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Calculating the water and heat balances of the Baltic Sea using ocean modelling and available meteorological, hydrological and ocean data

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ABSTRACT

In this paper we aim to analyse Baltic Sea water and heat balances for the BALTEX/*BRIDGE* study period and to put these into a climatic perspective. The study period—the three years starting October 1999—was a time of enhanced observational and modelling activities in the Baltic Sea region and of the major field activity of BALTEX Phase I programme. The present study follows the example of earlier work, where Baltic Sea modelling was used as a tool for synthesizing available data and closing the water and heat balances. The modelling approach was validated with independent data sets of observations from salinity and temperature. The model simulation was also compared with the coupled atmosphere–Baltic Sea model system, HIRLAM–BALTEX, which was run in a delayed data assimilation mode.

The results indicate that accurate long-term net water and net heat balances (mean errors over decadal time scales are about 600 m^3 s^{-1} and 2 W m^{-2} respectively) can be calculated using current Baltic Sea modelling and meteorological and hydrological data available from the BALTEX data centres. The accuracy of the individual terms in the water and heat balances is, however, still unknown. The study illustrated that negative net precipitation rates are possible, with the year 2002 standing out from the rest of the 30-yr study period. The calculated inter-annual variability of the net heat loss between atmosphere and Baltic Sea during the BALTEX/*BRIDGE* period indicated large variations ($\pm$10 W m^{-2}). It has also been shown that the Baltic Sea annual mean temperature has not increased during the studied period despite an atmospheric warming of 1 °C. The reason has been explained by the heat balance that indicated no trend in the Baltic Sea net heat loss.

1. Introduction

The Global Energy and Water Experiment (GEWEX) was developed within the framework of the World Climate Research Programme (WCRP). Its aim was to improve understanding of global, regional, and local processes that exchange water and energy in the climate system. Within GEWEX, several continental-scale experiments were initiated in various regions, including the Baltic drainage basin. In the Baltic Sea Experiment (BALTEX), the whole drainage basin includes a region that has about 90 million inhabitants. Planning for the BALTEX programme (Fig. 1) started in early 1990 and has now been running for 10 yr (BALTEX, 1995). Several key questions about water and heat cycles were raised in the programme. For example, is net precipitation over the Baltic Sea positive (freshwater being added to the sea) or negative?

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The main experiment of BALTEX Phase I period (1993–2002) was called *BRIDGE*, to signal the collaboration of scientists from various scientific backgrounds from around the Baltic Sea (BALTEX, 1997). The *BRIDGE* experiment was performed from October 1999 to March 2002, the first three months being the pilot phase and the remaining 27 months the basic observational phase.

Different aspects of the Baltic Sea water and heat cycles are given in Bengtsson (2001), Jacob (2001), Lehmann and Hinrichsen (2002), Meier and Döscher (2002), Omstedt and Rutgersson (2000), Raschke et al. (2001), Hennemuth et al. (2003) and Ruprecht and Kahl (2003). Several recent results related to the understanding of these cycles can also be found in special issues of journals emerging from some BALTEX Study Conferences. These include issues of *Tellus* (48A, No. 5, 1996), *Meteorological and Atmospheric Physics* (77, 2001), *Meteorologische Zeitschrift* (9, 2000), and *Boreal Environment Research* (7, 3 and 4, 2002).

In the present paper we examine the water and heat balances of the Baltic Sea during the *BRIDGE* period in relation to

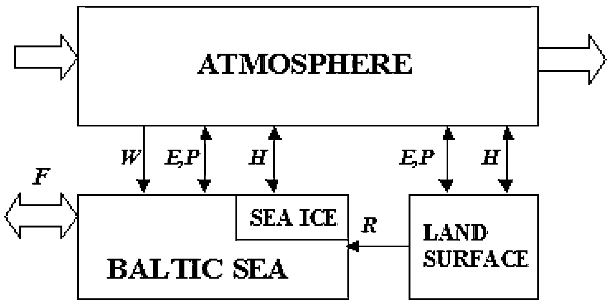

Fig 1. The BALTEX box where W indicates wind, E and P are evaporation and precipitation, H denotes heat fluxes, F is inflows and outflows, and R is river runoff.

current climatic conditions (1970–2002), using the PROBE-Baltic ocean model (Omstedt and Axell, 2003). The paper is intended to contribute to improving our basic understanding of the Baltic Sea and to validating climate models (as in Omstedt et al., 2000). The approach follows that of some earlier studies (Omstedt et al., 1997; Rutgersson et al., 2002), where Baltic Sea modelling is used as a tool for synthesizing available data and to improve our physical understanding of the marine system. The study asks three basic questions. (1) What are the values of the individual terms of the water and heat balances during the BALTEX/*BRIDGE* period and how do they vary over time? (2) How accurately can these balances be calculated? (3) Can detection of climate change signals be done more easily for the water and heat-cycle components compared to standard parameters such as temperature?

