BALTIC SEA MODELLING INCLUDING COUPLED ICE-OCEAN AND ICE-OCEAN-ATMOSPHERE MODELS

Andreas Lehmann
Institute of Marine Research, Kiel
Germany

Abstract

Understanding the role of the Baltic Sea in energy and water cycles requires models for the relevant transport processes. Models must be capable of accurately representing the response of currents and sea level to direct forcing by wind, and by wind-induced changes of sea level in the Kattegat leading to exchange flows through the Danish Straits. The models must further describe the response of the circulation to forcing by river runoff, precipitation/evaporation and by melting/freezing, with specific emphasis on freshwater budget and thermohaline circulation. A quantification of the energy and water cycle requires the utilization of coupled numerical systems. After 4 years of BALTEX research it is now useful to review the progress in modelling and give an outlook of future requirements and developments.

1. Introduction

The investigation of the energy and water budget of the Baltic Sea and its catchment area is one main aim of BALTEX. The understanding of the role of the Baltic Sea in energy and water cycles requires models for the relevant transport processes. The models must describe the response of the circulation to forcing by river runoff, precipitation/evaporation and by melting/freezing with specific emphasis on the freshwater budget and thermohaline circulation. Due to the strong interaction of atmosphere, ice and ocean a quantification of the fluxes between the components requires the utilization of coupled numerical systems. From the oceanographic point of view, the components ice, ocean and atmosphere are strongly interacting, whereas, to the hydrology less distinct re-coupling exists. The atmosphere provides the forcing for the ice-ocean system, namely, momentum, salt and heat fluxes which include precipitation, evaporation and radiation. A re-coupling of the ocean to the atmosphere is provided by sensible and latent heat fluxes. In case of sea ice, the oceanic heat flux to the atmosphere is strongly reduced or even prevented. However, the back-scattered short-wave radiation is strongly affected by the increased albedo. In case of open water, the atmospheric fluxes can act directly on the ocean surface, and in case of ice, the fluxes act on the ice surface and the ocean receives a modified forcing, depending on ice dynamics, thickness and compactness. The ocean, in turn, supplies heat and momentum fluxes to the lower ice surface, thereby strongly modifying the ice evolution. The net fresh water flux which is a combination of evaporation/precipiation and river runoff is a further component which has a strong impact on the water mass exchange with the North Sea and the salinity distribution within the Baltic Sea (Fig. 1). River runoff has a regional impact on the local salinity distribution and also affects due to its volume flow and dynamics the transports through the Danish Straits.

After 4 years of BALTEX research, it is now useful to review the progress in modelling and give an outlook of future requirements and developments. In view of BRIDGE, the Main BALTEX Experiment (1997), which is planned to take place from April 1999 to March 2001, it is important to identify deficiencies in the numerical models and try to remedy most of the problems during the preparation phase of the experiment.

Following the BALTEX Implementation Plan, a number of oceanographic modelling projects were planned, which will be discussed in the following.

- Baltic Sea response to atmospheric and hydrological forcing

- Development of a coupled ice-ocean model for the Baltic Sea
- Thermohaline circulation and long-term variability of the Baltic Sea
- Development of a coupled atmosphere-ice-ocean model of the Baltic Sea

In general, modelling activities appear to be in a good shape and progress, except three-dimensional model simulations of the thermohaline circulation and long-term variability of the Baltic have not been started yet. However, first results from a 15 year integration with the process model PROBE-Baltic (Omstedt and Nyberg, 1996) has been recently presented. The three-dimensional ocean modelling in the oceanograpphc community of the Baltic Sea is mainly based on the GFDL-type ocean model (Geophysical Fluids Dynamics Laboratory; Bryan, 1969; Cox, 1984; Semtner, 1974; Killworth et al. 1991) with a free surface and the modular descendants MOM 1 & 2 (Modular Ocean Model). But there are also other models available which differ more from technical aspects such as grid-types (B- and C-grid), the vertical discretization (z-, sigma-coordinates or sigma layers), the horizontal resolution than from the physics involved. A comparison of the different models could be helpful to explore the specific potential of the different verisons. Up to now, no such model intercomparison has been scheduled for the oceanographic models applied to the Baltic Sea.

With respect to oceanographic data assimilation which is also a part of the Baltic Sea modelling the situation is less encouraging, there is no ocean general circulation model available which assimilates the full range of hydrographic observations.

