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Modeling the seasonal, interannual, and long-term variations of salinity and temperature in the Baltic proper

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ABSTRACT

Salinity and temperature variations in the Baltic proper and the Kattegat have been analyzed with a numerical ocean model and a large amount of observational data. In the model, the Baltic Sea is divided into 13 sub-basins with high vertical resolution, horizontally coupled by barotropic and baroclinic flows and vertically coupled to a sea-ice model which includes dynamics as well as thermodynamics. The model was integrated for a 15-year period (1980–1995) by using observed meteorological forcing data, river-runoff data and sea-level data from the Kattegat. The calculated 15-year median profiles of salinity and temperature in the different sub-basins are in good agreement with observations. However, the calculated mid-depth salinities in the Arkona Basin and Bornholm Basin were somewhat overestimated, and the calculated deep-water temperatures in the Arkona Basin and the Bornholm Basin are somewhat lower than the observed values. Frontal mixing and movements in the Kattegat and the entrance area of the Arkona Basin were important to consider in the model. Water masses were simulated well, and prescribing constant deep-water properties in the Kattegat proved to be a reasonable lateral boundary condition. Further, comparisons were made between observed and calculated seasonal and interannual variations of the hydrographic properties in the Eastern Gotland Basin, as well as the interannual variations of the annual maximum ice extent. We conclude that the model can simulate these variations realistically. The major Baltic inflow of 1993 was also simulated by the model, but the inflowing water was 1–2° degrees too cold. Finally, the response times to changes in forcing of the Baltic proper and the Kattegat were investigated by performing the so-called lock-exchange experiment. Typical stratification spin-up times were of the order of 10 years for the Kattegat, and 100 years for the Baltic proper.

1. Introduction

Studies of energy and water cycles have a long tradition in the countries surrounding the Baltic Sea. The latest large international effort to investigate the water cycle of the Baltic Sea, in particular in terms of long-term means, was summarized by the Helsinki Commission in 1986 (HELCOM, 1986). However, the water cycle was only studied with simple budget calculations, without the use of ocean models, and without considering the energy cycle or the feedback mechanisms in the system. New efforts are now being made to increase our understanding of the energy and water cycles of the atmosphere-land-ocean system, e.g., the Baltic Sea Experiment (BALTEX, 1995), and new ocean models are under development. Most earlier ocean models have only been designed to study specific aspects of the Baltic Sea, and therefore only a few are yet available that can simulate the main features of the energy and water cycles; see below.

The Baltic Sea is a large inland sea, with positive water balance and restricted exchange through the narrow and shallow connections (the Öresund

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and the Belt Sea) to the Kattegat (Fig. 1). Sea ice is formed every year and the weather as well as river and meteorological fresh-water input and inflows through the entrance area show large seasonal, interannual, as well as decadal variations (Bergström and Carlsson, 1994; Elken, 1996; Fischer and Matthäus, 1996; Fonselius, 1969; Matthäus and Franck, 1992; Omstedt and Nyberg, 1996; Omstedt et al., 1997). The coupling between the atmosphere and the Baltic Sea is strong (Gustafsson et al., 1998), and variations in the forcing has thus a large impact on the Baltic Sea.

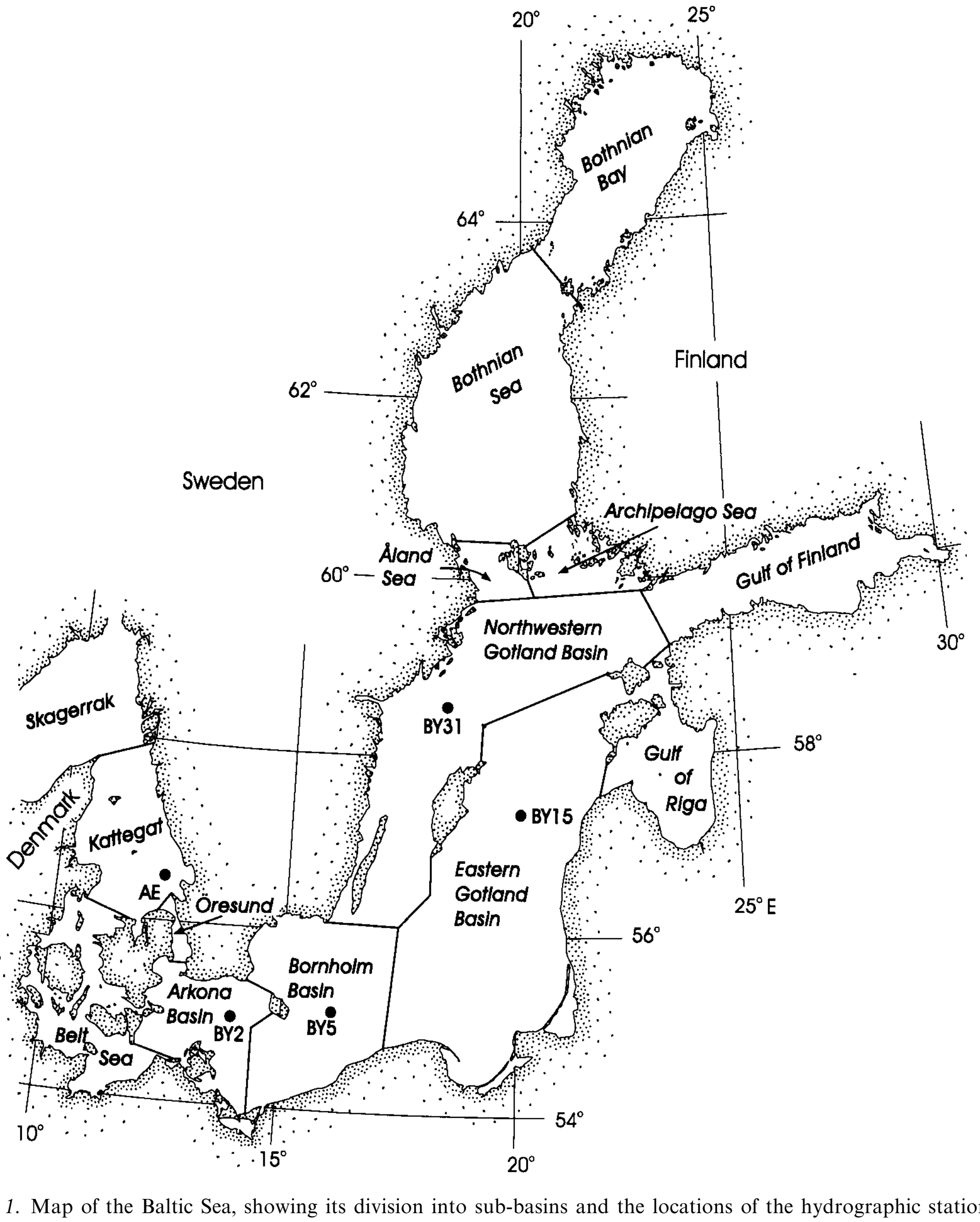

Fig. 1. Map of the Baltic Sea, showing its division into sub-basins and the locations of the hydrographic stations used in the study.

