BOREAL ENVIRONMENT RESEARCH 7: 327–334 ISSN 1239-6095
Helsinki 23 December 2002

Simulated water and heat cycles of the Baltic Sea using a 3D coupled atmosphere–ice–ocean model

H. E. Markus Meier* and Ralf Döscher

*Rossby Centre, Swedish Meteorological and Hydrological Institute, SE-60176 Norrköping, Sweden (*e-mail: markus.meier@smhi.se)*

Meier, H.E.M. & Döscher, R. 2002: Simulated water and heat cycles of the Baltic Sea using a 3D coupled atmosphere–ice–ocean model. — *Boreal Env. Res.* 7: 327–334. ISSN 1239-6095

The heat and water cycles of the Baltic Sea are calculated utilizing multi-year model simulations. This is one of the major objectives of the BALTEX program. For the period 1988–1993, results of a 3D ice-ocean model forced with observed atmospheric surface fields are compared with results of a fully coupled atmosphere-ice-ocean model using re-analysis data at the lateral boundaries. The state-of-the-art coupled model system has been developed for climate study purposes in the Nordic countries. The model domain of the atmosphere model covers Scandinavia, Europe and parts of the North Atlantic whereas the ocean model is limited to the Baltic Sea. The annual and monthly mean heat budgets for the Baltic Sea are calculated from the dominating surface fluxes, i.e. sensible heat, latent heat, net longwave radiation and solar radiation to the open water or to the sea ice. The main part of the freshwater inflow to the Baltic is the river runoff. A smaller part of about 11% is added from net precipitation. The heat and water cycles are compared with the results of a long-term simulation (1980–1993) using the stand-alone Baltic Sea model forced with observed atmospheric surface fields. In general, both approaches, using the uncoupled or coupled Baltic Sea model, give realistic estimates of the heat and water cycles and are in good agreement with results of other studies. However, in the coupled model the parameterizations of the latent heat flux and the incoming longwave radiation need to be improved.

Introduction

The Baltic Sea is one of the world's largest brackish water seas with hampered water exchange to the world ocean. The semi-enclosed character of the Baltic Sea supports studies on the water and heat cycles using either observations, regional atmosphere models, Baltic Sea models or even coupled atmosphere-ice-ocean models. A comprehensive study of this kind has been published earlier by the Helsinki Commission based on empirical results (HELCOM 1986). The first study utilizing a Baltic Sea model has been performed by Omstedt and Rutgersson (2000). They used a horizontally integrated model of 13 boxes and found that in a long-term mean the Baltic Sea is almost thermodynamically closed like a lake. The dominating fluxes, as annual means, are the sensible heat, the latent heat, the net longwave radiation, the solar radiation to the open water and the heat flux between water and ice. In water and heat cycle studies for the BALTEX program, the response of the salinity and heat content of the Baltic Sea are important parameters to study when evaluating and improving the atmosphere, ocean and river runoff models.

The BALTEX program has initiated a comprehensive integration of atmospheric, oceanic, land surface and hydrological modeling incorporating inter alia snow, sea ice and lake models of various complexity. These models have been validated, improved and combined with data assimilation. Consequently, major progress has taken place in our understanding of the heat and water cycle in the Baltic Sea area during the last years. Of particular importance has been the advance in atmospheric modeling making the use of coupled atmosphere-ocean models feasible. An overview of recent research achievements of the BALTEX research program on this subject is given by Bengtsson (2001).

The objective of the present paper is to analyze the water and heat cycles of the Baltic Sea. A comparison for a five year period is performed between the results of a state-of-the-art Baltic Sea model forced with observed atmospheric surface fields and the results of this ice-ocean model coupled to a regional atmosphere model. The advantage of the first strategy is that the results do not include typical biases of regional atmosphere models. However, meteorological observations over the open sea are sparse. Land-sea gradients are underestimated within the utilized gridded atmospheric data set. The second strategy aims to overcome this limitation. As coupled atmosphere-ice-ocean models are used more and more for regional applications, the objective of the present study is to identify and to quantify biases of the water and heat cycles of the Baltic Sea in a coupled system.