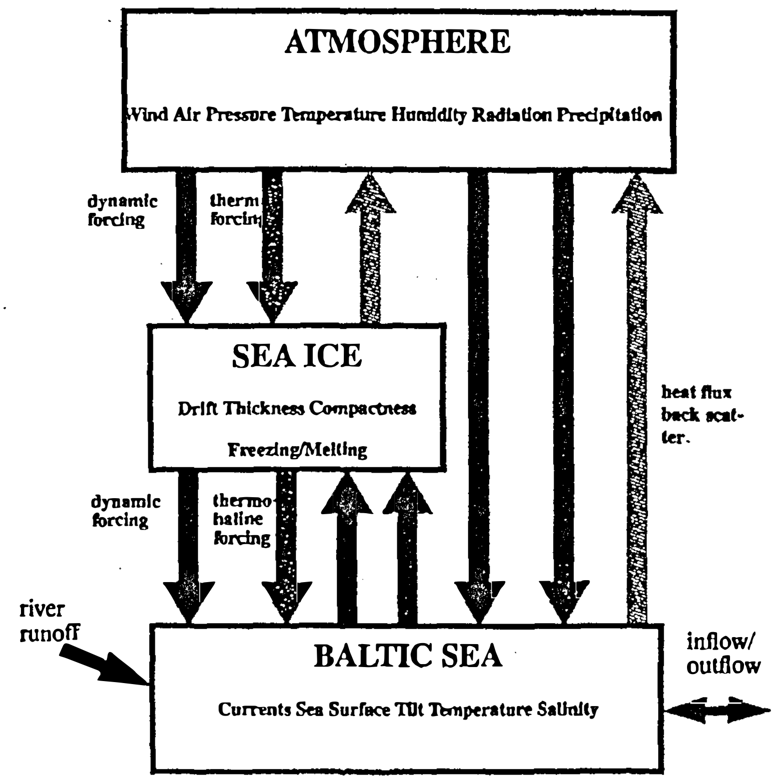

Figure 1: Fluxes in a coupled atmosphere-ice-ocean model

2. Baltic Sea response to atmospheric and hydrological forcing

The modelling efforts within BALTEX are directed towards the development and verification of models which describe relevant components of the energy and water cycle in the BALTEX region. The models must be suitable to describe the physical state of the Baltic Sea in response to atmospheric and hydrological forcing, including its variability on time scales from weeks to decades, on spatial scales ranging from 10-20 km to the entire basin size. With respect to the water budget, the models must be able to describe the transport of water and salt through the Danish Straits which requires an understanding of the dynamics of the in- and outflow processes and of the thermohaline circulation and mixing processes which determine the long-term distribution of water masses in the Baltic Sea. Besides short-term modelling of specific hydrographic situations with reasonable initial conditions for the sea state, simulations which cover time scales from years to decades need at least ice to be additionally considered.