Within a sea-ice climate modeling program for the Baltic Sea (Haapala et al., 1993), some Baltic Sea models including sea ice have been developed. Haapala and Leppäranta (1996; 1997) examined the sensitivity of the Baltic Sea ice with a simple analytical sea-ice model and a coupled two-dimensional ice-ocean model. Howver, they neglected the exchange with the Kattegat. A model system for the forecasting of sea ice and water levels on shorter time scales has been developed by Omstedt et al. (1994) and Omstedt and Nyberg (1995). Moreover, Gustafsson et al. (1998) developed a two-way coupled atmosphere-ocean system. Also in this case the Baltic Sea was treated as a closed basin. A three-dimensional Baltic Sea model, including sea ice and coupling to the North Sea, is in operational use for daily short-range forecasts at the Bundesamt für Seeschiffahrt und Hydrographie in Hamburg and at the Swedish Meteorological Institute (Huber et al., 1994). Schrum (1997) presented a coupled three-dimensional ice-ocean model of the Baltic Sea and the North Sea. The model was run for one year, including one winter (1983/1984) with normal ice extent. The three-dimensional Baltic Sea model by Lehmann (1995) considers the exchange between the Baltic Sea and the North Sea and has been verified with observations from the major Baltic inflow in January 1993. A regional high-resolution three-dimensional model for the western Baltic Sea has also been developed by Meier (1996). This model was used for process studies as overflow and mixing.

For long-term and climate studies, Omstedt and Nyberg (1996) developed the ocean model PROBE-Baltic, where they treated the Baltic Sea and the Kattegat as 13 sub-basins with high vertical resolution, horizontally coupled by barotropic and baroclinic flows and vertically coupled to a sea-ice model which includes dynamics and thermodynamics. The model has been verified extensively for a 15-year period with respect to sea ice, sea surface temperature and meteorological fresh-water inflow (precipitation minus evaporation) (Omstedt et al., 1997) and has been used for climate studies as well.

Long-term variations of the Baltic Sea have also been analyzed by Stigebrandt (1983, 1987) and Gustafsson (1997a) using process-oriented models for the water and salinity exchange between the Baltic Sea and the Kattegat.

Some of the models mentioned above have focused the verification on special winters as well as the major inflow event to the Baltic Sea in the beginning of 1993. A realistic simulation of the severe ice winter 1986/1987 as well as the mild winter 1992/1993 including the major inflow in January 1993, should be a good first test of models intended for studies of the energy and water cycles within the Baltic Sea, as well as for models intended for climate-impact studies. In a second stage, however, one also needs to consider interannual and long-term variations. The model by Omstedt and Nyberg (1996) simulates the time period 1980–1995, a period which includes mild, normal and severe winters as well as the major Baltic inflow in the beginning of 1993 and should therefore be a good candidate for long-term studies.

The aim of the present investigation was to analyze how well we can simulate seasonal, interannual and long-term variations of the energy (temperature) and water (salinity) cycles using the Baltic Sea model by Omstedt and Nyberg (1996). The focus of the paper is on the vertical structure of temperature and salinity in different regions of the Baltic proper and the Kattegat. First the 15-year median profiles of salinity and temperature are verified by comparison with a large amount of data from research vessels. Then the observed and numerically calculated temperatures and salinities are compared, and the quality of the model simulations is assessed by simulating the major inflow of 1993 to the Baltic Sea. Finally, some long-term model runs and implications are presented.

The model and some details of the calculations are presented in Subsection 2.1, and information about the verification data is given in Subsection 2.2. The comparison between observed and modeled data is discussed in Section 3. Model implications based upon long-term runs are then presented in Section 4, and finally, in Section 5, a summary is given along with some conclusions.

2. Material and methods

2.1. Model elements and details of calculations

In the model by Omstedt and Nyberg (1996), the Baltic Sea is divided into 13 sub-basins (Fig. 1) and the properties of each sub-basin are calculated with the horizontally averaged, time-dependent, advective-diffusive conservation equations for temperature, salinity, and momentum, as well as the conservation equations for volume and ice. Further, each sub-basin is coupled to surrounding sub-basins via horizontal flows. A full description of the model is given in Omstedt and Nyberg (1996) and will not be repeated here. However, some improvements of the model have been introduced, as frontal mixing in the entrance area of the Baltic Sea; see further details below.

The model was run for a 15-year period, namely from 1 November 1980 to 1 November 1995, and the initial profiles were approximated from available oceanographic measurements. The energy (temperature) and water (salinity) cycles were calculated by using meteorological forcing fields of wind, air temperature, moisture, and total cloudiness. The meteorological data were extracted every three hours from seven synoptic stations, and were used for the coupling between air and water. The air drag coefficient was put as a function of the wind speed W $[0.8 \times 10^{-3} + 0.065 \times 10^{-3} \times \max(W, 7.5)]$ according to The WAMDI Group (1988).

The lateral boundary conditions were modeled by using daily means of observed sea-level data in the Kattegat and prescribed long-term means of deep-water salinity and temperature in the Kattegat. Monthly means of river runoff, Q_f, and long-term means of meteorological runoff, $P - E$, to each sub-basin were adopted from Bergström and Carlsson (1994) and Omstedt et al. (1997), respectively.

All sub-basins were included in the calculations, but in the present paper only the results from the Kattegat and the Baltic proper (the Arkona Basin, the Bornholm Basin, the Eastern Gotland Basin and the Northwestern Gotland Basin; Fig. 1) were analyzed.

The fresh-water input was treated as a flow running through all sub-basins, adding up the river runoff from the different sub-basins. In addition to the fresh-water input, some baroclinic flows were included in the model that were assumed to be controlled by the stratifications in the upstream sub-basins; see Omstedt and Nyberg (1996). They were calculated at specific transition areas, e.g. between the Kattegat and the Skagerrak, above the Darss Sill, the Bornholm Channel, and the Stolpe Channel. In the Bornholm Channel the sill depth was assumed to be 41 m (Liljebladh and Stigebrandt, 1996), whereas the sill depths at Darss Sill and in the Stolpe Channel were assumed to be 18 m and 71 m, respectively. The effective sill depth between the Eastern and the Northwestern Gotland Basins was assumed to be 120 m. Apart from the baroclinic flows, we need to consider the barotropic flows, which show large temporal variations in the entrance area. By analyzing sea-level data, Samuelsson and Stigebrandt (1996) found that the Baltic Sea behaves like an open fjord on time scales longer than one month, and like a closed lake for shorter time scales. The barotropic flow calculations follow Omstedt and Nyberg (1996), and only forcing from the Kattegat and river runoff were considered in the barotropic model. This implies that faster variations of the barotropic flow within the Baltic Sea associated with wind setup etc., were neglected in the calculations.

