BOREAL ENVIRONMENT RESEARCH 7: 405–415 ISSN 1239-6095
Helsinki 23 December 2002

Water, heat and salt exchange between the deep basins of the Baltic Sea

Andreas Lehmann* and Hans-Harald Hinrichsen

*Institute of Marine Research, Düsternbrooker Weg 20, D-24105 Kiel, Germany (*e-mail: alehmann@ifm.uni-kiel.de)*

Lehmann, A. & Hinrichsen, H.-H. 2002: Water, heat and salt exchange between the deep basins of the Baltic Sea. — *Boreal Env. Res.* 7: 405–415. ISSN 1239-6095

From numerical model simulations, fluxes of volume, heat and salt have been calculated for different hydrographical sections in areas which are important for the deep water exchange in the Baltic Sea. The calculated deep water flow in the Arkona basin is in accordance with independent estimations obtained from profile data. Model results reveal strong seasonal and inter-annual variability in the calculated fluxes. The variability is governed by the prevailing atmospheric conditions. It is found that the strength of the upper layer low saline flow in the Arkona Basin which on average is directed to the west, opposite to the mean wind direction, is compensated by a high saline flow in deeper layers. The upper layer flow is a combination of a flow forced by the fresh water surplus directed to the west, and a wind-driven part. In dependence on the prevailing wind conditions the resulting flow is either increased or decreased. Furthermore, increasing upper layer flow results in an increased lower layer flow in opposite direction. The annual mean flow is weakly correlated with the annual mean runoff to the Baltic Sea. In accordance with the mean circulation, the flow through the Bornholm Channel is on average directed to the east, and south of Bornholm to the west indicating an import of heat and salt to the Bornholm Basin through the Bornholm Channel and an export south of Bornholm. Flux characteristics change further downstream in the Stolpe Channel. The volume flow in the upper layer shows a strong seasonal signal. During autumn to spring the flow is mainly directed to the east, in summer, the flow direction is reversed. Flow in westerly directions is related to increased lower layer flow in easterly directions. On average, the net flow through the Stolpe channel is directed to the east which is in accordance with the mean circulation. Calculated fluxes show high intra- and inter-annual variability with no obvious trend during the simulation period. The variability of the deep water stratification in the deep basins of the Baltic Sea is directly controlled by the changing flux characteristics.

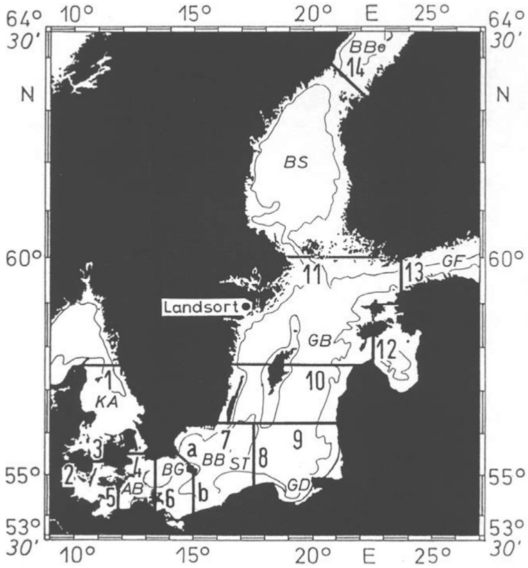

Fig. 1. Hydropgraphic sections taken for analysis of volume, heat and salt fluxes; KA = Kattegat, AB = Arkona Basins, BG = Bornholm Channel, BB = Bornholm Basin, ST = Stolpe Channel, GB = Gotland Basins, GF = Gulf of Finland, BS = Bothnian Sea, BBo = Bothnian Bay.

Introduction

The central aim of BALTEX (Baltic Sea Experiment 1995) is the accurate determination of the energy and water budget of the catchment area of the Baltic Sea, an area of about 2.1×10^6 km^2. The Baltic Sea together with the Kattegat and Skagerrak cover about 20% (415 000 km^2) of the entire BALTEX area. The closing of the budgets is only possible with the accurate knowledge of the in- and outflows through the Danish Sounds and the storage of water, heat and salt. To achieve this aim, consistent methods where both models and observations are closely linked with each other are required.

The quality of coupled numerical ocean models can be estimated by the ability to model accurately the penetration of highly saline water from the Kattegat into the deep basins of the Baltic Sea. The haline stratification in the Baltic Sea is determined by the huge fresh water contribution from rivers and the net effect of precipitation minus evaporation and the advection of highly saline water from the Kattegat. The water above the permanent halocline can directly interact (heat exchange) with the atmosphere, whereas the water below the halocline is insulated due to strong stratification which restricts an effective convective exchange across the halocline. Thus, any changes in fresh water and salt fluxes have an impact on the haline stratification and in turn will affect the heat budget of the Baltic Sea. The thickness of the brackish water mass above the halocline thus influences the development of the sea surface temperature and sea ice during winter, which both affect the interaction with the atmosphere.

The accurate knowledge of the saline deep water flow is an important pre-condition to close the energy and water cycle of the Baltic Sea. In this paper, we present volume, heat and salt fluxes between the deep basins of the Baltic Sea calculated from an eleven-year (1979–1990) coupled sea ice-ocean model simulation. The period is regarded as stagnation period with no major inflows into the Baltic Sea. However, smaller inflows occurred for the years 1980, 1982 and 1983. The model results are linked to the general circulation of the Baltic Sea (Lehmann and Hinrichsen 2000a, 2000b, 2002) and compared with estimations which have been recently published by Gustafsson (2001). In Lehmann and Hinrichsen (2000a), heat, salt and volume transports across 14 hydrographical sections have been calculated for specific years. Here, we concentrate on an eleven-year period and focus on the mean fluxes of heat, salt and volume across hydrographical sections through the Arkona Basin, Bornholm Channel, along 15°E and Stolpe Channel (Fig. 1).