The outline of the paper is as follows. In Section 2 we provide the data and models used. Then, in Section 3, the current modelling system is validated using independent data obtained from the Baltic Sea. The meteorological conditions during the study period are discussed in Section 4. In Section 5 we present the results regarding the water and heat cycles. In Section 6 we compare the HIRLAM–BALTEX system and the present modelling approach. In Section 7 we provide a summary and some conclusions.

2. Material and methods

The meteorological forcing data were extracted from the SMHI gridded data base, which has a time resolution of 3 h and $1^\circ \times 1^\circ$ grid resolution, available from the BALTEX Hydrological Data Centre (BHDC). The meteorological parameters include U- and V-components of geostrophic winds, temperature at 2 m, relative humidity at 2 m, total cloudiness, surface pressure and precipitation. River runoff data were also made available from BHDC as monthly mean data. The water level forcing from the North Sea was calculated on the basis of daily mean sea levels from the Kattegat. For validation, vertical profiles of observed salinity and temperature were extracted from the Swedish national database, SHARK, and made available by the Ocean Data Centre of BALTEX (ODCB). Annual maximum ice extent values were made available by the Finnish Institute of Marine Research. For details about the forcing and validation data, the reader is referred to Omstedt and Axell (2003).

In calculating the water and heat cycles, the PROBE-Baltic model was used without any data assimilation. This is a process-oriented, time-dependent coupled basin model, a description of which is given in Omstedt and Axell (2003). For purposes of comparison, monthly mean atmospheric fluxes from the HIRLAM–BALTEX reanalysis were also used. The HIRLAM–BALTEX model uses a special version of the atmospheric model, HIRLAM (Källén 1996), where data assimilation and a coupled ice–ocean model for the Baltic Sea are used (Gustafsson et al., 1998). In the HIRLAM–BALTEX model, calculated sea surface temperatures were adjusted (twice a week) through a nudging process using observed sea surface temperatures obtained from the marine service at SMHI.

3. Validation

3.1. Modelled and observed mean salinity

The model simulation has been carefully examined using a large number of measured salinity and temperature profiles. Some examples are given in Fig. 2, which depicts both observed and calculated data from three sub-basins in the Baltic Sea. The figure illustrates that the model results follow the observations closely and that the observations are irregularly distributed in space and time. Typical values of mean error and root mean square (rms) error for sea surface salinity are -0.3 and 0.5 psu for individual sub-basins (Omstedt and Axell 2003).

To draw conclusions as to the quality of the water balance calculations, we need to examine the observed and modelled mean salinity of the whole Baltic Sea, excluding the Kattegat and the Belt Sea (Fig. 3). We used the mean Baltic Sea salinity (vertically as well as horizontally integrated) as a measure of the quality of the water balance. The calculated mean salinity was compared with the estimated mean salinity by Winsor et al. (2001, 2003). The estimated mean salinity was calculated by first using salinity profiles from all major sub-basins of the Baltic Sea for the 1977–1987 period, a period with good coverage in all sub-basins. Then this mean was compared with data from the central Baltic Sea (BY15), a station that has observations for more than 100 yr. The comparison illustrated that the station BY15 well represents the Baltic Sea and based on data from this station the mean salinity was estimated for the 20th century. From the data presented in Fig. 3 we can note that the present calculated mean salinity is 0.57 less than that calculated by Winsor et al. (2003), which is due to different means when initializing the ocean model. The salinity in our paper is given according to the Practical Salinity Scale defined as a pure ratio without dimensions or units. This is the standard since 1981 when UNESCO adopted the scale. After adjusting the initial value in the Winsor curve to that calculated