New estimates of the exchange in the entrance area of the Baltic Sea indicate that the partition between the barotropic flow through the Öresund and the Belt Sea is 2:8 (Mattsson, 1996a), and that the corresponding partition for the baroclinic flow is around 1:1. These ratios were introduced in the model and have been used in the present calculations.

To simulate the surface properties in the Kattegat, frontal mixing must be considered (Pedersen, 1993). The outflowing brackish water from the Öresund and the Belt Sea into the Kattegat forms surface plumes that are advected and mixed in the Kattegat. The water returning through the Öresund and the Belt Sea during inflow events carries properties from the surface layer of the Kattegat. The plume mixing in the Kattegat is now included in the model by assuming instantaneous mixing of the outflowing surface water from the Öresund and the Belt Sea with the Kattegat surface water, and assuming a mixing ratio of 1:1. A similar mixing ratio was also found by Gustafsson (1997a).

In the transition area between the Danish Sounds (the Öresund and the Belt Sea) and the Arkona Basin, frontal movements occur as well as mixing due to shallow sills. These transition zones have been modeled by introducing buffer zones similar to Stigebrandt (1983) and Gustafsson (1997a), with buffer volumes of 3 and 30 km^3, respectively (Mattsson, 1996b; Stigebrandt, 1983).

The turbulent mixing in the surface layer was calculated with a standard k–ε model (Omstedt and Nyberg, 1996). In deeper layers, where the k–ε model yields unrealistically low mixing rates, the turbulent mixing was parameterized as being inversely proportional to the buoyancy frequency (Stigebrandt, 1987). The implications of deep-water mixing in the Baltic proper will be further discussed in Subection 4.1.

2.2. *The observational data*

As mentioned previously, the present Baltic Sea model is divided into 13 horizontally homogeneous sub-basins. In this study, the properties of five of these sub-basins were compared with data from representative hydrographic stations (Fig. 1). The vertical profiles of observed salinity and temperature were extracted from the national data base SHARK (Swedish Ocean Archive) for the period 1 November 1980 to 1 November 1995. Tables 1, 2 show that the observations are reasonably well distributed over the different seasons as well as over the whole 15-year period. In the calculations, however, we saved profiles from every 2nd day. For the 15-year integration, this means that the calculated data were based upon about 3000 profiles for each sub-basin. The observations were thus based upon one order of magnitude less profiles compared with calculations, and during winter seasons with ice present, only few observations were available. Further, added to these data were salinity and temperature observations made from research vessels during the major Baltic inflow of 1993.

Table 1. *Annual distributions of observations*

Year	Anholt E	BY2	BY5	BY15	BY31
1980	0	2	0	1	2
1981	6	13	21	10	17
1982	17	21	26	12	17
1983	21	23	22	14	13
1984	21	21	26	26	18
1985	11	22	20	15	15
1986	21	26	25	13	7
1987	23	29	34	17	13
1988	29	35	26	10	18
1989	32	24	31	13	14
1990	28	28	27	8	11
1991	25	19	11	6	6
1992	33	19	7	18	9
1993	31	23	13	24	6
1994	23	23	14	27	32
1995	23	18	12	27	30
sum	344	346	315	241	228

Table 2. *Monthly distributions of observations*

Month	Anholt E	BY2	BY5	BY15	BY31
Jan.	31	33	17	22	19
Feb.	28	28	26	13	11
Mar.	30	38	32	23	20
Apr.	26	22	18	25	17
May	28	42	39	28	27
Jun.	32	20	24	12	23
Jul.	26	20	16	20	10
Aug.	37	46	50	26	32
Sep.	38	28	36	22	17
Oct.	27	26	17	14	19
Nov.	34	29	34	25	23
Dec.	7	14	6	11	10
sum	344	346	315	241	228

3. Results

In this section, we present results from the 15-year (1 November 1980 to 1 November 1995) model integration along with corresponding observations. First the 15-year median properties are studied. Second, the water masses in the different sub-basins are analyzed with T–S diagrams, as well as the seasonal and interannual variations of the salinity and temperature structures in one of the sub-basins. Then the interannual variations of observed and calculated annual maximum ice extent are studied, which is a good measure of the severity of ice winters and gives us information on how well the energy balance at the sea surface is modeled. Finally, the quality of the model simulations is assessed by examining the major Baltic inflow of 1993.

3.1. *Long-term means*

The meteorological forcing and the inflows to the Baltic Sea are subject to large seasonal and interannual variations. This implies that for a proper simulation of the Baltic Sea, we need to consider forcing data with high resolution in time over a period that includes main events such as cold and mild winters, minor and major inflows, wet and dry years, etc. The extreme events are probably of major importance for determining the long-term means, and thus, they need to be determined from simulations that include all these kinds of events. The approach in the present subsection is to calculate long-term medians from the period 1980–1995, which we believe is a representative 15-year period with respect to today's climate.

In the top panels of Fig. 2, the results from observed and calculated long-term medians for the Kattegat are given. It should be noted that the model prescribes constant properties for the Kattegat deep water, namely a salinity of 34 PSU and a temperature of 6.5°C. The surface salinity in the Kattegat depends on the plumes coming