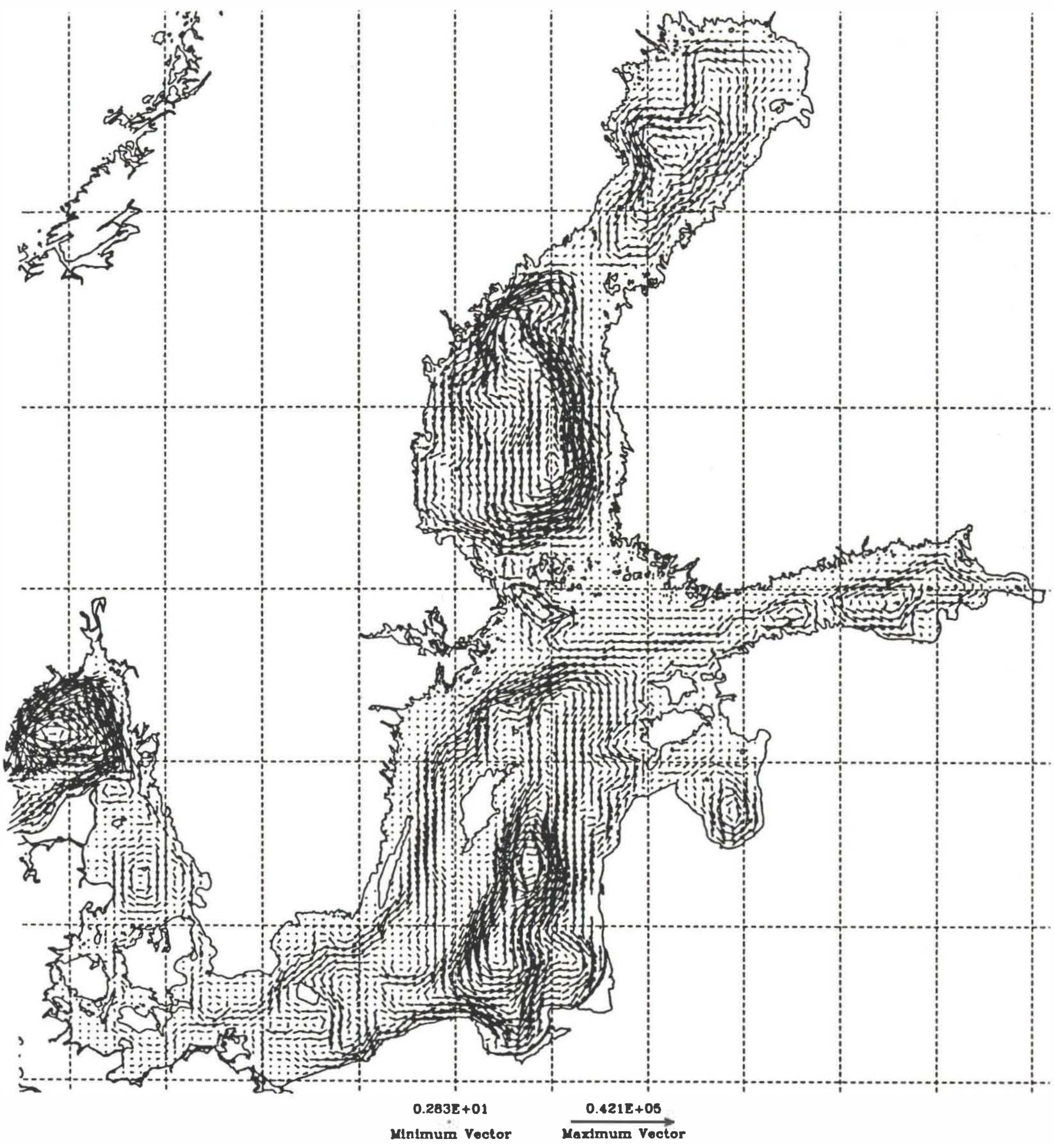

Figure 2: *Annual average of the barotropic circulation [m^3/s] for 1992*

The years 1992/93 which were chosen to be of particular interest for BALTEX have been simulated extensively. Lehmann (1997) presented results from an uncoupled run of the Kiel Baltic Sea model which was forced by atmospheric data provided by the Europa-Model (EM; Majewsky, 1991) of the German Weather Service (DWD, Deutscher Wetterdienst Offenbach) and river runoff (Bergström and Carlsson, 1994). The model was integrated for the years 1992/93 starting in Januray 1992 from initial distributions of temperature and salinity which represented a typical winter situation in the Baltic Sea. From the model run, mean circulation and averaged volume transports were calculated (Fig. 2). The annual mean of the barotropic circulation for the specific years shows only minor deviations. The circulation in the Baltic Proper is determined by a cyclonic circulation pattern comprising Bornholm and Gotland Basin, with water entering by a branch from the Gulf of Finland and through the Åland Sea. Through the Bornholm Gat water is leaving this circulation cell with a further flow through the Arkona Sea and the Danish

Straits feeding the Baltic Current. Within the subbasins, there are cyclonic circulation patterns with the net transport between the basins is determined by the river runoff into the subbasin, each. The internal barotropic circulation between Gotland and Bornholm Basin ($1000 - 2000\,km^3/year$) is about an order of magnitude higher compared with the total river runoff to the Baltic Sea ($470\,km^3/year$). On the annual average, the water volume which is supplied by the river runoff leaves the Baltic Sea through the Danish Straits. Thus, the net volume flow from the Baltic Sea into the North Sea corresponds to the river runoff modified by the net effect of precipitation minus evaporation. The rates of evaporation and precipitation for the year 1993 are dislayed in Fig. 3. The precipitation rates were prescribed from monthly mean values (Dahlström, 1986), whereas, the evaporation rates were diagnostically calculated from atmospheric parameters and from the simulated sea surface temperatures. The simulated mixed layer temperatures were verified against SST's observed from satellite. The evolution of the mixed layer temperature was satisfactorily simulated by the model. However, during spring and summer modeled sea surface temperatures lay 1-3 ^0C below the observations. Thus, the calculated evaporation rates underestimated the real conditions. The simulated total annual volume flow out of the the Baltic Sea for 1993 amounted to $\sim 495\,km^3$ including $22\,km^3$ from the precipitation surplus.