The deep water exchange in the Baltic Proper has been investigated earlier by Kõuts and Omstedt (1993). In their study, profile data from a 20-year period, 1970–1990 were analysed on the basis of conservation principles, the two-layer approach and the geostrophic flow assumption. No direct current observations where used to determine the deep water exchange between the deep basins of the Baltic Sea. Our simulation period is partly covered by the period for which observational data have been analysed (Kõuts and Omstedt 1993). Thus, results from three-dimensional model simulation can directly be compared with flow calculation based on traditional methods.

Baltic Sea model and forcing data

The coupled sea ice-ocean model of the Baltic Sea, used in this study, is based on the Bryan-Cox-Semtner general circulation model with a free surface (Killworth *et al*. 1991). The model is based on primitive equations derived from the Navier-Stokes equations, applying the shallow water, the traditional and the hydrostatic approximation. The conservation equations for momentum, temperature and salinity, along with their boundary conditions, are solved on a staggered Arakawa B-grid using a finite difference technique. For the advection of momentum and tracers, central differences are applied. For turbulence closure, a $k-\varepsilon$ model has been implemented (e.g. Meier 2000). The general ocean circulation model has been adapted to the Baltic Sea (Lehmann 1995), and coupled to a dynamic-thermodynamic sea ice model (Stössel and Owens 1992, Lehmann and Hinrichsen 2000a). Sea ice dynamics are described by a viscous-plastic rheology (Hibler 1979), and the thermodynamical ice growth rates are derived from the surface energy balance following Parkinson and Washington (1979), using the Semtner zero-layer approach. The horizontal resolution of the coupled sea ice-ocean model is 5 km (eddy-permitting), and in the vertical 60 levels are specified, which enables us to resolve the upper 100 m with levels of 3-m thickness. The model domain comprises the Baltic Sea including the Skagerrak and the Kattegat. At the western boundary, a simplified North Sea is connected to the Skagerrak in order to provide characteristic North Sea water masses in case of inflow conditions, and to take up sea level elevations due to different forcing conditions (Lehmann 1995). At the western boundary of the simplified North Sea (4°E), the sea level is adjusted to a constant reference value, which has been determined from the sea level inclination calculated from the initial density distribution. With respect to the reference level, volume is supplied/extracted from the North Sea in case of in/outflow conditions. The salinity in the North Sea basin is relaxed to a climatology. Thus, sea level changes in the Skagerrak are determined by the atmospheric forcing acting on the total model domain including the area of the simplified North Sea and river runoff supplied to the Baltic Sea and the Kattegat. Sea level changes propagating into the North Sea from the Atlantic and tides are not considered. The baroclinic mode and the tracer equations are stepped forward in time with a leapfrog time step (300 s). For the barotropic mode, an Euler backward scheme is used (30 s). A detailed description of the finite difference formulation can be found in Killworth *et al*. (1989).

The model has been proven to be suitable to simulate the major features of the Baltic Sea. These include the general circulation, thermal and haline stratification, major Baltic inflows as well as the general water mass exchange with the North Sea and within the deep basins of the Baltic Sea (Lehmann 1995, Lehmann and Hinrichsen 2000a, Lehmann and Hinrichsen 2000b, Lehmann *et al*. 2002). The model has also been applied to explain variability in Baltic cod recruitment processes (Voss *et al*. 1999, Hinrichsen *et al*. 2001).

The coupled sea ice-ocean model is forced by realistic atmospheric conditions taken from the SMHI (Swedish Meteorological and Hydrological Institute Norrköping, Sweden) meteorological data base (Lars Meuller pers. comm.) which covers the whole Baltic drainage basin on a regular grid of $1 \times 1°$. The temporal increment of data records is 3 hours. The data base includes: geostrophic wind, 2-m air temperature, 2-m relative humidity, surface pressure, cloudiness and precipitation. Additionally, river runoff has been prescribed from a monthly mean runoff data set (Bergström and Carlsson 1984). Runoff data are specified for 42 individual rivers distributed around the Baltic Sea and the Kattegat. In Fig. 2, the monthly and annual mean values of the specified runoff are displayed. For the eleven-year period a mean value of about 16 500 $m^3 s^{-1}$ results. Besides the seasonal variability there is clear inter-annual variation in river runoff to the Baltic Sea. Maximum values (> 17 000 $m^3 s^{-1}$) occur for the years 1981, 1982, 1986, 1987 and 1988.

Prognostic variables of the coupled sea ice-ocean model are: sea ice thickness and compactness, sea ice drift, the oceanic baroclinic current field, the 3-D temperature, salinity and oxygen distributions, the 2-D surface elevation and the barotropic transport. These prognostic variables