Material and methods

Within the Swedish Regional Climate Modeling Program (SWECLIM) a 3D coupled ice-ocean model for the Baltic Sea has been developed to simulate physical processes on time scales of hours to decades. This model is the Rossby Centre Ocean model (RCO) which has open boundary conditions in the northern Kattegat (Meier *et al*. 1999, Meier 2001, Meier and Faxén 2002, Meier *et al*. 2002). In this paper, results of 13-year simulations (1980–1993) forced with observations of the data base of the Swedish Meteorological and Hydrological Institute (SMHI) are used to calculate the water and heat cycles of the Baltic Sea. Thereby, standard bulk formulae are utilized (Meier 2002a). Recently, also the coupling with a regional atmosphere model has been performed (Döscher *et al*. 2002). This model is the Rossby Centre Atmosphere Ocean model (RCAO). At the lateral boundaries of the atmosphere model re-analysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) are used. The simulation period is September 1988 to August 1993. For that period results of coupled and uncoupled runs of the Baltic Sea model are compared and budgets of surface fluxes are calculated.

The total heat flux (Q_a) from the atmosphere into the coupled ice-ocean system consists of the following components: shortwave radiation (Q_{SW}), incoming and outgoing longwave radiation (Q_{LW}), sensible (Q_S) and latent (Q_L) heat flux into the ocean and into the sea ice:

$$Q_a = Q_a\,|_{\,\mathrm{noice}}\,(1 - A) + Q_a\,|_{\,\mathrm{ice}}\,A \qquad (1)$$

with

$$\begin{aligned} Q_a\,|_{\,\mathrm{noice}} = {} & Q_{SW}\,|_{\,\mathrm{noice}} + Q_{LW}\,|_{\,\mathrm{noice}} \\ & + Q_S\,|_{\,\mathrm{noice}} + Q_L\,|_{\,\mathrm{noice}}, \end{aligned} \qquad (2)$$

and with a corresponding formula for the ice case. A is ice concentration. For the calculation of the heat budget (Table 1) changes of the heat content and minor important heat fluxes are disregarded, e.g., fluxes associated with river runoff and precipitation, and with transports through the Danish Straits. However, the latter heat flux is only small in the long-term mean. A similar approach is applied to calculate the water cycle (Table 2).

For validation purposes, sea surface temperatures (SSTs) of the uncoupled RCO are compared to observations from 9 monitoring stations for the period 1980–1993. The agreement is regarded as good. The rms error is increasing from Anholt East in Kattegat (1 °C) to F9 in the northern Gulf of Bothnia (1.7 °C). The monthly mean SST error is within the range of –1 °C and 1 °C. Independent of the used heat flux parameterizations, the mean SST error has a clear seasonal cycle with overestimated SSTs in summer and underestimated SSTs in winter (Meier 2002a). This is the consequence of the atmospheric forcing data set which includes mainly land stations. Simulated sea ice extent, ice thickness and snow thickness at the monitoring station Kemi in the northern Gulf of Bothnia are in good correspondence with observations (Meier 2002b). The mean error of maximum ice extent is 15×10^9 m^2 (model overestimation of about 8%) and the rms error is 39×10^9 m^2. The model simulation shows also high skill for the timing of the maximum ice extent. As compared with climatological data for the eastern Gotland Basin (Dera 1992) monthly mean shortwave radiation is somewhat underestimated. We find that this lack is compensated in summer by an overestimation of longwave incoming radiation due to overestimated total cloud coverage in the atmospheric forcing data set. For a more detailed model validation of RCO the reader is referred to Meier *et al*. (2002). For the validation of RCAO the reader is referred to Döscher *et al*. (2002).

Results

The heat cycle

In the annual mean, the ocean gains heat from the atmosphere mainly in the southern Gotland Basin (south of Gotland), in the southern Gulf of Bothnia and in coastal areas in the Kattegat, in the Gulf of Finland close to the Finnish coast, and in the southern Gulf of Riga (Fig. 1). The ocean loses heat in the eastern and northern Gotland Basin, and in the central Gulf of Bothnia.