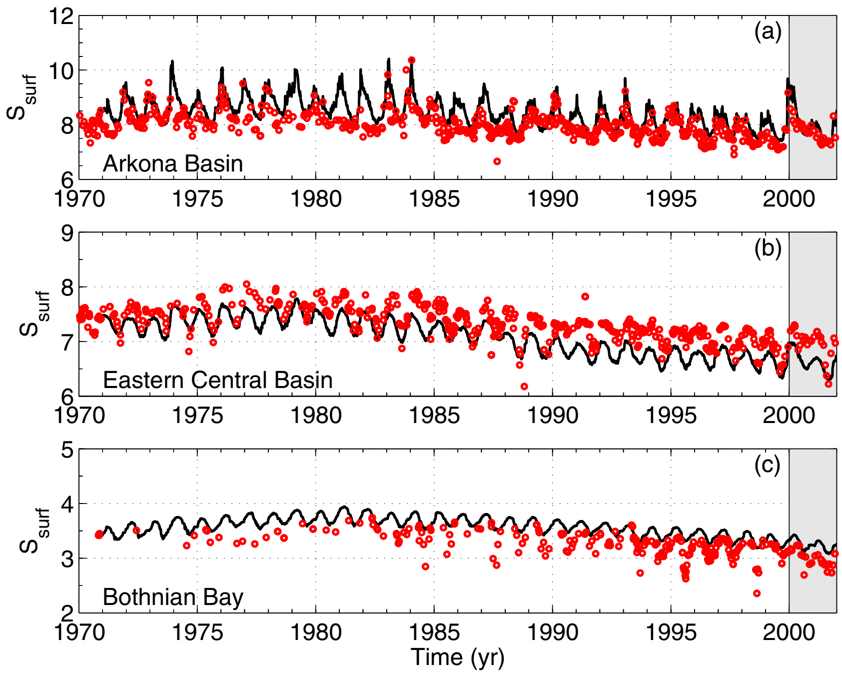

Fig 2. Observed (circles) and modelled (lines) sea surface salinity (S_{surf}) from the Arkona Basin (a), the Eastern Gotland Basin (b), and Bothnian Bay (c). The BALTEX/*BRIDGE* period is marked.

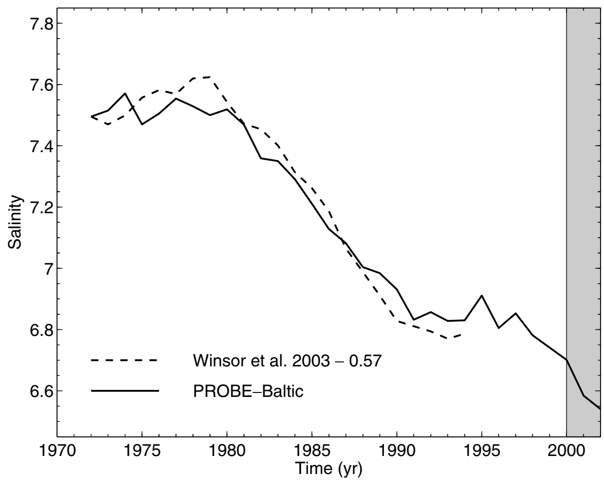

Fig 3. Observed (dashed line) and modelled (solid line) annual variation of Baltic Sea mean salinity. The BALTEX/*BRIDGE* period is marked.

from 1972, we find that the curves follow each other closely. We now translate the error between calculated and observed mean salinities into an estimation of the accuracy in the net water balance. Referring to salt conservation principles, the freshwater change (ΔQ) associated with a salinity difference (ΔS) can be written as

$$\Delta Q = -\frac{V \Delta S}{S \Delta t}, \tag{1}$$

where V is the water volume, S is the salinity and Δt is the time period. With $V = 2 \times 10^{13}$ (m^3) and Δt equal to 1 yr, the mean and rms errors in the freshwater balance are less than 600 and 6000 m^3 s^{-1}, respectively. The mean error is calculated as the sum of the differences between calculated and observed annual mean salinities divided by the number of observations. The rms error is calculated as the square root of the sum of the square of the difference between calculated and observed annual means divided by the number of observations. If we can trust the Winsor estimated mean salinity, the mean error in the water balance calculation is much less than the river runoff (4% of the river runoff), less than the net precipitation (40% of the net precipitation rate) and of the same size as the estimated ground-water flow to the Baltic Sea (Peltonen, 2002), a term often neglected in water balance studies. This is of course a positive result, indicating that the net freshwater balance averaged over decades is quite accurate. The rms error is 10 times as large as the mean error; which implies that water balance studies on time-scales shorter than a decade could have quite large errors. The accuracy of the individual terms in the water balance is, however, not known.

The observed mean salinity could include errors, as the sampling of the salinities in the Baltic Sea was not well distributed in time and space, particularly in the large gulfs. Further work is therefore needed in analysing and calculating the observed Baltic Sea mean salinity, as this information is of great value in water balance studies.