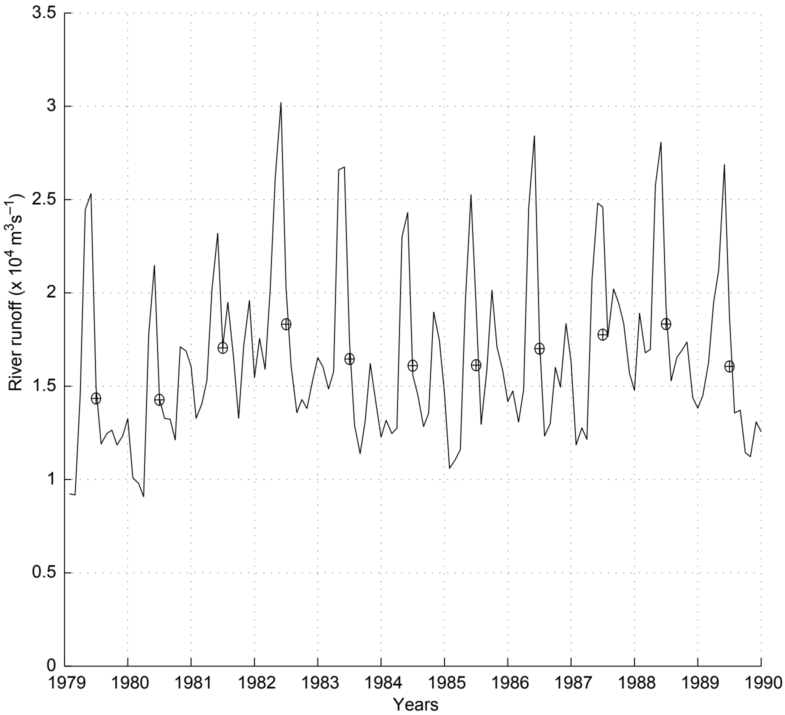

Fig. 2. River runoff to the Baltic Sea for the years 1979–1990. Continuous line represents monthly mean runoff and circle-plus symbols annual mean values.

have been extracted from the model every 6 hours and form the data base for the subsequent analysis.

Results and discussion

In order to determine the fluxes of heat, salt and water within the Baltic Sea and the Kattegat/Skagerrak area, simulated currents, temperature and salinity values have been extracted along 14 hydrographical sections (Fig. 1) from an eleven-year model run at six-hourly intervals. Horizontal and vertical scales of the cross-sections were chosen in accordance with the model's three-dimensional resolution. In order to take into account the occurrence of different water masses of different character in the Baltic Sea, additionally, flux calculations were separately performed for water masses typical for the central Baltic Sea, the permanent halocline and below it. Water masses in and below the halocline have their origin in the Kattegat/Skagerrak area. Inter- and intra-annual variations of transports of heat, salt and volume have been discussed in Lehmann and Hinrichsen (2000a). Here, we will focus on monthly and annually averaged fluxes between the deep basins of the Baltic Sea for an eleven-year period.

Fluxes through the Arkona Basin (section 6)

Through the Arkona Basin, a section along 13.5°E has been chosen (Fig. 3). From this section, the salt flux into the Baltic Sea can directly be calculated for water masses which have already entered the Baltic Sea. Inflowing water moves as a dense bottom current through the Danish Straits. Once this water has entered the Arkona Basin, the highly saline water sinks to the bottom and forms a dense bottom pool. From the Arkona Basin, the water leaks through the Bornholm Channel into the Bornholm Basin.

Transport and fluxes of heat and salt have been calculated for salinity less equal and greater than 9 PSU (Fig. 3). Mean values for the eleven-year period of volume, salt and heat fluxes are given in Table 1. Net fluxes are directed to the west due to the fresh water surplus. The long-term mean volume flux amounts to 1.626 ×