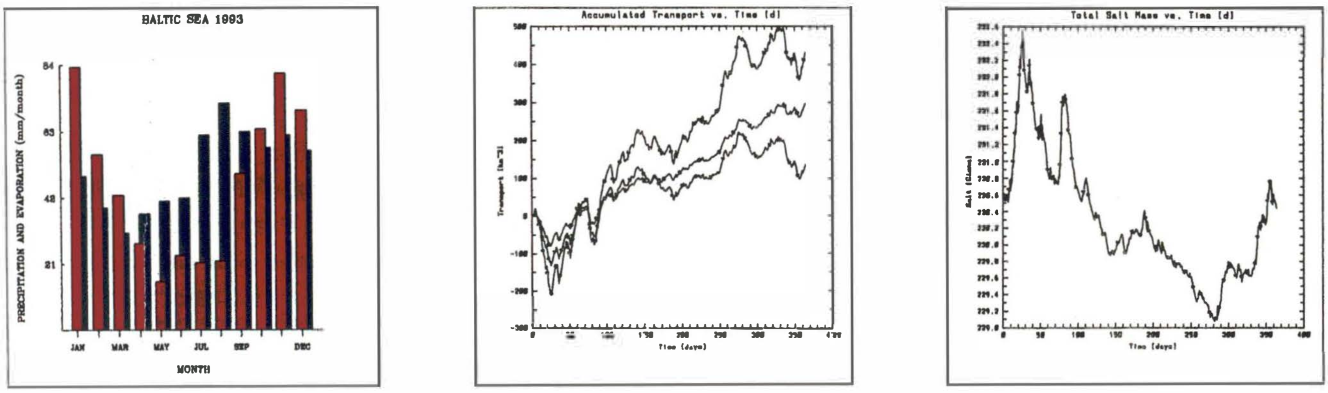

Figure 3: *Left:Rates of precipitation (blue) and evaporation (red) [mm/month] of the total Baltic Sea for 1993. Precipitation rates are taken from Dahlström, 1986. Middle and right: Accumulated volume transport through the Danish Straits (A:Sound, B: Great belt, C: total) and total salt content of the Baltic Sea for 1993.*

The model results give a first estimate of the heat, salt and water budget of the Baltic Sea (Fig. 3), however the results show also the limitation of the simulation. Compared with observations, the accumulated transports through the Danish Straits for the year 1993 are underestimated by the model, and hence the salt flux into the Baltic Sea is also underestimated. Three aspect are mainly responsible for uncertainties in the simulation of the volume and salt transport. Firstly, EM surface wind data underestimate the real conditions espically for high wind speeds. Secondly, the western boundary condition of the ocean model (Lehmann, 1995) fails in case of strong wind forcing from western directions, i.e. the pile-up of water in the Kattegat is not satisfactorily simulated. Thirdly, the initial conditions for temperature, salinity and sea surface elevation represent mean values for a typical winter situation, they cannot be prescribed from observations for the whole Baltic Sea. To remedy these deficiencies, a better representation of the atmospheric parameters is necessary which may be achieved by coupled atmosphere-ice-ocean models, and additionally, the western boundary condition must be improved to simulate the fluctuations of the sea surface elevation in the Kattegat more realistically. Furthermore, assimilation of hydrographic parameters into the model could improve the simulation.

A further problem of three-dimensional baroclinic modelling is the parameterization of the vertical turbulent mixing. Meier (1997) compared different turbulence closure schemes for a three-dimensional regional model of the western Baltic Sea. The most sophisticated mixed layer model seems to be the $k - \epsilon$ turbulence model. Additionally, two prognostic equations for the turbulent kinetic engery (TKE) and the dissipation of TKE have to be solved at every grid point of the three-dimensional model. Compared to the Richardson number dependent parameterization which underestimates the mixed layer depths, the second moment turbulent closure model improves the mixed layer dynamics considerably (Fig. 4).