3.2. Modelled and observed mean water temperature

In this section we examine both the observed and modelled temperatures. Figure 4 depicts the match between the observed and modelled sea surface temperatures from three

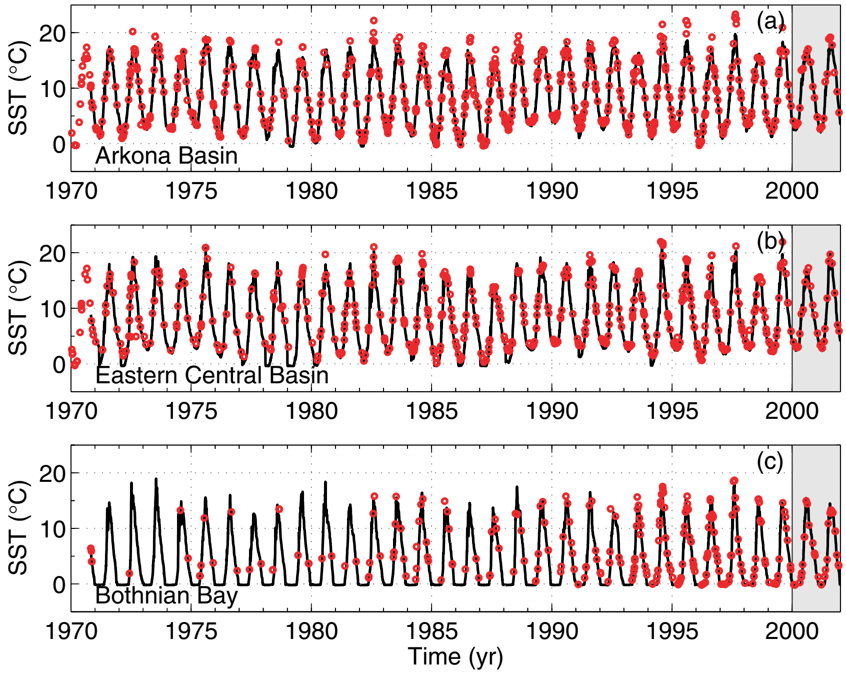

Fig 4. Observed (circles) and modelled (lines) sea surface temperatures (SST) from the Arkona Basin (a), the Eastern Gotland Basin (b), and Bothnian Bay (c). The BALTEX/*BRIDGE* period is marked.

sub-basins. Sea surface temperature is of major importance in the atmosphere–ocean heat exchange, and accurate modelling is needed. The calculated sea surface temperatures closely match the observed data, while the modelled data fills in for missing observations in a realistic manner. Typical values of mean error and rms error for sea surface temperatures are -1 °C and 1–2 °C for the individual sub-basins (Omstedt and Axell, 2003).

We then consider the mean (vertically as well as horizontally integrated) water temperature of the Baltic Sea (Fig. 5). The observed and calculated mean temperatures follow each other closely without any drift. In this case, the observed Baltic Sea mean temperature time series is calculated from 1744 measured profiles from the major sub-basins in the Baltic Sea.

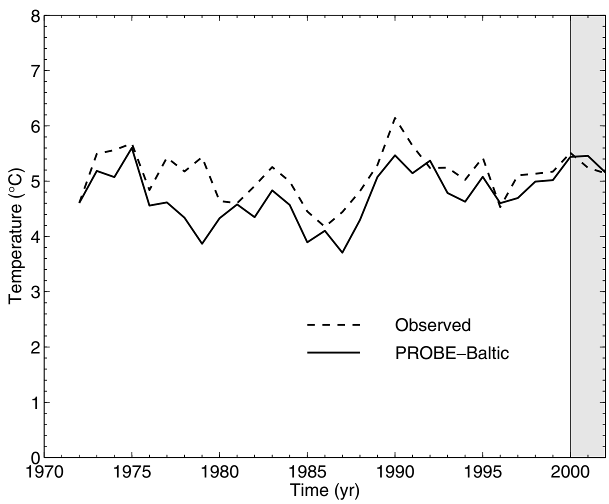

Fig 5. Observed (dashed line) and modelled (solid line) annual variation of Baltic Sea mean water temperature. The BALTEX/*BRIDGE* period is marked.