In winter, the net heat flux is directed towards the atmosphere (not shown). The heat loss is largest in the eastern and northern Gotland Basin and in the south-eastern Gulf of Bothnia. In spring, the Baltic Sea gains heat from the atmosphere

Table 1. Heat balance of the Baltic Sea (without Kattegat) in W m^{-2}.

Authors	Q_a	Q_{SW}	Q_{LW}	Q_S	Q_L
Omstedt and Rutgersson 2000	1	89	–43	–7	–35
RCO (13 y)	1	90	–45	–12	–32
RCO (5 y)	1	93	–46	–11	–35
RCAO (5 y)	0	105	–53	–10	–41
Henning 1988	–16	41*	–	–18	–39
Jacob 2001	16	119	–57	–11	–35
Lindau 2002	–1	122	–69	–12	–42

* $Q_{SW} + Q_{LW}$

Table 2. Water balance of the Baltic Sea (without Kattegat) in m^3 s^{-1}.

Authors	Runoff	Net precipitation	Total
Bergström and Carlsson 1994	14 151	–	–
HELCOM 1986: table 11g	13 816	1268	15 084
Omstedt *et al*. 1997	–	1986	–
Omstedt and Rutgersson 2000	–	1868	–
Rutgersson *et al*. 2002	–	1527	–
Jacob 2001	14 165	2345	16 510
RCO (13 y)	15 070	1843	16 913
RCO (5 y)	14 760	1452	16 212
RCAO (5 y)	16 090	119	16 209