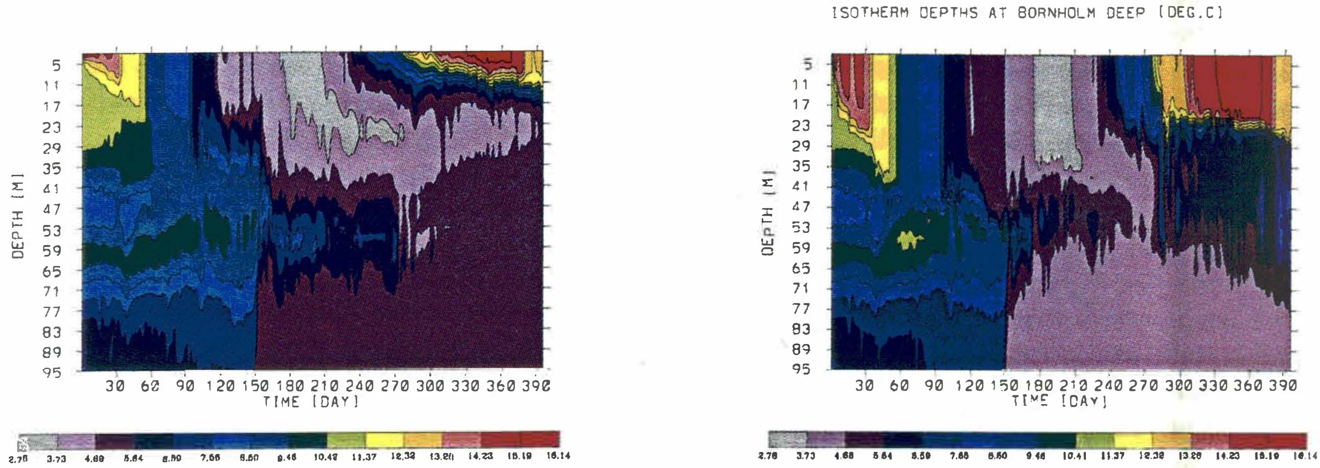

Figure 4: *Isotherm depths (in °C) at Bornholm Deep from September 1992 to September 1993; left: Richardson dependent friction parameterization; right:* $k-\epsilon$ *turbulence model (Meier, 1997).*

3. Development of a coupled ice-ocean model of the Baltic Sea

The circulation of the Baltic Sea and the water mass exchange with the North Sea are influenced by ice coverage during the winter season. Ice occurs annually in the Baltic. On average the annual maximum sea ice extent is 45% and the length of the ice season is 6 months in the northern parts. Ice plays a major role at the air-sea interface and largely modifies the momentum transfer and the exchange of heat, freshwater and other materia between atmosphere and ocean. Freezing and melting of ice have also notable effects on the stratification of the Baltic Sea water masses. Thus, including thermodynamics and dynamics of sea ice is essential for a realistic description of the annual cycle of the external forcing of the Baltic Sea.

The Baltic Sea is located in the Seasonal Ice Zone with first year ice forming every year. During the last 100 years the maximum ice extent has ranged from 12 to 100 % and the length of the ice season varied from 4 to 7 months. First ice appears in the innermost bays of the Bothnian Bay during mid-November. In a normal winter, the entire Bothnian Sea, Sea of Åland, Gulf of Finland and the northernmost part of the Baltic are also covered by ice. In severe ice-winters additionally the Kattegat, the Belt Sea, the Sound and large parts of the Baltic Proper are ice covered. Several different types of ice are found at sea. As the ice moves with currents and winds, leads (openings in sea ice) and ridged ice are formed. Due to the mechanical deformation, the sea ice becomes rough and ice keels of several meters deep (5-15 m) are frequent with deep keels up to 28 m have been measured in the Bothnian Bay. During calm conditions, columnar ice starts to grow when cooling has passed the freezing point. The ice growth is, however, most sensitive to snow which reduces the growth rate. During windy conditions, frazil ice forms which may generate pancake ice. Old ice, which is melting, is usually called rotten ice and has a much reduced albedo compared to snow covered sea ice.

As can be seen from the description above, sea ice is a complex physical component of the Baltic Sea. For a realistic simulation of the circulation of the Baltic Sea and the water mass exchange with the North Sea, sea ice and its coupling to the ocean has to be considered. Sea ice is a rather rigid film of complex morphology at the ocean-atmosphere interface. It strongly modifies the fluxes between ocean and atmosphere. In recent years, several ice models and coupled ice-ocean models of the Baltic Sea have been developed (Omstedt and Nyberg, 1996; Haapala and Leppäranta, 1996; Kleine and Skylar, 1996; Schrum, 1997; Lehmann, 1997). Within the EU-MAST project BASYS (Baltic Sea System Study) the Subproject 6 (Baltic Sea Ice) has the aim to couple and systematically improve an eddy-resolving general circulation model of the Baltic with an ice model and compare its results with observations from field cruises and satellite data. In a systematic assessment, the ability of the coupled ice-ocean model to reproduce currents and stratification in the basins of the Baltic, ice formation, coverage, drift and melting will be investigated. BASYS/SP6 will simulate and compare mild, normal and servere winters (mild: 1992/93, normal:1993/94, severe: 1986/87).

