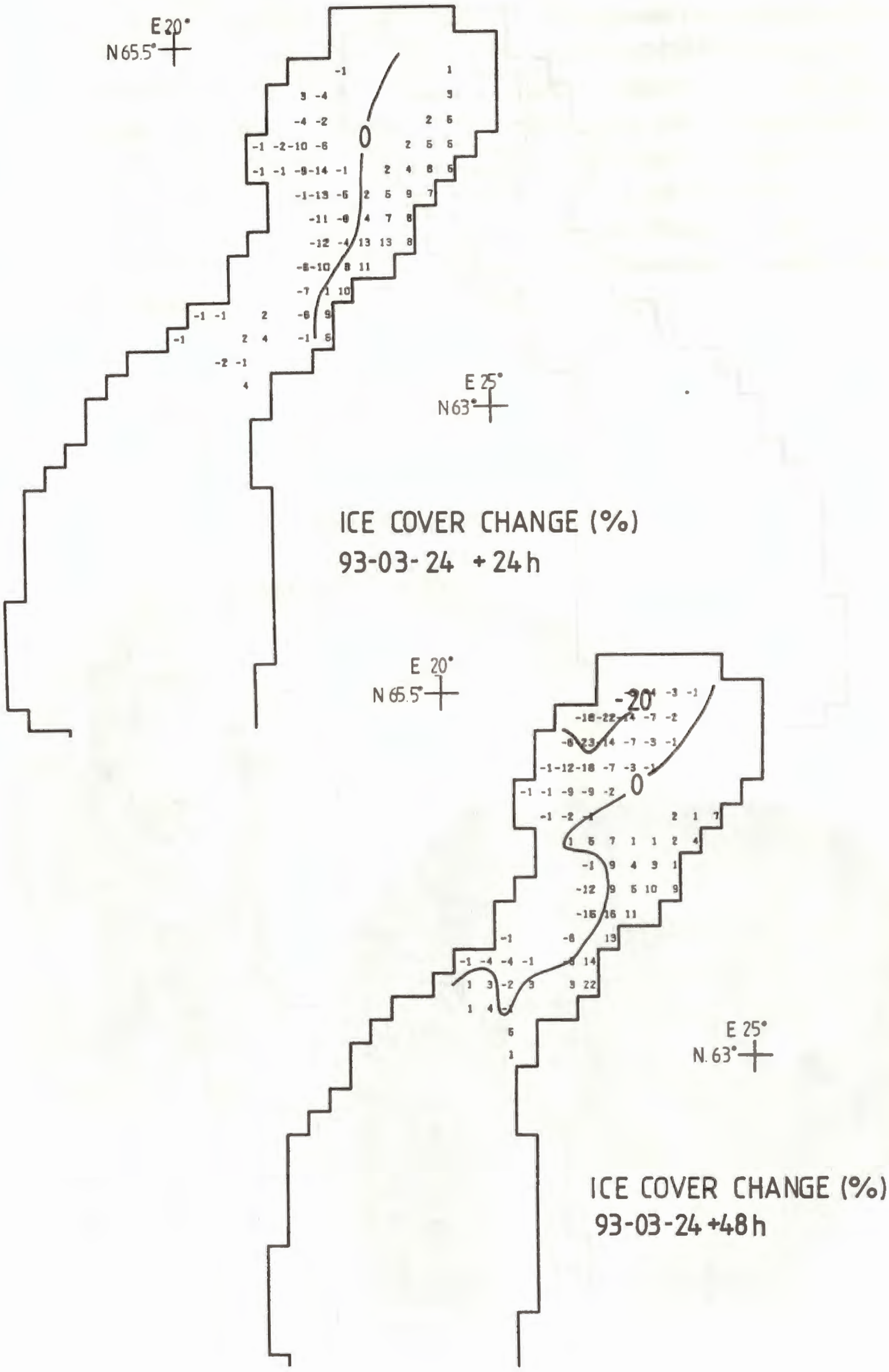

Figure 9. *An operational forecast of changes in ice concentrations in the Bothnian Bay from March 24, 1993. The maps show forecasted changes in ice concentration between March 24 - 25 and March 25 - 26, respectively.*

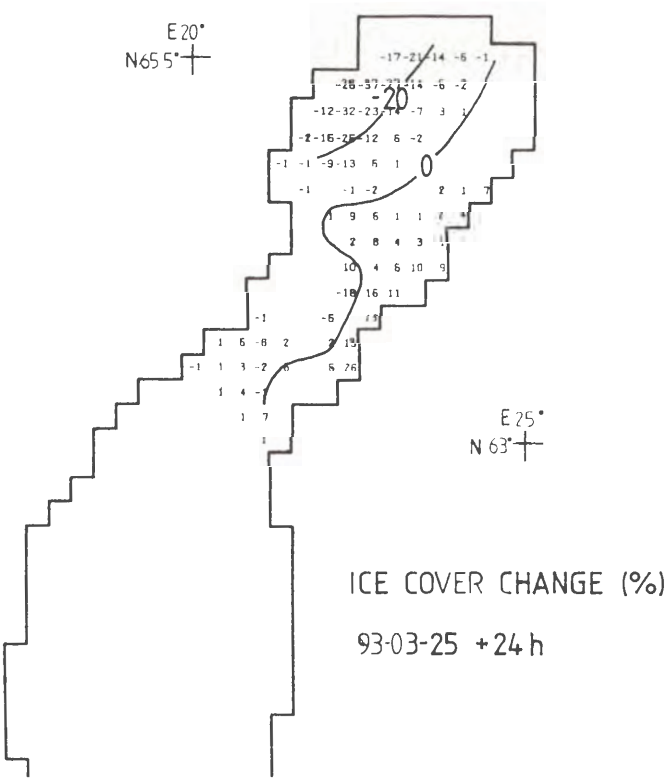

Figure 10. An operational forecast of changes in ice concentrations in the Bothnian Bay from March 25, 1993. The map shows forecasted changes in the ice concentration between March 25 and 26.

5. DISCUSSION

The atmosphere, the sea ice and the sea constitute a physical system with strong coupling. For a proper simulation and forecasting, coupled models are needed. In this paper we have presented a coupled ice-ocean model for the prediction of sea ice drift and water levels. The reducing effect on water level variations during severe ice conditions and the influence of the currents on the ice drift, particularly in straits, are two important features of the model. From operational tests during the mild winter of 1992/93, it has been demonstrated that the model is most useful. Some numerical diffusion was observed, that may require a higher resolution in the future, but the numerical code was stable and safe. The meteorological forcing were taken from the HIRLAM system. The HIRLAM system was, however, not coupled to the ice-ocean model, and it also treated the sea ice in the Baltic Sea in a rough way. In future it is therefore of main importance to couple HIRLAM closer to the ice-ocean model and to improve the atmosphere-ice parametrization in HIRLAM.

Thermodynamic processes as cooling, ice formation, ice growth and melting, were not dealt with in the model. Even though thermodynamic processes often are slower than the dynamic ones, it is important to incorporate them in the future. For example, during early winter ice formation may rapidly cover the sea. In general, models that neglect thermodynamic processes are only good at mid winter periods. Another important argument for introducing thermodynamics is that the calculations can be better used as initial data for the next day's forecast. During the winter of 1992/93 the initial data were manually digitized, this is a time-consuming work, and more automatic methods for creating initial data to the model need also to be developed.

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