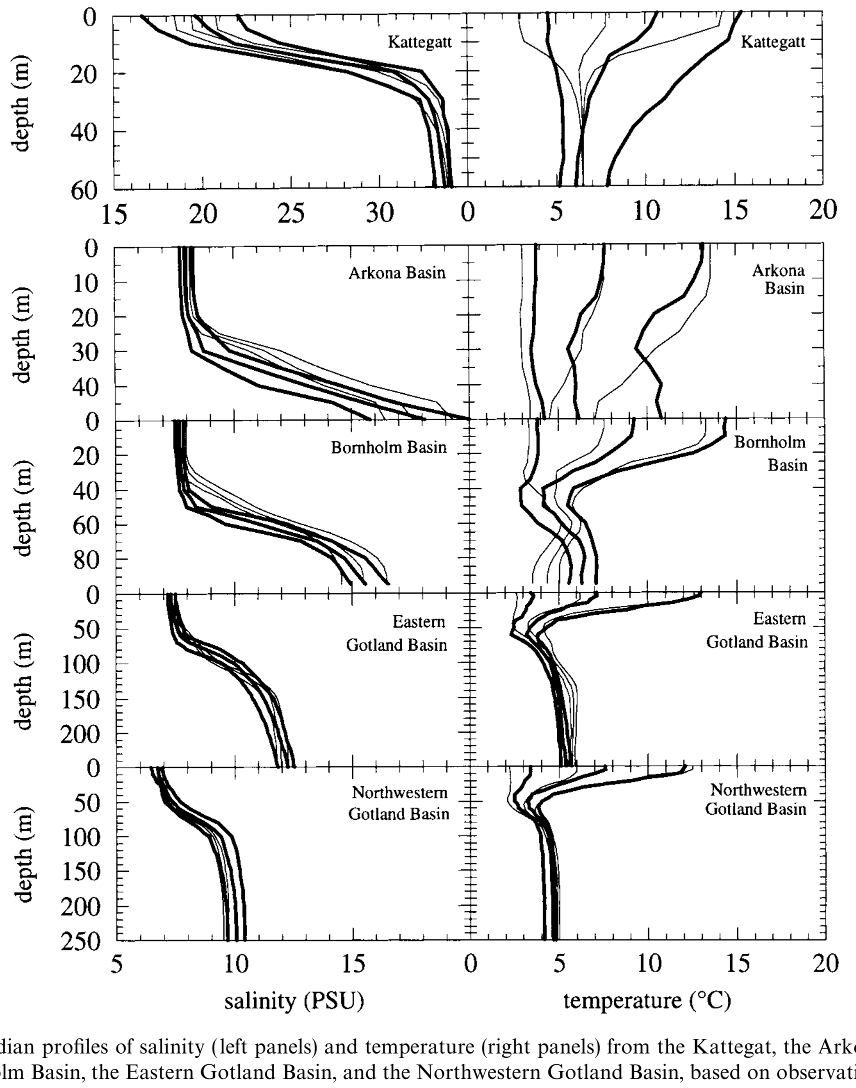

Fig. 2. Median profiles of salinity (left panels) and temperature (right panels) from the Kattegat, the Arkona Basin, the Bornholm Basin, the Eastern Gotland Basin, and the Northwestern Gotland Basin, based on observations (thick lines) and calculations (thin lines) from 1 November 1980 to 1 November 1995. The curves represent the 3 quartiles, the middle ones being the medians.

out from the Öresund and the Belt Sea as well as plume mixing, and the model-calculated median is close to the observed median at Anholt East. Without the plume mixing in the Kattegat, the surface salinities would have become too low in the model.

The corresponding results for the Arkona Basin, the Bornholm Basin, the Eastern Gotland Basin, and the Northwestern Gotland Basin, are illustrated in the other subpanels of Fig. 2. The overall agreement is good, but the calculated mid-depth salinities in the Arkona Basin and the Bornholm Basin are somewhat overestimated. Moreover, the calculated surface temperature in the Kattegat and the deep-water temperatures in the Arkona Basin and the Bornholm Basin were somewhat lower than the observed values. In Table 3, the vertical mean errors between the calculated and observed median profiles are given. The errors decrease in the down-stream direction, but in general they show that the model was too cold (mean errors up to about 1°C) and too saline (mean errors up to about 1 PSU).

3.2. *Water masses*

The observed and calculated water masses based on all data from the 15-year period were compared by plotting *T–S* diagrams. To reduce the influence of the initial profiles, which were only approximated from observations, the calculated data from the first year are excluded in the figures. In the two top panels of Fig. 3, we can see the result from the Kattegat, and again notice how the constant boundary conditions in the Kattegat deep water impose only a low variability of the deep-water properties. However, there is a closer similarity between observed and calculated surface properties. As the interaction of water between the Kattegat and the Arkona Basin is through shallow channels, with sill depths of 8 and 18 m for the Öresund and the Belt Sea, respectively, the model only needs to be able to simulate the Kattegat surface properties correctly. Assuming constant deep-water properties in the Kattegat is therefore a reasonable limitation. It was also shown by Stigebrandt (1983) that there is only a low sensitivity of the Baltic equilibrium (very long-term) surface salinity to variations in the Kattegat deep-water salinity. Sensitivity tests (not presented here) show that this is also true in the present model.

Table 3. *Vertical mean errors and rms errors*[a)]

	Anholt E	BY2	BY5	BY15	BY31
$\langle \Delta S \rangle$	+0.009	+0.766	+0.627	+0.013	−0.295
$\langle \Delta T \rangle$	−0.851	−0.146	−0.809	+0.332	−0.036
ΔS_{rms}	0.429	1.171	0.847	0.263	0.325
ΔT_{rms}	1.402	0.738	1.280	0.583	0.451

[a)] Based on the difference between the modeled and the observed median profiles of salinity and temperature in Fig. 2; units in PSU and °C, respectively.

The *T–S* diagrams from the other subbasins are illustrated in the remaining subpanels of Fig. 3. Three water masses can be distinguished in each subbasin: the surface water, with varying temperatures and only small variations in salinity; the halocline water, with small variations in temperature and salinity; and the deep water, with some variations in temperature (the Arkona Basin is an exception) but with larger variations in salinity. However, all things considered, the water masses are well simulated by the model.

3.3. *Seasonal and interannual variations*

The seasonal variations in one of the subbasins, the Eastern Gotland Basin, are illustrated in Fig. 4. The results indicate that the seasonal variations are mainly in terms of temperature variations in the surface layer. The main difference between the observed and calculated data is for the winter seasons, where the calculated surface temperatures were lower than observations. The reason for the discrepancy is probably that only few observations are available from cold winters.

Several aspects of interannual variations need to be considered. For example, the decade 1981–1990 was the wettest in 70 years (Bergström and Carlsson, 1994). Here we will first consider the interannual variation of the annual maximum ice extent; see Fig. 5. The studied period includes mild, normal, and severe ice winters, and the model simulations are close to the observations. This indicates that the energy exchange between air and water during years with large interannual variations are modeled in a realistic way.

The observed and calculated temperatures and salinities are illustrated in Figs 6, 7. We can notice