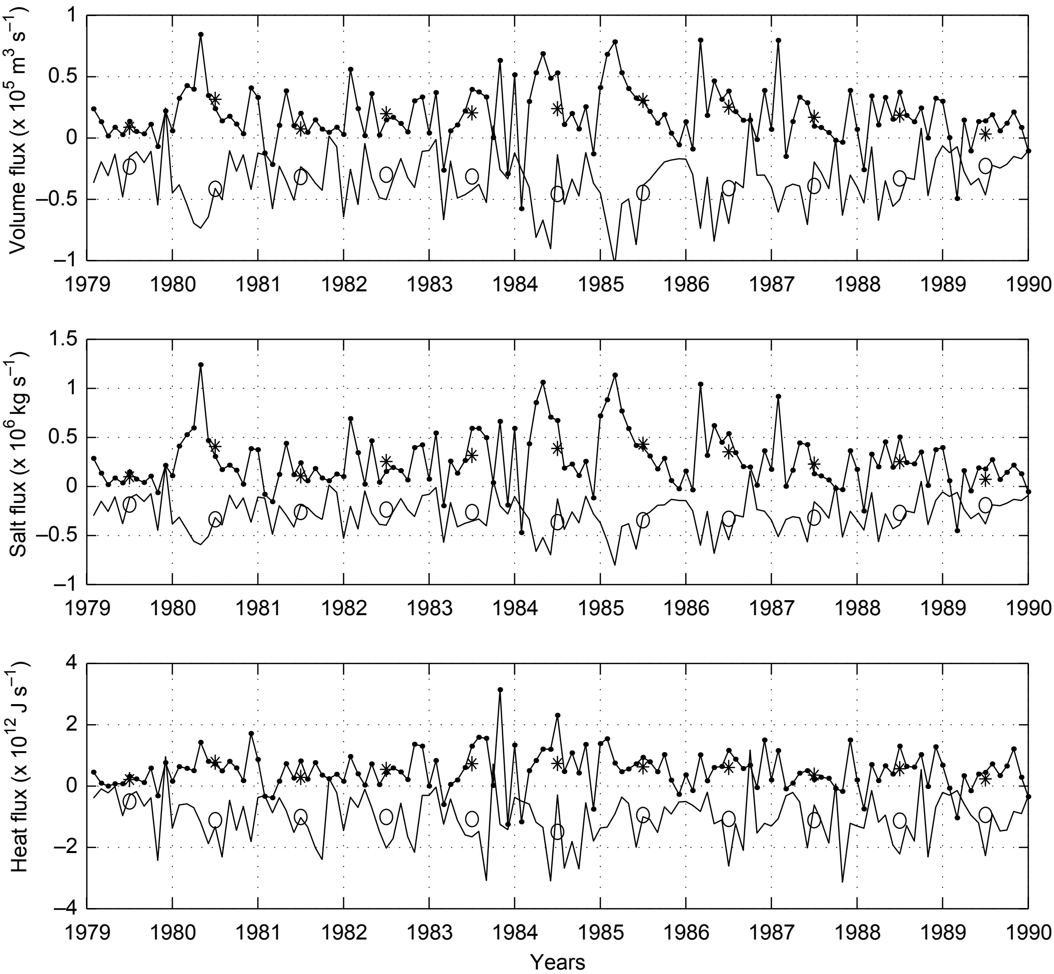

Fig. 3. Volume, salt and heat fluxes from the Arkona Basin obtained from a hydrographical section along 13.5°E. Continuous line represents fluxes for salinity ≤ 9 PSU, dotted line represent fluxes for salinity > 9 PSU. Symbols represent corresponding annual mean values.

10^4 m^3 s^{-1} which is about the average runoff to the Baltic Sea. The correlation between the net volume flux and the river runoff to the Baltic Sea is nevertheless weak.

The averaged values of volume and salt fluxes into the Baltic Sea are in the same range as the values which have been calculated by Gustafsson (2001) obtained from geostrophic flow calculations based on profile data from the Arkona Basin. In this work, previous estimations of volume and salt fluxes are compared and discussed. Gustafsson (2001) based his calculations on a 50-year time series of profile data starting in 1950, and found that the long-

Table 1. Eleven-year average of volume, heat and salt fluxes through section 6. Positve values define fluxes to the east, negative values to the west.

Salinity range (PSU)	Volume	Salt	Heat
Total	-1.627×10^4 m^3 s^{-1}	-1.880×10^4 kg s^{-1}	-5.246×10^{11} J s^{-1}
$s \leq 9$	-3.496×10^4 m^3 s^{-1}	-2.824×10^5 kg s^{-1}	-1.038×10^{12} J s^{-1}
$s > 9$	1.896×10^4 m^3 s^{-1}	2.636×10^5 kg s^{-1}	5.131×10^{11} J s^{-1}

term averaged flow was about 2.2×10^4 m^3 s^{-1} with salinity greater than 14 PSU. The estimates presented in Gustafsson (2001) were regarded as an upper limit. The mean salt flux was about 3.0 $\times 10^5$ kg s^{-1}. It should be noted that for the period 1979–1989 the averaged volume flow and salt flux were below the long-term means.

For the eleven-year period, the simulated fluxes show high intra- and inter-annual variability. Increasing transport in the upper layer is related to increasing transport in the lower layer and vice versa. The same holds for the salt and heat fluxes. The volume flux through the Arkona Basin can be described by a two-layer system in which the transport in the upper layer is directed to the west and in the lower layer to the east (Fig. 3). The upper layer flow is mainly a combination of the flow forced by the fresh water surplus and the wind-driven part. In dependence on the prevailing wind conditions, the resulting flow is either increased or decreased. Increasing lower layer flow is related to an increased transport of dense water to the east. West wind conditions may block the general outflow and lead to a volume increase of the Baltic Sea although no direct inflow has been forced (Lehmann *et al*. 2002). Thus, the variability in the upper layer flow is governed by the variability in atmospheric forcing over the western Baltic Sea. This is confirmed by the correlation (r = 0.6) of the upper layer flow with the BSI (Baltic Sea Index) which is the difference of normalised sea level pressure (SLP) anomalies between Oslo and Szczecin (Lehmann *et al*. 2002). A positive BSI corresponds to an anomalous SLP difference, with westerly winds over the Skagerrak/Kattegat and the western Baltic which pile up water in the Kattegat and lower the sea level in the western Baltic Sea, leading to inflow conditions. A negative BSI corresponds to easterly winds, favouring outflow conditions.

In contrast to the salt fluxes which generally show a similar structure compared with the volume fluxes, the heat fluxes reveal a different behaviour. Volume fluxes have been calculated for different salinity ranges, thus, an increasing flow is related to an increasing salt flux, only modified by the mean salinity of the corresponding salinity ranges. Heat fluxes remain relatively small although volume fluxes may increase (e.g. 1984–1986). This effect can be explained by the advection of cold water masses. Nevertheless, salt and heat fluxes show that a considerable amount of salt and heat is exchanged between the deep basins of the Baltic Sea.

Fluxes through the Bornholm Channel and 15°E (section 7)

Section 7 is separated into two parts. Section 7a runs through the Bornholm Channel and section 7b along 15°E (Fig. 1). These sections will be separately considered because of their different flux characteristics. The net flow as well as the heat and salt flux through the Bornholm Channel (section 7a) is directed to the east. Eleven-year mean values are given in Table 2. The flux behaviour through the Bornholm Channel (Fig. 4) is similar as for the Arkona Basin. Again, increasing fluxes of the upper layer are accompanied by increasing fluxes in the lower layer. Flux calculations for section 7 have been performed for three salinity ranges ($s \leq 8$ PSU, $8 < s \leq 10$ PSU, $s > 10$ PSU; Table 2). The mean flow of water masses with salinity > 8 PSU is directed to the east, and the upper layer flow, on average less in its intensity, is directed to the west (Fig. 4). Maximum inflow into the Bornholm Basin occurred in the years 1980, 1984, 1985 and 1986. Stronger volume flow is accompanied by

Table 2. Eleven-year average of volume, heat and salt fluxes through section 7a. Positve values define fluxes to the east, negative values to the west.