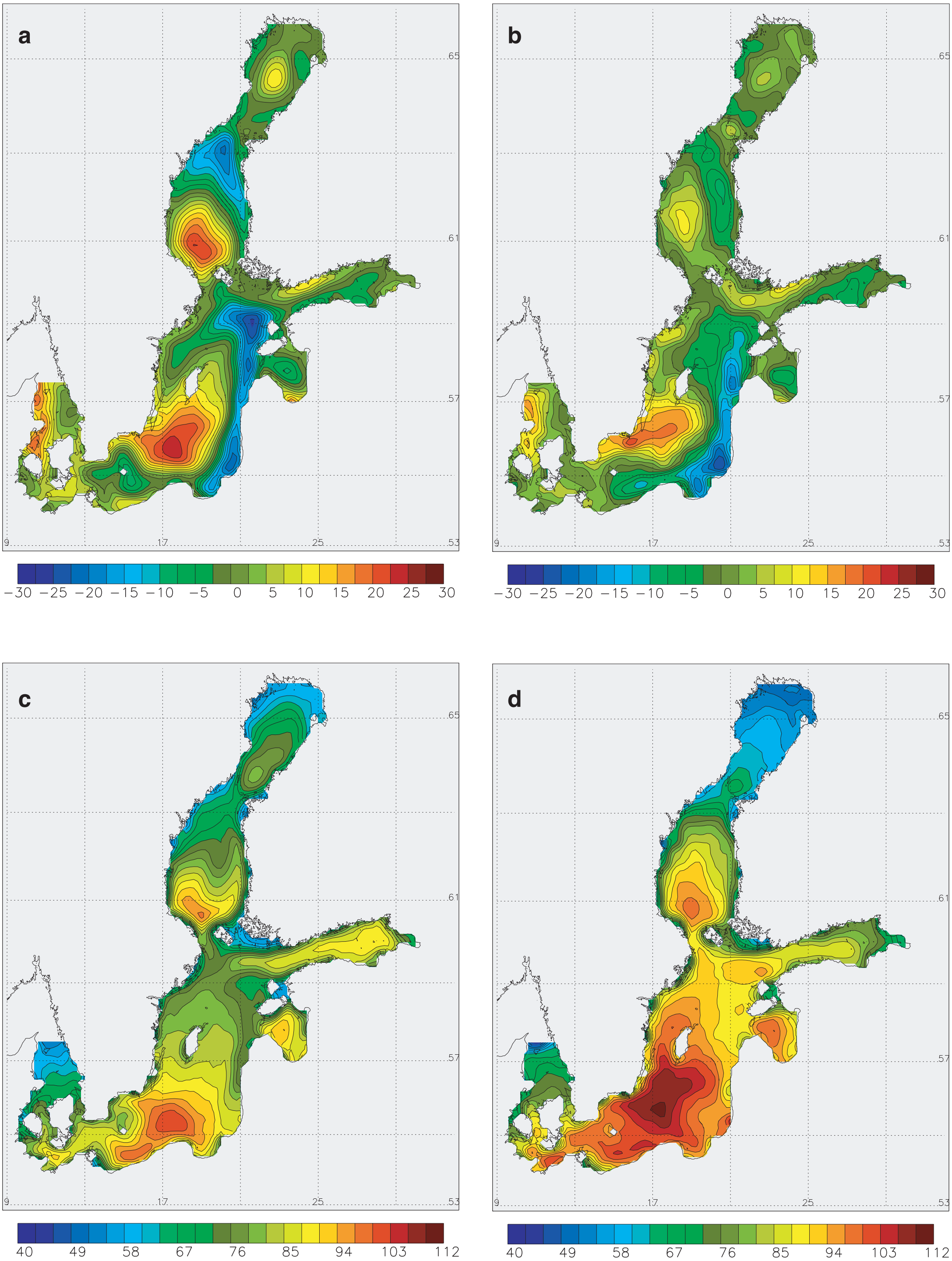


Fig. 1 (**a**–**d**). Annual (**a** and **b**) and seasonal (**c** and **d**) mean total heat fluxes for spring (March–May) in W m^{-2}: RCO (left) and RCAO (right). Positive values indicate heat fluxes into ice or ocean. The investigated period is September 1988 to August 1993.

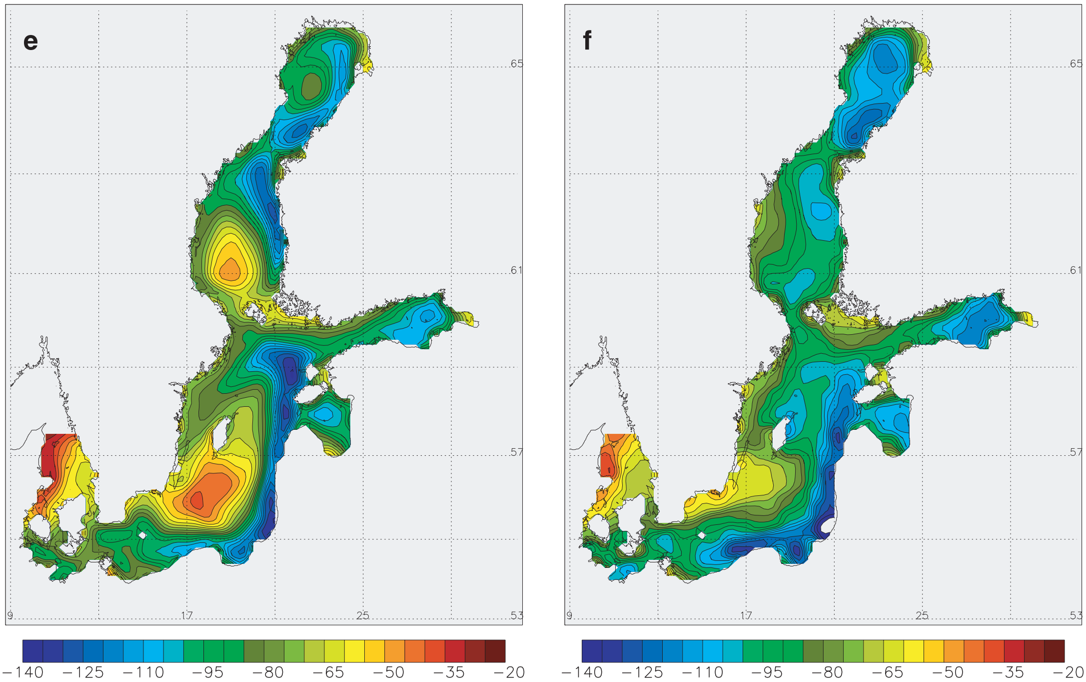
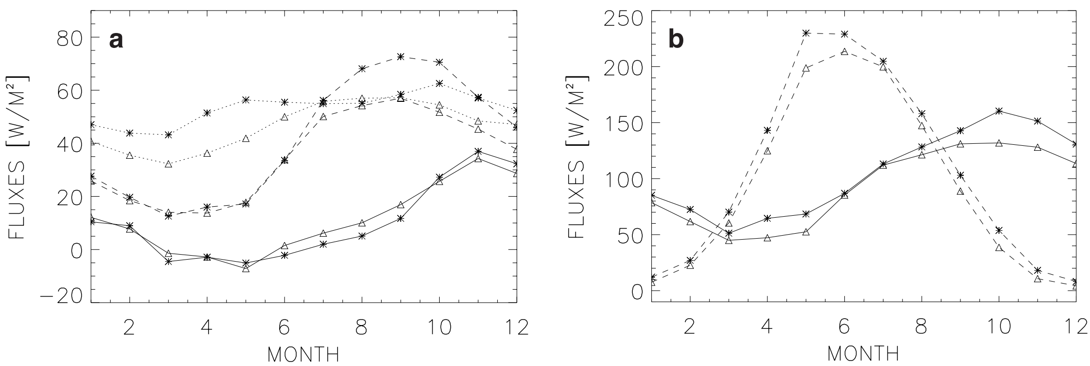