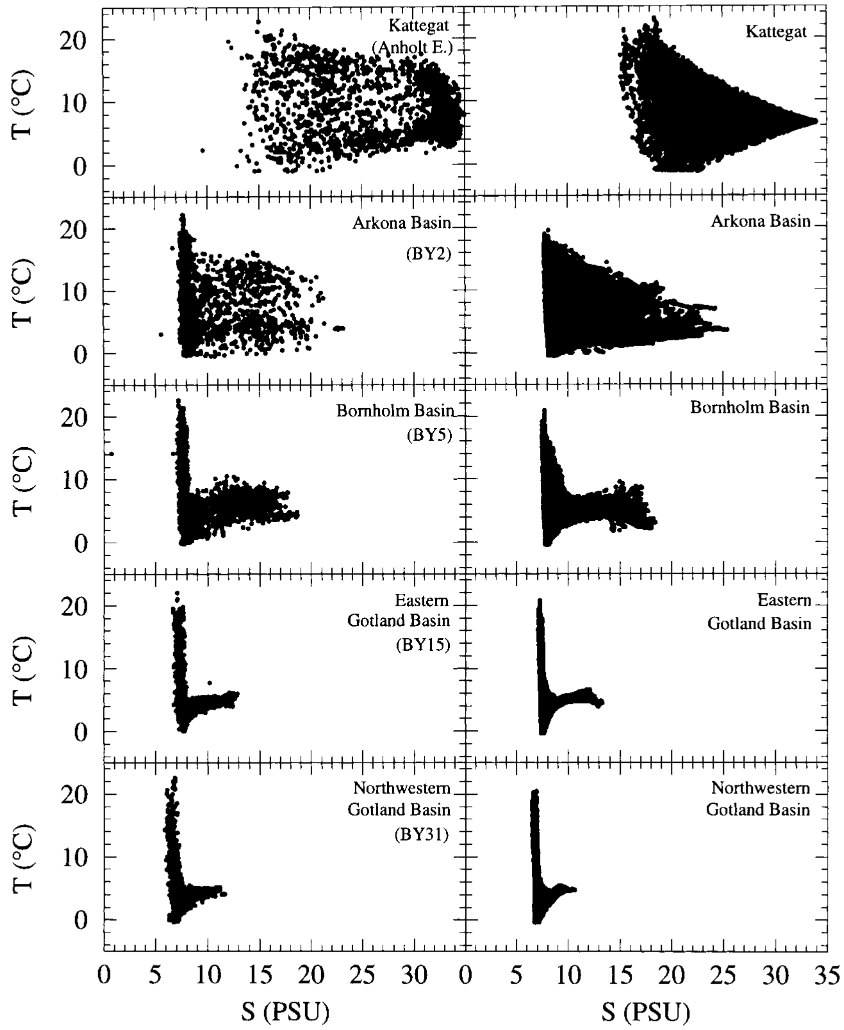

Fig. 3. T–S diagrams based on observations (left panels) and calculations (right panels) from the Kattegat, the Arkona Basin, the Bornholm Basin, the Eastern Gotland Basin, and the Northwestern Gotland Basin.

large seasonal variations in the surface properties due to the formation of summer thermoclines and due to increased river runoff during spring and summer. Interannual variations can be seen in the surface properties but are more clearly seen in the salinity field in the deeper layers, particularly during the major Baltic inflow in 1993. It is also interesting to notice the seasonal variation in the halocline. During the fall and winter seasons the salinity gradient in the halocline increases, whereas during the summer seasons the gradient decreases. The reasons are that during the summer, the halocline is protected from the atmospheric forcing by a thermocline, and the gradient decreases due to vertical diffusion and advection. During fall, the wind usually increases and the surface water is mixed down to the permanent halocline. The seasonal variations within the halocline can be noticed in the observed as well as in the calculated data fields. It should be remembered, however, that in the Figs. the calculated fields are based on one order of magnitude larger amount of data compared to the observed fields. Similar results (not

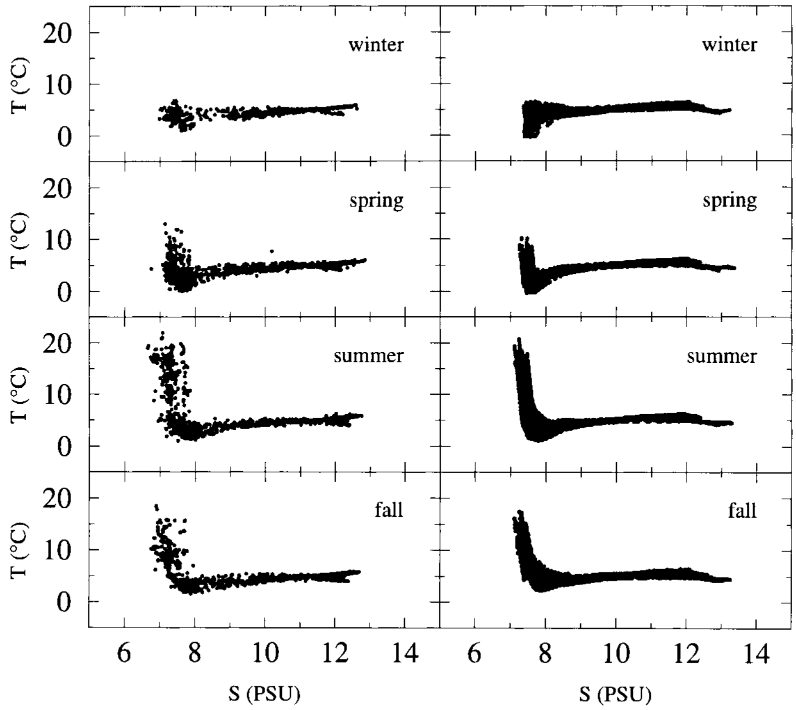

Fig. 4. Seasonal *T–S* diagrams based on observations (left panels) and calculations (right panels) from the Eastern Gotland Basin. The observations are from BY15.

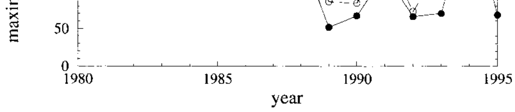

Fig. 5. Observed and calculated annual maximum ice extent for the Baltic Sea.

shown here) can be found during the whole studied period and in all sub-basins. However, the sub-basins closer to the entrance area showed larger variations. The general dynamics illustrated in Figs. 6, 7 are in good agreement with the results from Stigebrandt (1987).

3.4. *The inflow of 1993*

In the middle of the 1970s, a very long stagnation period began, during which the salinity of the deep water of the Baltic proper decreased steadily. The stagnation period was more or less uninterrupted until the major Baltic inflow of January 1993. This inflow has been studied by several authors, e.g. Matthäus and Lass (1995), Lehmann (1995), Håkansson et al. (1993), and Liljebladh and Stigebrandt (1996). During 3 days in February 1993, extensive measurements were performed in the Arkona Basin by the Department of Oceanography, Göteborg University, Sweden. One month later, similar measurements were performed in the Bornholm Basin by the Institute of Marine Research at the University of Kiel, Germany. In this subsection, we compare the calculated and