Salinity range (PSU)	Volume	Salt	Heat
Total	1.646×10^4 m^3 s^{-1}	2.363×10^4 kg s^{-1}	4.498×10^{11} J s^{-1}
$s \leq 8$	-1.400×10^4 m^3 s^{-1}	-1.049×10^5 kg s^{-1}	-2.986×10^{12} J s^{-1}
$8 < s \leq 10$	1.215×10^4 m^3 s^{-1}	1.098×10^5 kg s^{-1}	3.121×10^{11} J s^{-1}
$s > 10$	1.832×10^4 m^3 s^{-1}	2.313×10^5 kg s^{-1}	4.363×10^{11} J s^{-1}

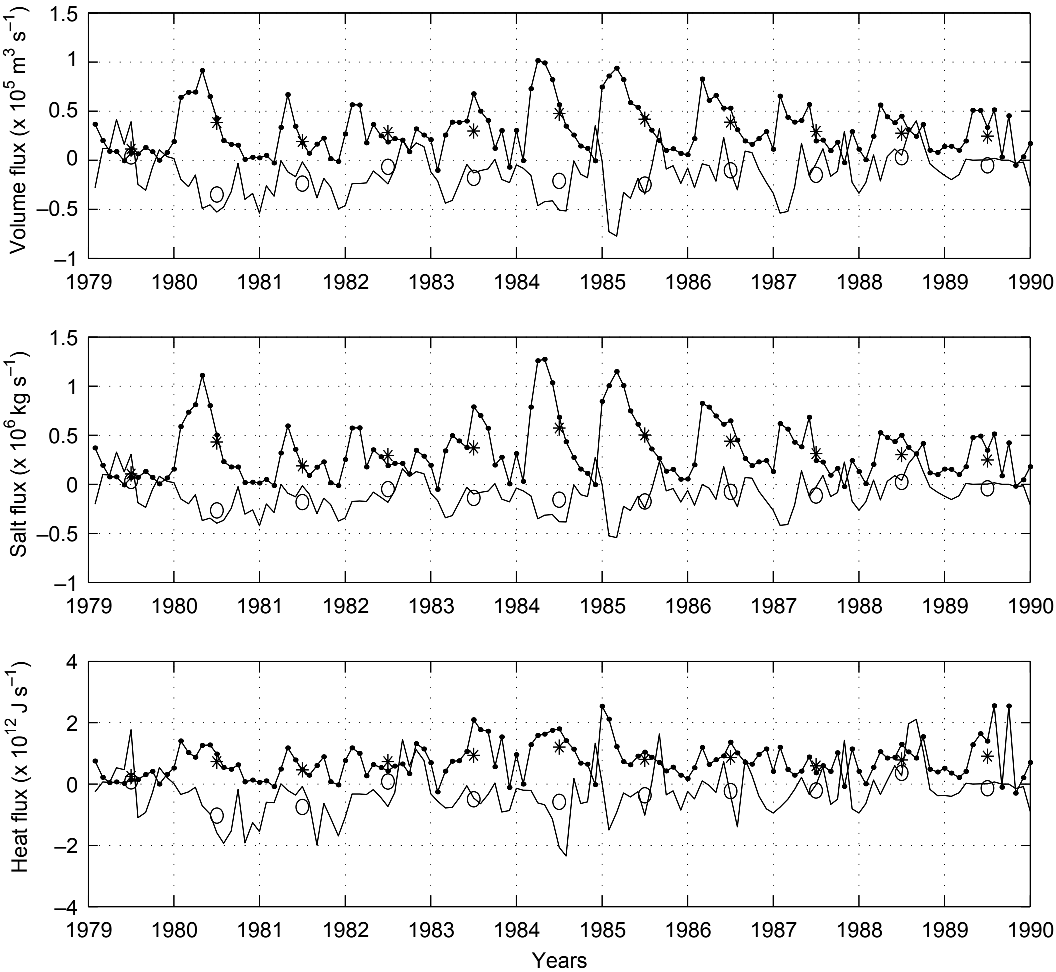

Fig. 4. Volume, salt and heat fluxes through the Bornholm Channel. Continuous line represents fluxes for salinity ≤ 8 PSU, dotted line represent fluxes for salinity > 8 PSU. Symbols represent corresponding annual mean values.

increasing salt and heat fluxes which directly affect the temperature and salinity distribution in the Bornholm Basin by advection. The flux of water with salinity > 10 PSU is about 18 000 m^3 s^{-1} which is higher than the mean river runoff to the Baltic Sea. Kõuts and Omstedt (1993) calculated a mean inflow rate of 25 000 m^3 s^{-1} for the salinity range from 11 to 18 PSU. This inflow rate is considerably higher compared with our value. The difference is due to the fact that in Kõuts and Omstedt (1993) calculations, minimum flow rates were almost always higher than 15 000 m^3 s^{-1}.

Section 7b reveals a completely different flux characteristics (Fig. 5 and Table 3). There is almost no flow for water masses with salinity > 8 PSU. The flow for water masses with salinity ≤ 8 PSU is mainly directed to the west, only occasionally a flow in eastward direction can be found. There is import of volume, heat and salt through the Bornholm Channel into the Bornholm Basin, and export through the section along 15°E. This is in accordance with the mean circulation described in Lehmann and Hinrichsen (2000b) and Lehmann *et al*. (2002).