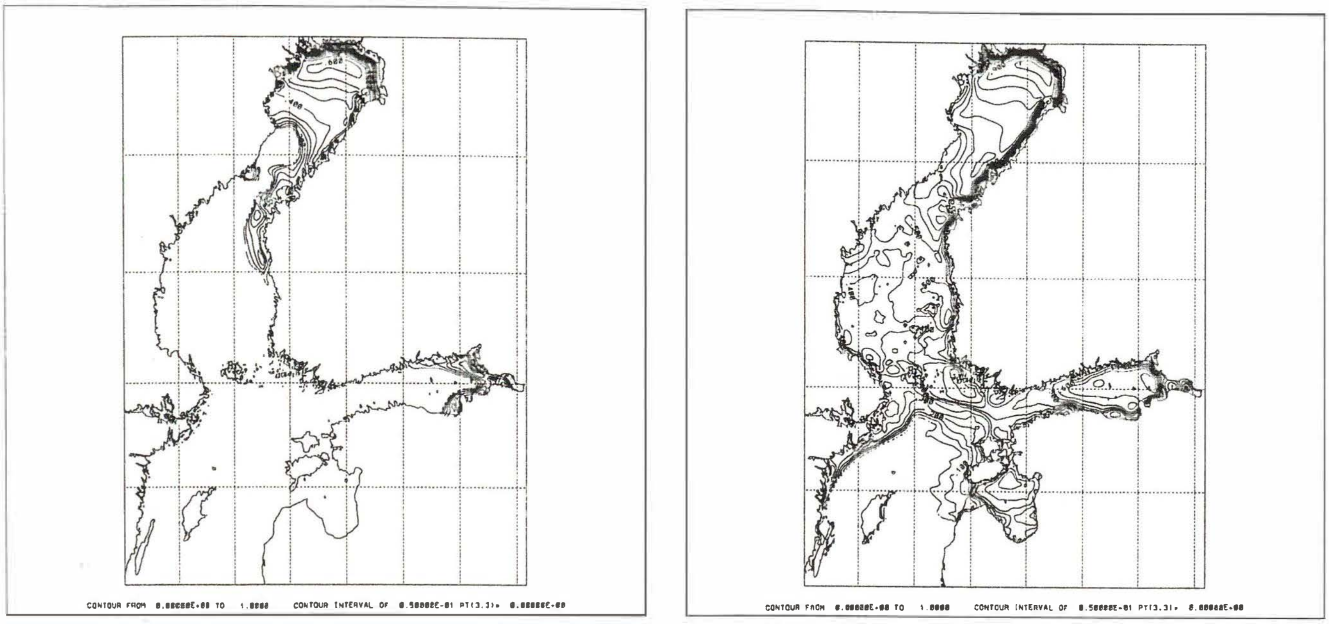

Figure 5: *Ice thickness (in m) for the mild winter 1992 (left) and the normal winter 1994 (right) from coupled ice-ocean simulations.*

Ice thicknesses and ice edges for the winters 1992 (mild) and 1994 (normal) at the end of February are displayed in Fig. 5. Both simulations were started from Januray with the same initial oceanic temperature and salinity distribution, but were forced with the corresponding atmospheric forcing provided by the SMHI data base. The simulated ice edges and thicknesses are in good agreement with observed ice conditions, however the ice extent for February 1992 is slightly overestimated. The specific atmospheric conditions are controlling the ice evolution, whereas the initial heat content of the Baltic Sea and the corresponding oceanic heat flux are of secondary importance.