Fig. 1 (**e–f**). Seasonal mean total heat flux for autumn (September–November) in W m^{-2}: RCO (left) and RCAO (right). Positive values indicate heat fluxes into ice or ocean. The investigated period is September 1988 to August 1993.

with maximum in the eastern Bornholm Basin or southern Gotland Basin (Fig. 1). In summer, the maximum is shifted towards the Gulf of Bothnia (not shown). The maximum in the northern Gulf of Bothnia exceeds even 135 W m^{-2}. In autumn, the net heat flux is directed towards the atmosphere with maximum loss in the eastern Gotland Basin and minimum loss in the southern Gotland Basin (south of Gotland) and in the southern Gulf of Bothnia (Fig. 1). The autumn pattern shows up clearly in the annual mean.

During all months of the year the area averaged net heat loss to the atmosphere without shortwave radiation ($Q_n = Q_S + Q_L + Q_{LW}$) is larger in RCAO than in RCO due to larger net longwave radiation in winter and spring and due to higher latent heat flux in autumn (Fig. 2a and b). Incoming shortwave radiation is also higher in RCAO than in RCO which might be an improvement as compared with observations (Fig. 2b). Summing up both components, the amplitude of the mean seasonal cycle of the heat fluxes in RCAO is increased (Fig. 2c). Maximum differences (RCAO minus RCO) occur in May (–15 W m^{-2}) and in November (+16 W m^{-2}). Despite of these quite large differences, horizontal annual and seasonal mean heat flux patterns are relatively similar in RCO and RCAO (Fig. 1). In RCAO, the autumn minima of heat loss in the southern Gotland Basin (south of Gotland) and in the southern Gulf of Bothnia are less pronounced and shifted towards the coasts.

The empirical and modeled results of the mean heat budget presented by different authors are not directly comparable since they represent different time periods, e.g., 1981–1995 by Omstedt and Rutgersson (2000) or 1979–1988 by Jacob (2001) (Table 1). In our model, the Baltic Sea gains heat at the sea surface of about 1 W m^{-2} in the long-term mean (1980–1993). This heat is transported through the Danish Straits out of the system. Shortwave radiation, longwave radiation, sensible and latent heat amount to 90, –45, –12 and 32 W m^{-2}, respectively. These results agree very well with results by Omstedt and Rutgersson (2000). We found the largest difference for the sensible heat of 5 W m^{-2}. Differences of up to 3 W m^{-2} occur when the same version of RCO is used but for the shorter period 1988–1993.