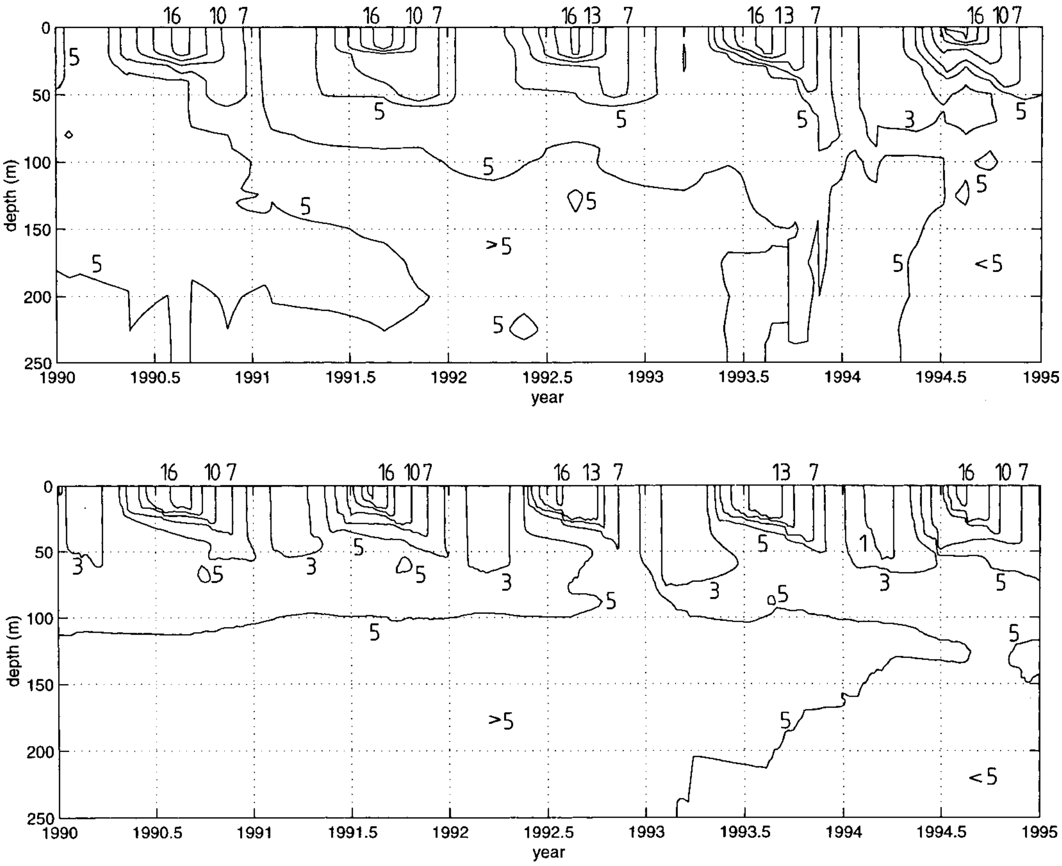

Fig. 6. Observed (top) and calculated (bottom) temperature fields (°C) in the Eastern Gotland Basin for the period 1990–1995.

observed temperature and salinity data from these two measuring periods.

The calculated data for the Arkona Basin and the Bornholm Basin from the corresponding periods can be seen in Fig. 8. However, only 2 calculated profiles are plotted for the Arkona Basin, and 15 for the Bornholm Basin. The reason is that, in the 15-year simulation, data were only saved every 48 h. The number of observed profiles was much higher, and they were measured at several locations within each sub-basin. As can be seen in Fig. 8, the calculated salinity ranges (8–25 PSU in the Arkona Basin and 8–18 PSU in the Bornholm Basin) follow the observed salinities closely. However, the modeled temperatures are about 1–2° colder than the observed values. This is consistent with the calculation of the maximum ice extent, which overestimated ice coverage during this winter; see Fig. 5.

4. Model implications

4.1. Stratification spin-up

The stratification spin-up was investigated by performing the so-called lock-exchange experiment. This is a most relevant experiment for estuaries and simulates the exchange between two basins with different densities after the lock has been opened. The initial conditions for the subbasins were constant salinity profiles; 34 PSU for the Kattegat, the Öresund, and the Belt Sea, and 0.5 PSU in the other subbasins. The model was then run by repeatedly using the forcing fields from the

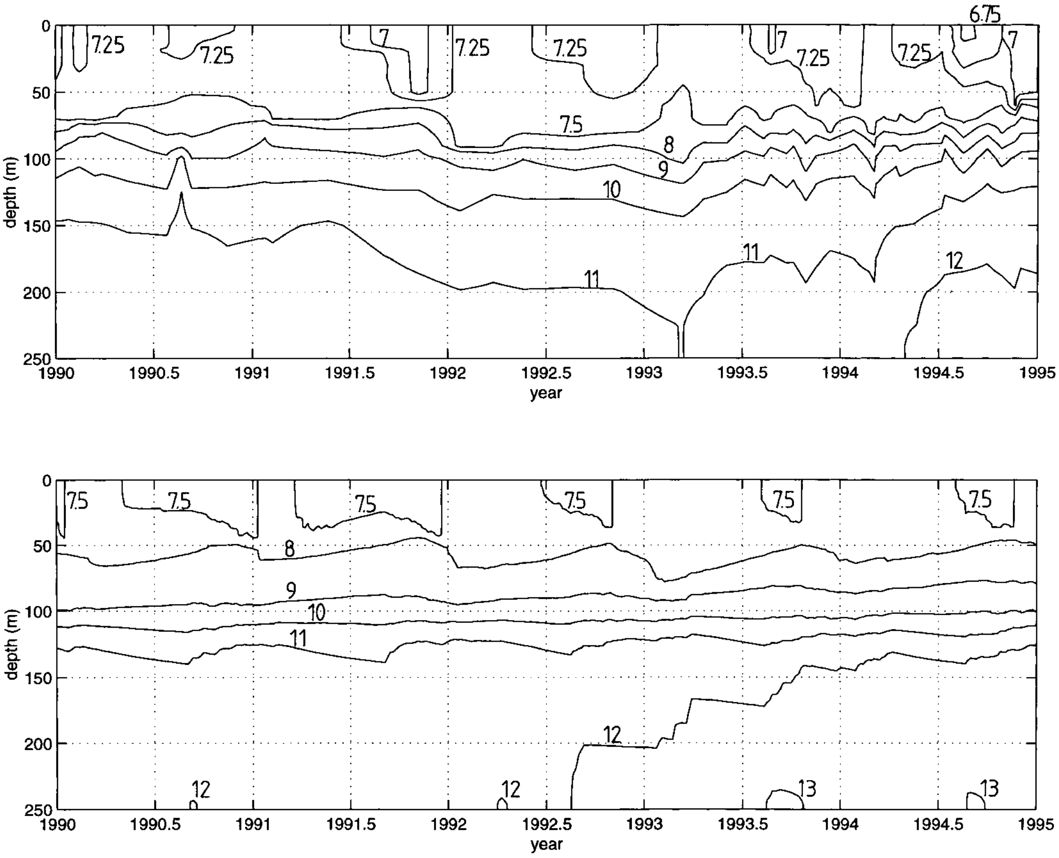

Fig. 7. Observed (top) and calculated (bottom) salinity fields (PSU) in the Eastern Gotland Basin for the period 1990–1995.

same 15-year period as before (1980–1995). The results from 7 such 15-year loops, representing 105 years of spin-up, are shown in Fig. 9. Two time scales can be distinguished. The 1st time scale is associated with the time the dense bottom water needs before it enters and fills the deeper parts of the different sub-basins. The 2nd time scale is associated with the time it takes for the saline bottom water to be vertically advected and diffused into the surface water. Kõuts and Omstedt (1993) studied the deep-water exchange of the Baltic proper by using historical data. They found that dense bottom currents need approximately six months to flow from the Bornholm Channel to the Stolpe Channel, and 12 months to the Fårö Channel.