4. Thermohaline circulation and long-term variability of the Baltic Sea

In order to understand the mean circulation and water mass distribution as a consequence of highly variable atmospheric forcing, river runoff and the water mass exchange with the North Sea, integrations over 10-20 years should be performed. Three-dimensional simulations of the thermohaline circulation of the Baltic Sea require a huge amount of computer power and resources. The investigation of the long-term variability of the Baltic Sea needs at least a reasonable understanding and modelling of mesoscale and mixing processes within the Baltic Sea and the water mass exchange with the North Sea. This demands a horizontal resolution of the three-dimensional models at least in the order of the internal Rossby Radius, and a high vertical resolution which allows a reasonable description of the flow of dense saline water intruding into the Baltic Sea and its further flow as a dense bottom current. The horizontal advection and diffusion of saline water maintains the perennial haline stratification in the central Baltic Sea. Three-dimensional simulations which have been performed so far (e.g. Lehmann, 1995 & 1997; Schrumm, 1997) show the basic weakness, to maintain the haline stratification after intergrations of one or two years which is mainly a result of a wrong or underestimated description of the water mass exchange with the North Sea. To remedy this problem, Meier and Krauss (1995) prescribed in a regional model of the western Baltic Sea observed sea surface elevations and vertical salinity distributions along the models boundary in the northern Kattegat. The water mass exchange, in terms of volume flows, between Kattegat and the Baltic Sea is mainly driven by the instantaneous sea level difference between these seas. Thus a knowlegde of the along-strait gradient of sea level determines together with the stratification and corresponding baroclinic flows the advection of salt into the Baltic Sea. However, sea level data for long-term investigations of the thermohaline circulation in the Baltic Sea are not always easy available. Furthermore, the sea surface inclination of any cross-section through the Baltic Sea or the Kattegat/Skagerrak area is not a linear function. Data assimilation methods could be helpful to improve the simulation of sea level and hence the volume tranport through the Danish Straits (Meier and Krauss, 1995).

While three-dimensional circulation models suffer from the correct simulation of advective-diffusive processes which determine the thermohaline circulation and its long-term variability of the Baltic Sea, process models which are much faster than three-dimensional models could be helpful for comparison and process studies (Omstedt and Nyberg, 1996). The model PROBE-Baltic has been run for 15 years, starting from 1 November 1980. The model treats the Baltic Sea as 13 sub-basins with high vertical resolution, horizontally coupled by estuarine and barotropic circulation and vertically coupled to a sea ice model which includes both dynamic and thermodynamic processes. The results (Fig. 6) indicate that the main physical processes as in- and outflows as well as vertically and frontal mixing and river runoff were treated in a realistic way. Furthermore, the seasonal maximum ice extent could be well captured by the model.

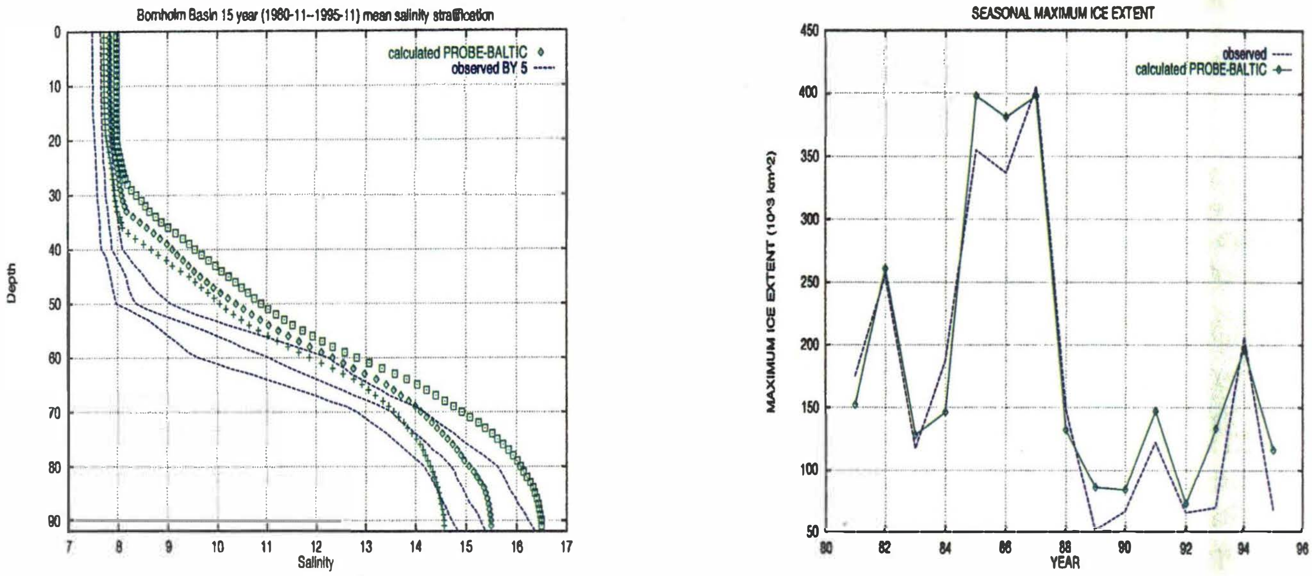

Figure 6: *Left: Median salinity profiles based upon observations and calculations from 1 November 1980 to 1 November 1995. The curves are medians, the first and third quartiles. Right: Observed and calculated seasonal maximum ice extent for the Baltic Sea. (Omstedt and Nyberg, 1996; Omstedt, 1997)*

5. Development of a coupled atmosphere-ice-ocean model of the Baltic Sea

One of the main aims of the modelling efforts within BALTEX is to develope a complete coupled atmosphere/ocean/land surface model. Some progress has been achieved since the last BALTEX Science meeting. The evolution of a complete system including the components atmosphere, ice/ocean and land is twofold. One branch is directed to a better understanding of the coupling of the land surface models to the atmosphere, and the other aims at the coupling of atmosphere with ice-ocean models.