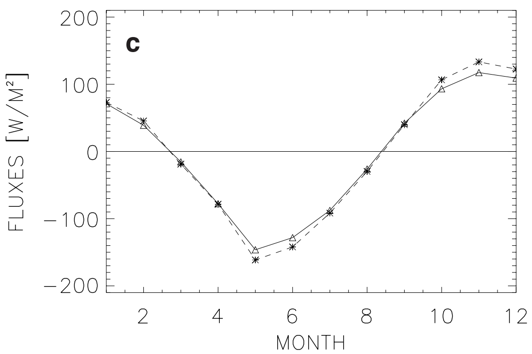


Fig. 2. Climatological monthly means (for the period September 1988 to August 1993) of (**a**) the sensible heat flux (Q_S, solid), the latent heat flux (Q_L, dashed), the net longwave radiation (Q_{LW}, dotted), (**b**) the heat loss to the atmosphere ($Q_n = Q_S + Q_L + Q_{LW}$, solid) and the solar radiation ($-Q_{SW}$, dashed). In (**c**) the total heat loss is depicted (Q_a, solid/dashed). Triangles and asterisks denote RCO and RCAO, respectively. Positive values indicate fluxes to the atmosphere.

The water cycle

In both models, RCO and RCAO, we found maxima of runoff, precipitation, and net precipitation in May, August, and March, respectively (Fig. 3). The mean seasonal cycle is simulated realistically. Runoff in RCAO is larger and precipitation smaller than in RCO, except for the winter months. Due to larger evaporation in RCAO, the net precipitation is negative between July and November.

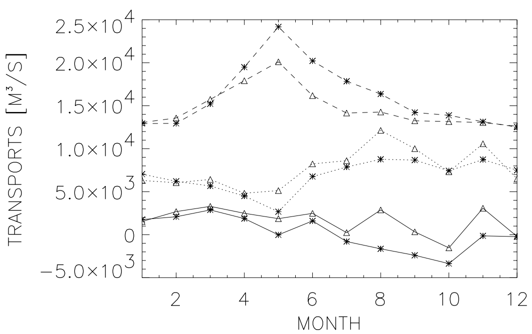


Fig. 3. Climatological monthly means of river runoff (dashed), precipitation (dotted), and net precipitation (solid), i.e. precipitation minus evaporation, for the period September 1988 to August 1993 in $m^3 s^{-1}$. Triangles and asterisks denote RCO and RCAO, respectively. Positive values indicate volume fluxes into ice or ocean.

In the annual mean, freshwater uptake occurs in the Gulfs in both models (Fig. 4). In the Baltic proper, we found large differences between the models. In RCO, evaporation is larger (smaller) than precipitation in the western (eastern) Baltic proper. To the contrary, we found in RCAO negative net precipitation in the entire Baltic proper.

The results of the mean water cycle presented by Bergström and Carlsson (1994) are based on observations over 41 years (1950–1990) (Table 2). As in Table 1, the results of different authors are not directly comparable since they represent different time periods, e.g., 1981–1998 by Rutgersson *et al.* (2002) or 1979–1988 by Jacob (2001). RCO runoff has been taken from the BALTEX Hydrological Data Centre (Bergström and Carlsson 1994). Therefore, these values are not (from the observations) independent estimates but show the inter-annual variability. Long-term mean RCO results of net precipitation agree very well with results by Omstedt *et al.* (1997) and by Omstedt and Rutgersson (2000). The bias amounts to about 8% only.