Axell (1998) calculated the vertical turbulent diffusion for the Baltic deep water from historical oceanographic data from the Eastern Gotland Basin and the Northwestern Gotland Basin. He found that a typical value of the diffusion coefficient in the deep water is 10^{-5} m^2 s^{-1}. The corresponding diffusive time scale for a 100 m thick layer is then about 30 years. This indicates that, in the lock-exchange experiment, dense bottom currents may rapidly fill the deeper parts of the sub-basins, whereas the salinity in the upper layer changes on a longer time scale. This is also illustrated in Fig. 9, where one can observe how the deep-water salinities increase rapidly, whereas the response of the surface layer is slower.

It should also be noticed that the surface salinity in the Kattegat approaches realistic values much more rapidly than it does in the Baltic proper.

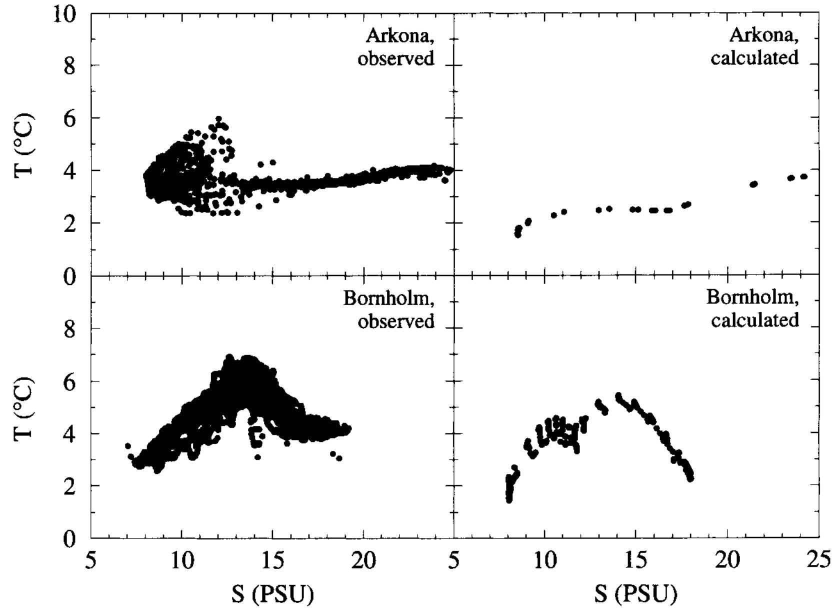

Fig. 8. Observed (left panels) and numerically simulated (right panels) temperature and salinity structures for the Arkona Basin (top panels), from 6–8 February 1993, and the Bornholm Basin (bottom panels), from 1–31 March 1993, during the major Baltic inflow.

For the large gulfs of the Baltic Sea (Gulf of Riga, Gulf of Finland and Gulf of Bothnia), the stratification spin-up times (results not shown in the present paper) are even larger than for the Baltic proper as the deep water in the gulfs are formed by surface water coming from the Baltic proper.

The implications of the lock-exchange experiment are that the typical time scales for adjusting the salinity fields to the forcing are of the order of 10 years for the Kattegat and 100 years for the Baltic proper. Changing conditions in the Kattegat region may thus be detected rather rapidly, whereas the response of the Baltic Sea is much slower.

4.2. *Water balance and salinity*

In climate research, ocean models can provide boundary conditions for atmosphere models, with high resolution in time and space, in terms of sea-surface temperature and sea ice. But ocean models can also serve as an important tool for the verification of the atmosphere and river-runoff models, as the modeled salinity can be used as a constraint on the fresh-water input. This is illustrated in Fig. 10, where 15-year median profiles of salinity for the Kattegat and the Eastern Gotland Basin are presented and the importance of the meteorological runoff (precipitation minus evaporation, $P-E$) is illustrated.

In the Kattegat, the surface salinity became 1 PSU higher in the case when the meteorological fresh-water inflow was neglected (Fig. 10). The fresh-water balance over the Baltic Sea thus controls the surface salinity in the Kattegat, where the inflowing water destined to become Baltic Sea deep water is formed. The Baltic Sea needs much longer time to adjust its surface layer to changes than the Kattegat does, as was discussed in Subsection 4.1. This implies that, in the present calculations, the surface salinity in the Kattegat has adjusted to the fresh-water input, whereas the Eastern Gotland Basin needs a longer time for adjustment. The results, indicated in Figure 10, are in good agreement with those obtained by Omstedt et al. (1997), who with simple arguments (Knudsen, 1900) estimated that a meteorological fresh-water inflow equal to 2000 m^3 s^{-1} should decrease the long-term mean surface salinity by 1 PSU. Gustafsson (1997a; 1997b) made sensitivity studies using an analytical

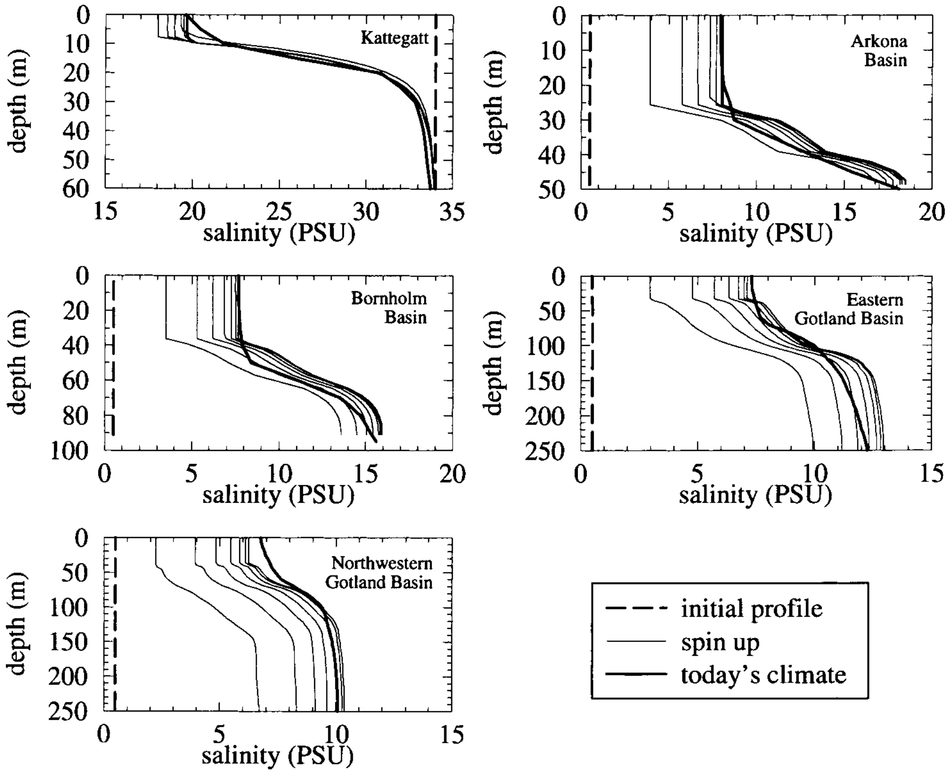

Fig. 9. An illustration of a 105-year stratification spin-up in the Kattegat, the Arkona Basin, the Bornholm Basin, the Eastern Gotland Basin, and the Northwestern Gotland Basin. The initial profiles are dashed, the results from the spin-up are shown as thin lines with 15-year intervals, and the observed median profiles are shown as thick lines.

and a time-dependent process-oriented model and found similar results.