Fluxes through the Stolpe Channel (section 8)

The hydrographical conditions in the deep layers of the eastern Gotland Basin and the Gdansk

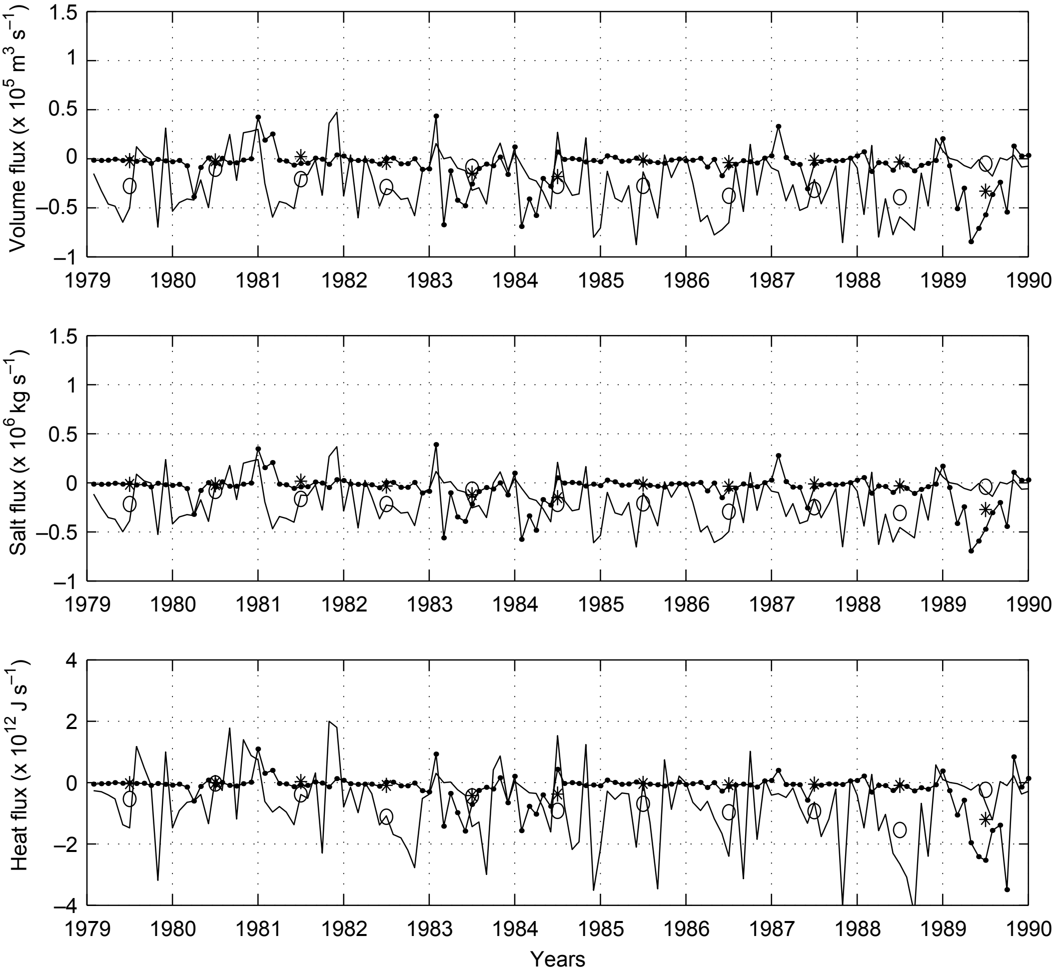

Fig. 5. Volume, salt and heat fluxes through a hydropgraphic section along 15°E. Continuous line represents fluxes for salinity ≤ 8 PSU, dotted line represent fluxes for salinity > 8 PSU. Symbols represent corresponding annual mean values.

Basin are controlled by the flow through the Stolpe Channel. On average the flow is directed to the east (Table 4), which is again in accordance with the mean circulation. Flux calculations through the Stolpe Channel have also been performed for three salinity ranges ($s \leq 8$ PSU, $8 < s \leq 10$ PSU, $s > 10$ PSU). There is a clear seasonal signal in the flow of the upper layer (Fig. 6). From autumn to spring, the flow is directed to the east, during summer the flow direction is reversed. In the lower layers, the main flow to the east occurs during summer when the flow

Table 3. Eleven-year average of volume, heat and salt fluxes through section 7b. Positve values define fluxes to the east, negative values to the west.

Salinity range (PSU)	Volume	Salt	Heat
Total	-3.168×10^4 m^3 s^{-1}	-2.505×10^4 kg s^{-1}	-9.248×10^{11} J s^{-1}
$s \leq 8$	-2.417×10^4 m^3 s^{-1}	-1.876×10^5 kg s^{-1}	-7.110×10^{12} J s^{-1}
$8 < s \leq 10$	-7.193×10^3 m^3 s^{-1}	-5.944×10^4 kg s^{-1}	-2.065×10^{11} J s^{-1}
$s > 10$	-3.154×10^2 m^3 s^{-1}	-3.512×10^5 kg s^{-1}	-7.383×10^{11} J s^{-1}