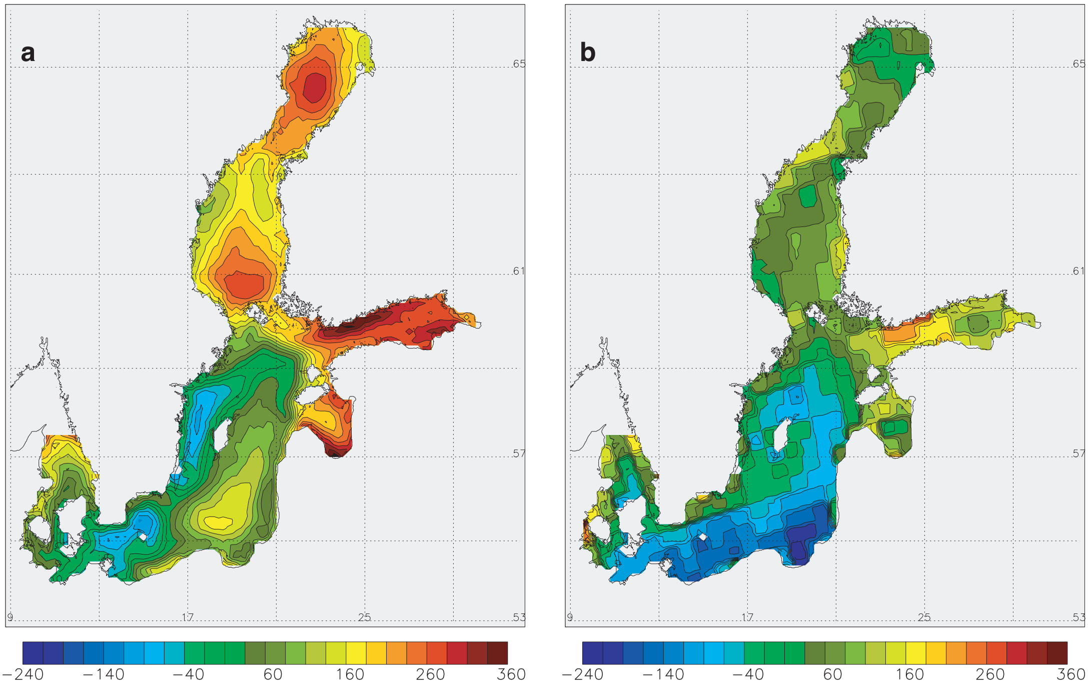


Fig. 4. Annual mean net precipitation, i.e. precipitation minus evaporation, for the period September 1988 to August 1993 in $m^3 s^{-1}$ in mm. Positive values indicate volume fluxes into ice or ocean.

Discussion

Simulated water and heat cycles are biased by a number of uncertainties. Due to the high interannual variability of the fluxes into the Baltic Sea system, i.e. water exchange through the Danish Straits, runoff, and surface fluxes, only water and heat cycles inferred from at least decade-long simulations are converging. The 5-year simulations presented here, are somewhat too short. The magnitude of this bias is estimated to be of the order of 3 W m^{-2} for mean heat flux components and of about 4% for runoff.

In stand-alone RCO runs, bulk formulae of limited accuracy and land biased atmospheric surface fields cause uncertainties in the simulated water and heat cycles. Contrary, biases of the ocean model itself are of minor importance, e.g. the underestimated mixed layer depth or the neglected variability of the extinction lengths of shortwave radiation in the ocean due to biological activity (Meier 2001). Another smaller uncertainty is related to the albedos of different types of sea ice.

Uncertainties due to different bulk formulae for surface heat fluxes and evaporation will be discussed thoroughly in a forthcoming paper.

The uncertainty sources in RCAO are connected with the calculation of the surface freshwater and heat fluxes in the atmosphere model and with the details of the coupling implementation, e.g. the handling of interpolation between the grids (Döscher *et al*. 2002).

The spread of results from other studies gives an impression of our knowledge of the water and heat cycles (Tables 1 and 2). As in both models, RCO and the process-oriented PROBE-Baltic model (e.g. Omstedt and Rutgersson 2000), the same atmospheric forcing and similar bulk formulae are applied and as almost the same period is simulated to calculate the water and heat cycles, the agreement of results suggests that the horizontal integrated flux budgets are relatively insensitive to processes on the sub-basin scale. However, fluxes calculated on the sub-basin scale may be very different in 3D ocean models compared to fluxes in horizontally integrated models. The advantage of using a 3D ocean model like

RCO is that the impact of sub-basin scale processes, e.g. up- and downwelling, on the regional climate, e.g. in coastal areas, can be studied.