Different estimates of the long-term water balance are given in Table 4. The HELCOM (1986) estimates were based on data from the period 1951–1970, whereas Kõuts and Omstedt (1993) studied the period 1970–1990, and Omstedt et al. (1997) studied the period 1981–1994. The river runoff, Q_f, used by Omstedt et al. (1997) was based on data from Bergström and Carlsson (1994). In the 3 studies cited in Table 4, different methods, data sources, and periods were used. In the HELCOM (1986) study, salt budgets were not considered at all. Kõuts and Omstedt (1993) used the values in Table 4 in diagnostic calculations of deep-water properties of the Baltic proper. They used the observed salinity to calculate the flows, which has been done in other water-balance studies as well. In the present study, we used the model to calculate the salinities, and the results agree well with observations. The water-balance is thus consistent with the observed salinity.

5. Summary and conclusions

In the present work, the seasonal, interannual and long-term variations of salinity and temperature in the Baltic proper and the Kattegat have been simulated by using the model by Omstedt and Nyberg (1996). In the model, the Baltic Sea, including the Kattegat, was divided into 13 sub-basins with high vertical resolution, horizontally coupled by estuarine circulation (barotropic as well as baroclinic flows) and vertically coupled to a sea-ice model which includes dynamic as well as thermodynamic processes. The main purpose of the investigation was to analyze the ability of the model to simulate variations in the salinity and temperature fields. Forcing data (wind, air temper-

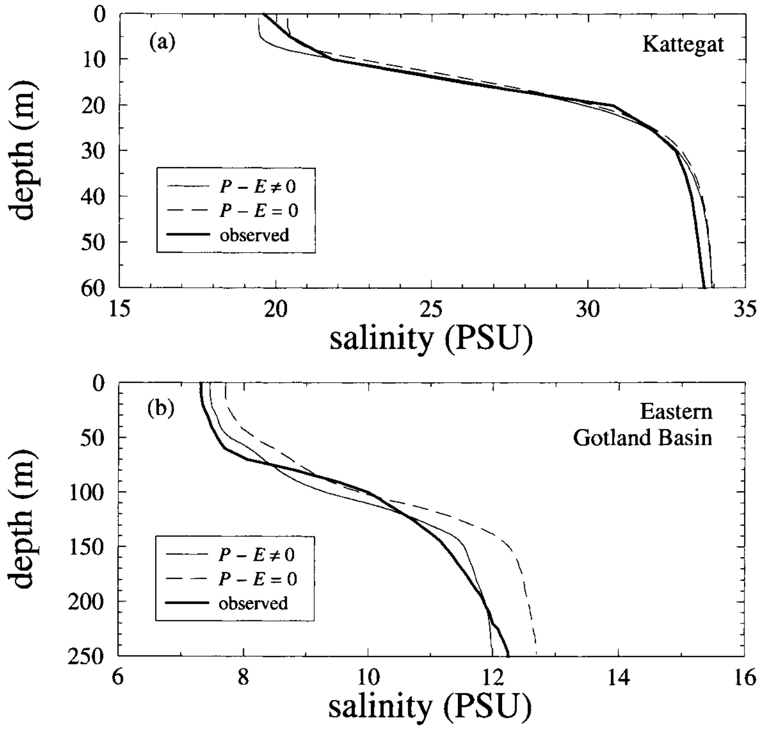

Fig. 10. Median salinities for the Kattegat (a) and the Eastern Gotland Basin (b) from 15-year calculations (1980–1995), with and without the meterological runoff (precipitation minus evaporation, $P-E$).

Table 4. *Water balance for the Baltic Sea*[a)]

Authors	Q_f ($m^3 s^{-1}$)	$P-E$ ($m^3 s^{-1}$)
Omstedt et al. (1997)	15,100[b)]	1,769
Kõuts and Omstedt (1993)	15,000	2,000
HELCOM (1986)	13,798	1,302

[a)]The Belt Sea and the Kattegat excluded.
[b)]According to Bergström and Carlsson (1994).

ature, relative humidity, total cloudiness, water levels from the Kattegat, river runoff, and precipitation) for the period 1 November 1980 to 1 November 1995 were used in the simulation. Moreover, the model was improved by the parameterization of frontal mixing and movements in the Kattegat and in the transition areas between the Danish Sounds and the Arkona Basin.

The model results were verified with observational data from the national data base SHARK for the same 15-year period. In addition, data collected from research vessels during the major Baltic inflow of 1993 were also used to verify the model. The conclusions may be summarized as follows.

(1) The calculated long-term (1980–1995) median profiles of salinity and temperature in the different sub-basins of the Baltic proper and the Kattegat are in good agreement with the observations from the same period. However, the calculated mid-depth salinities in the Arkona Basin and the Bornholm Basin were somewhat overestimated, and the calculated deep-water temperatures in the Arkona Basin and the Bornholm Basin are somewhat lower than observed values.

(2) The water masses were analyzed with *T–S* diagrams and were well simulated by the model. Prescribing constant deep-water properties in the Kattegat proved to be a reasonable boundary condition.

(3) The seasonal and interannual variations were examined in terms of temperature and salinity fields, *T–S* diagrams and the annual maximum ice extent, which showed that the model can simulate these variations realistically.

(4) The major Baltic inflow of 1993, which was analyzed by comparing observed and calculated *T–S* diagrams from the Arkona Basin and the Bornholm Basin, was also captured by the model. However, the calculated temperatures were 1–2° too cold.

(5) The stratification spin-up time of the different sub-basins were examined by running the so-called lock-exchange experiment. The typical time scales for adjusting the salinity fields to realistic values were of the order of 10 years for the Kattegat and 100 years for the Baltic proper. This implies that changes in, e.g., the fresh-water inflow may be observed rather soon in the Kattegat, whereas the response of the Baltic proper is much slower.

(6) Frontal mixing and movements in the Kattegat and in the entrance areas of the Arkona Basin were important to consider in the modeling efforts.

For the first time, we have been able to close the energy and water budgets of the Baltic proper, in the sense that the evaporation rates are consistent with the calculated latent heat fluxes. Moreover, we have also shown that realistic temperature and salinity profiles can be modeled from known forcing fields. The results show that the model is capable of simulating the present climate of the Baltic proper, which is a prerequisite for any model that is to be used to simulate regional climate change. In future work, the coupling between the Baltic proper and the large gulfs (the Gulf of Bothnia, the Gulf of Finland, and the Gulf of Riga) needs further research.

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