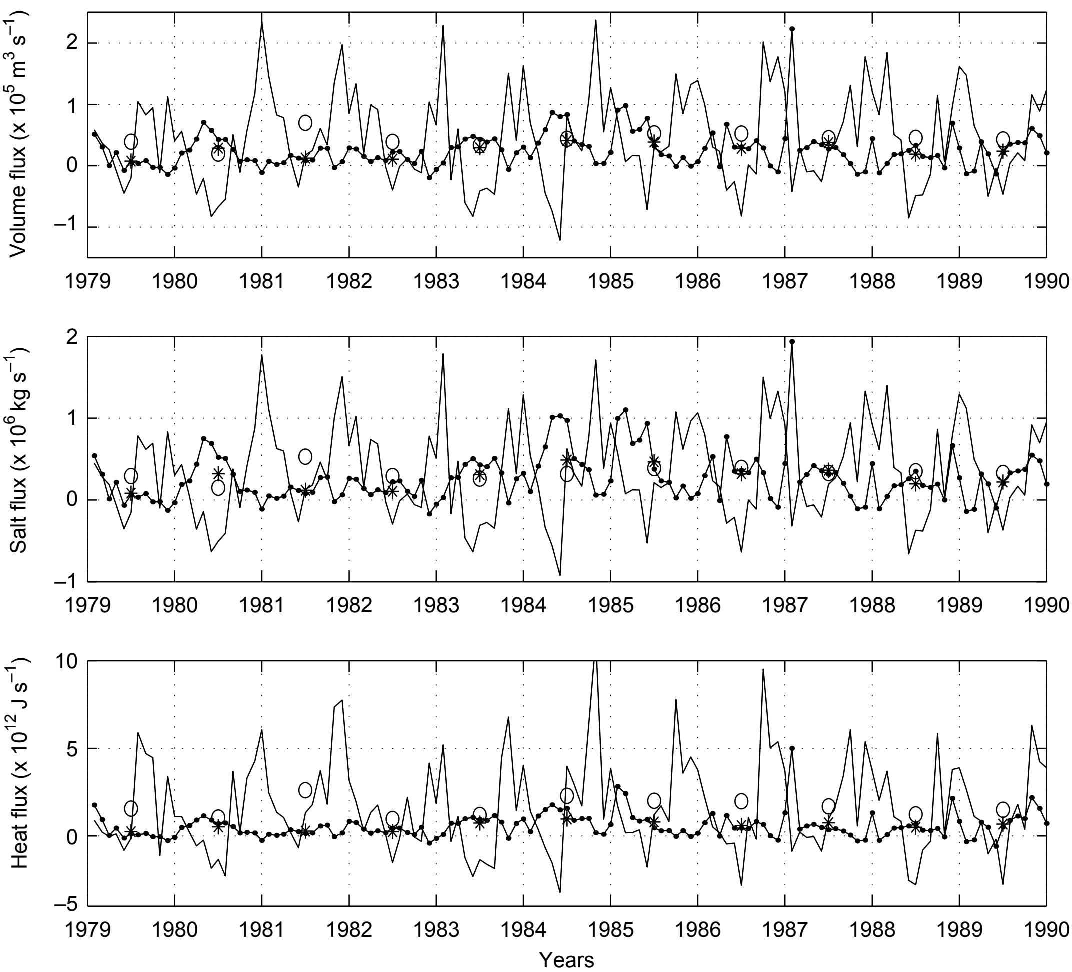

Fig. 6. Volume, salt and heat fluxes through a hydropgraphic section across the Stolpe Channel. Continuous line represents fluxes for salinity ≤ 8 PSU, dotted line represent fluxes for salinity > 8 PSU. Symbols represent corresponding annual mean values.

of the upper layer is directed to the west. The strong seasonal signal in the fluxes suggests that the flow through the Stolpe Channel is mainly controlled by the wind with an increased salt flux into the Gotland and Gdansk Basin during easterly wind conditions (Krauss and Brügge 1991, Lehmann *et al*. 2002). Similar as in section 7a, maximum flow to the east occurred for the years 1980, 1984, 1985 and 1986. The volume flow of water with salinity > 10 PSU is as high as the mean river runoff to the Baltic Sea.

Kõuts and Omstedt (1993) calculated a mean

Table 4. Eleven-year average of volume, heat and salt fluxes through section 8. Positve values define fluxes to the east, negative values to the west.

Salinity range (PSU)	Volume	Salt	Heat
Total	6.885×10^4 m^3 s^{-1}	6.033×10^5 kg s^{-1}	2.214×10^{12} J s^{-1}
$s \leq 8$	4.377×10^4 m^3 s^{-1}	3.302×10^5 kg s^{-1}	1.642×10^{12} J s^{-1}
$8 < s \leq 10$	8.792×10^3 m^3 s^{-1}	7.782×10^4 kg s^{-1}	2.079×10^{11} J s^{-1}
$s > 10$	1.626×10^4 m^3 s^{-1}	1.943×10^5 kg s^{-1}	3.639×10^{11} J s^{-1}

inflow rate of 37 500 $m^3 s^{-1}$ for the salinity range from 10 to 12 PSU. This inflow rate is again considerably higher compared with our value. The difference may be due to the fact that in Kõuts and Omstedt (1993) calculations, the flow rates by definition never changed sign.

Summary and conclusions

Fluxes of volume, heat and salt have been calculated from numerical model simulations for different sections in areas which are important for the deep water exchange in the Baltic Sea. It should be emphasized that the flux calculations presented here are based on three-dimensional model simulations which include the three-dimensional flow field of the Baltic Sea. Furthermore, in contrast to previous analysis, fluxes have been calculated from high spatially and temporally resolved data. In contrast to previous work (Gustafsson 2001, Kõuts and Omstedt 1993), we involved the atmospheric conditions being mainly responsible for the variability in the fluxes. Three-dimensional ocean circulation models have reached a sufficient state of accuracy that a coherent picture of the circulation and the water mass exchange within the Baltic Sea can be described.