Conclusions

The main conclusions are:

- As sea ice and SST in the Baltic Sea are sensitive to biases of simulated surface heat fluxes, the calculation of the heat cycle should include ocean models.
- Due to the high variability of the system, multi-year runs are necessary to calculate reliable water and heat cycles of the Baltic Sea.
- In general, the largest uncertainties in the heat cycle are related to the radiative fluxes in both, coupled and uncoupled, models. In addition, the parameterization of the latent heat flux in the coupled model needs to be improved. Large mean evaporation causes smaller net precipitation than calculated in other studies.
- Despite of still available biases, the water and heat cycles of the fully coupled model are simulated satisfactory.
- The ocean dynamics have a quite large impact on horizontal mean heat and freshwater flux patterns.These patterns are similar simulated in RCO and RCAO.

Acknowledgments: The SWECLIM program and the Rossby Centre are funded by the Foundation for Strategic Environmental Research (MISTRA) and by the Swedish Meteorological and Hydrological Institute (SMHI). The simulations have been performed on the CRAY-T3E at the Swedish National Supercomputer Centre (NSC) in Linköping, Sweden.

References

Bengtsson L. 2001. Numerical modelling of the energy and water cycle of the Baltic Sea. *Meteorol. Atmos. Phys.* 77: 9–17.

Dera J. 1992. *Marine physics*. Elsevier, Amsterdam, 516 pp.

Döscher R., Willén U., Jones C., Rutgersson A., Meier H.E.M., Hansson U. & Graham L.P. 2002. The development of the regional coupled ocean-atmosphere model RCAO. *Boreal Env. Res.* 7: 183–192.

HELCOM 1986. Water balance of the Baltic Sea. In: *Baltic Sea environment proceedings*, vol. 16, Baltic Marine Environment Protection Commission, Helsinki, Finland, 174 pp.

Henning D. 1988. Evaporation, water and heat balance of the Baltic Sea. Estimates of short- and long-term monthly totals. *Meteorol. Rdsch.* 41: 33–53.

Jacob D. 2001. A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin. *Meteorol. Atmos. Phys.* 77: 61–73.

Lindau R. 2002. Energy and water balance of the Baltic Sea derived from merchant ship observations. *Boreal Env. Res.* 7: 417–424.

Meier H.E.M. 2001. On the parameterization of mixing in three-dimensional Baltic Sea models. *J. Geophys. Res.* 106: 30997–31016.

Meier H.E.M. 2002a. Regional ocean climate simulations with a 3D ice-ocean model for the Baltic Sea. Part 1: Model experiments and results for temperature and salinity. *Clim. Dyn.* 19: 237–253.

Meier H.E.M. 2002b. Regional ocean climate simulations with a 3D ice-ocean model for the Baltic Sea. Part 2: Results for sea ice. *Clim. Dyn.* 19: 255–266.

Meier H.E.M. & Faxén T. 2002. Performance analysis of a multiprocessor coupled ice-ocean model for the Baltic Sea. *J. Atmos. Oceanic Technol.* 19: 114–124.

Meier H.E.M., Döscher R., Coward A.C., Nycander J. & Döös K. 1999. RCO — Rossby Centre regional Ocean climate model: model description (version 1.0) and first results from the hindcast period 1992/93. *Reports Oceanography* No. 26, SMHI, Norrköping, Sweden, 102 pp.

Meier H.E.M., Döscher R. & Faxén T. 2002. A multiprocessor coupled ice-ocean model for the Baltic Sea: application to salt inflow. *J. Geophys. Res.* [In press].

Omstedt A. & Nyberg L. 1996. Response of Baltic Sea ice to seasonal, interannual forcing and climate change. *Tellus* 48A: 644–662.

Omstedt A. & Rutgersson A. 2000. Closing the water and heat cycles of the Baltic Sea. *Meteorologische Zeitschrift* 9: 55–66.

Omstedt A., Nyberg L. & Meuller L. 1997. Interannual, seasonal and regional variations of precipitation and evaporation over the Baltic Sea. *Ambio* 26: 644–662.

Rutgersson A., Omstedt A. & Räisänen J. 2002. Net precipitation over the Baltic Sea during present and future climate conditions. *Clim. Res.* 22: 27–39.

Received 23 January 2002, accepted 22 October 2002