At the SMHI, a high resolution weather forecasting model has been coupled to an advanced 2.5-dimensional ice-ocean model. The ice-ocean model includes two-dimensional, horizontally resolved ice and storm surge models and a one-dimensional, vertically resolved ocean model applied to 31 Baltic Sea regions. The coupled model system is applied operationally at the SMHI. From case studies it could be demonstrated that improvements of short range weather forecasting in the area of the Baltic Sea require an accurate description of the lower boundary condition over sea. Sea state variables used in the model influence the weather forecast both directly on the local scale due to the local impact of the surface fluxes of sensible and latent heat, and on the regional and larger scales. The convective snow bands during winters with cold air mass outbreaks over the open water of the Baltic Sea are extreme examples of the influence of sea state variables on the regional scale (Gustafsson et al., 1997).

In a joint effort, the Kiel Baltic Sea model has been coupled to the atmospheric model REMO (Regional Model) of the MPI Hamburg (Jacob and Podzun, 1997; Hagedorn et al, 1997). The three-dimensional model REMO is based on the operational forecast model of the DWD. It is used in the so-called climate mode with the physical paramterizations which are implemented in the Europa-Model. The horizontal resolution is $1/6°$ on the rotated longitude/latitude grid. This is equivalent to approximately $18x18\,km^2$. The Kiel Baltic Sea Model is a three-dimensional eddy-resolving baroclinic model with a horizontal resolution of approximately $5x5\,km^2$ (Lehmann, 1995 & 1997). For a reference run, these two models have been run seperately and both were forced by DWD analysis or forecasts, respectively. The models were two-way coupled via the fluxes of heat, water and momentum (Fig. 1). The coupled atmosphere-ocean system has been applied to the PIDCAP period (July-October 1995). From the coupled simulation, it turned out that the sea state variables influence the evolution of the regional climate over the Baltic Sea even if the simulation period is so short. While the basic structures of the pressure field were hardly affected by the difference in heat fluxes compared with the reference run (SST's from DWD analysis), there were remarkable deviations in the surface wind field and precipiation patterns.

6. Concluding remarks

During recent years much progress in Baltic Sea modelling has been achieved. In view of BRIDGE, coupled ice-ocean and atmosphere-ice-ocean models will be available for the simulation of the energy and water cycle of the Baltic Sea. The most challenging task for the oceanographic modelling community will be the investigation of the thermohaline circulation and long-term variability of the Baltic Sea on the time scale of decadal climate variability. To simulate the water mass exchange with the North Sea and to describe turbulent and mesoscale processes in the Baltic Sea, three-dimensional models with high vertical and horizontal resolution are necessary. But this requires an enormous amount of computer power and resources. The Kiel Baltic Sea coupled ice-ocean model with a horizontal resolution of 5 km and 28 vertical levels needs at least 240 CRAY-T90 CPU hours for the simulation of one year. To cover the whole spectrum of mesocale processes a grid refinement especially for the area of the Danish Straits and an extension of the model area to the whole North Sea would be necessary, but at the moment this is not feasible with available computer power. Furthermore, long-term simulations may require the utilization of assimilation methods which, additionally, will increase the requirments on computer power. However, less expensive methods such as nudging or partial re-initialisation of temperature and salinity fields by observations into a current model run are available and may be used to improve the simulation of the thermohaline circulation and its long-term variability.

While process models seem to reproduce fairly well thermohaline structures and the long-term variability of the Baltic Sea, three-dimensional baroclinic models suffer from the realistic description of advective-diffusive processes. It should be noted that process models such as the PROBE-Baltic have specific as well as general limitations. The horizontal resolution is limited by the number of specified thermodynamic basins. A refinement of these regions is one possiblitiy but on the long-term objective three-dimensional horizontally resolved models are necessary which are able to resolve the mesocale dynamics of the Baltic Sea.

With respect to coupled atmosphere-ice-ocean modelling, the progress achieved so far is encouraging, so that for BRIDGE coupled atmosphere-ice-ocean models will be available.

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