The calculated deep water flow in the Arkona basin is in accordance with independent estimations given in Gustafsson (2001) and Stigebrandt (1987). In Gustafsson's and Stigebrandt's (1987) investigations, it was assumed that the dispersal transport of salt due to the variable wind forced circulation was negligible. Further, it was assumed that the Arkona Basin pool is in geostrophic balance. Neither of these assumptions have been made in our calculations which are based on a three-dimensional numerical ocean general circulation model which has been forced by realistic atmospheric data and river runoff. It is found that the strength of the upper layer flow in the Arkona Basin which is on average directed to the west, opposite to the mean wind direction, is compensated by a flow in deeper layers. Increasing upper layer flow results in an increased lower layer flow in opposite direction and vice versa. The annual mean flow is only weakly correlated with the annual mean runoff to the Baltic Sea. In accordance with the mean circulation, the flow through the Bornholm Channel is on average directed to the east, and south of Bornholm, the flow is directed to the west indicating an import of heat and salt to the Bornholm Basin through the Bornholm Channel and an export south of Bornholm. The flow of the lower more saline layer is increased downstream due to entrainment (Kõuts and Omstedt 1993). The flux characteristics change further downstream in the Stolpe Channel. The volume flow in the upper layer shows a strong seasonal signal. During autumn to spring the flow is mainly directed to the east, in summer the flow direction is reversed. Flow in westerly directions is related to increased lower layer flow in easterly directions. This exchange mechanism is controlled by the prevailing wind direction, and has been described by Krauss and Brügge (1991) and Lehmann *et al*. (2002). On average, the net flow through the Stolpe channel is directed to the east which is in accordance with the mean circulation. According to Lehmann and Hinrichsen (2000a), the flow through the Stolpe Channel is part of a huge circulation cell comprising the eastern and western Gotland Basin. The difference in the flow charachteristics between the Arkona Basin and the Stolpe Channel is due to the fact that in the Stolpe Channel the river runoff has no direct influence on the upper layer flow. Thus, the flow can change its direction in dependence on the prevailing wind forcing.

The calculated fluxes show high intra- and inter-annual variability with no obvious trend during the eleven-year period. The variability of the deep water stratification in the deep basins of the Baltic Sea is directly controlled by the changing flux characteristics. Longer simulations are necessary to further investigate the impact of changes in atmospheric forcing and river runoff on the exchange of heat and salt in the deep basins of the Baltic Sea.

Acknowledgements: We are grateful to Lars Meuller (SMHI) who provided the atmospheric forcing data. The work was supported by the BMBF (German Ministry for Education and Research, 01 LD 0025, BALTEX/DEKLIM).

References

Baltic Sea Experiment BALTEX — Initial Implementaion Plan 1995. Int. BALTEX Secretariat Pub. Ser. No. 2, 84 pp.

Bergström S. & Carlsson B. 1994. River runoff to the Baltic Sea: 1950–1990. *Ambio* 23: 280–287.

Gustafsson B.G. 2001. Quantification of water salt, oxygen and nutrient exchange of the Baltic Sea from observations in the Arkona Basin. *Cont. Shelf Res.* 21: 1485–1500.

Hibler W.D. 1979. A dynamic thermodynamic sea ice model. *J. Phys. Oceanogr.* 9: 815–846.

Hinrichsen H.-H., St. John M.A., Aro E., Grønkær P. & Voss R. 2001. Testing the larvae drift hypothesis in the Baltic Sea: Retention vs. dispersion due to the influence of the wind-driven circulation. *ICES Mar. Sci. Symp.* 58: 973–984.

Killworth P., Stainforth D., Webb D.J. & Paterson S.M. 1989. A free surface Bryan-Cox-Semtner model. *Inst. of Oceanogr. Sci. Deacon Laboratory Rep.* 270, 184 pp.

Killworth P., Stainforth D., Webb D.J. & Paterson S.M. 1991. The development of a free-surface Bryan-Cox-Semtner ocean model. *J. Phys. Oceanogr.* 21: 1333–1348.

Kõuts T. & Omstedt A. 1993. Deep water exchange in the Baltic Proper. *Tellus* 45: 311–324.

Krauss W. & Brügge B. 1991. Wind-produced water exchange between the deep basins of the Baltic Sea. *J. Phys. Oceanogr.* 21: 373–384.

Lehmann A. 1995. A three-dimensional baroclinic eddy-resolving model of the Baltic Sea. *Tellus* 47: 1013–1031.

Lehmann A. & Hinrichsen H.-H. 2000a. On the thermohaline variability of the Baltic Sea. *J. Mar. Sys.* 25: 333–357.

Lehmann A. & Hinrichsen H.-H. 2000b. On the wind driven and thermohaline circulation of the Baltic Sea. *Phys. Chem. Earth* (B) 25: 183–189.

Lehmann A., Krauss W. & Hinrichsen H.-H. 2002. Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. *Tellus* 54: 299–316.

Meier H.E.M. 2000. The use of a $k - \varepsilon$ turbulence model within the Rossby Centre regional ocean climate model: Parameterization, development and results. *Rep. Oceanogr.* 28, SMHI, Norrköping, Sweden, 81 pp.

Parkinson C.L. & Washington W.M. 1979. A large-scale numerical model of sea ice. *J. Geophys. Res.* 84: 311–337.

Stigebrandt A. 1987. Computations of the flow of dense water into the Baltic Sea from hydrographical measurements in the Arkona Basin. *Tellus* 39A: 170–177.

Stössel A. & Owens W.B. 1992. The Hamburg sea-ice model. *DKRZ Techn. Rep.* 3. 61 pp.

Voss R., Hinrichsen H.-H. & St. John M.A. 1999: Variations in the drift of larval cod (*Gadus morhua* L.) in the Baltic Sea: Combining field observations and modeling. *Fish. Oceanogr.* 8: 199–221.

Received 23 January 2002, accepted 20 October 2002