The temperature error (difference between observed and calculate annual mean temperatures), ΔT, can be related to fluxes through the following relation:

$$\Delta F = \frac{\rho C_{\mathrm{p}} \Delta T D}{\Delta t}. \qquad (2)$$

Here, ΔF is the corresponding error in the atmosphere–ocean net heat flux, ρ is the water density, C_{p} is the specific heat of water, D is the mixed layer depth, and Δt is the studied time period. Using eq. (2) and calculating the mean and the rms flux errors based on the differences between observed and calculated annual mean temperatures, the errors become equal to 2 and 3 W m^{-2}, respectively. We may thus conclude that the net heat balance can be modelled with good precision. The errors in the individual terms in the heat balance are probably one order of magnitude larger.

In calculating the observed Baltic Sea mean temperature, data from stations in the deeper parts of the sub-basins have been used. The effects of the coastal zones are therefore not included, but over inter-annual and decadal time-scales these effects are probably quite small. This is because coastal zones represent only a fraction of the total sea volume, and because the seasonal temperature cycle is generally wider in range in the coastal zones, temperatures being both warmer and colder than in the open sea. However, effects on the coastal zone, including up- and downwelling, need further consideration when calculating the mean observed Baltic Sea temperature.

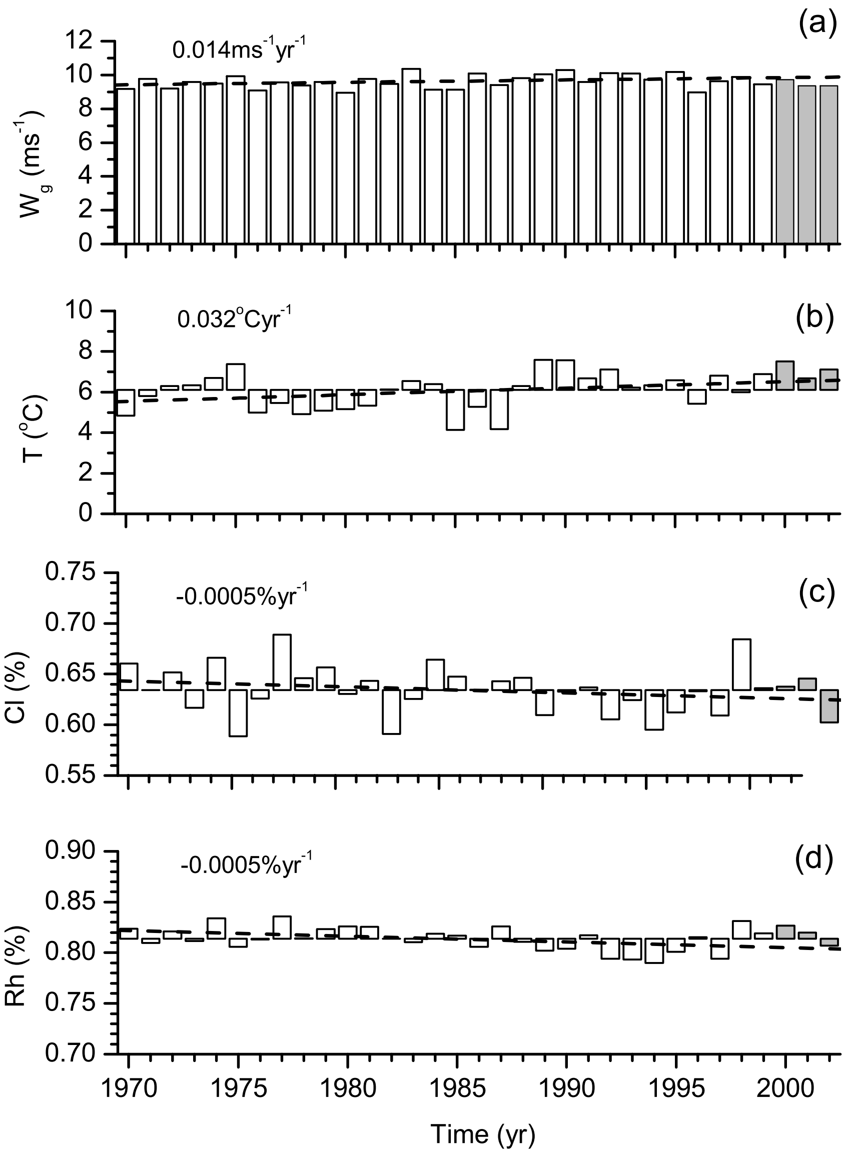

Fig 6. The Baltic Sea horizontal averaged geostrophic wind speed (a), air temperature (b), total cloudiness (c) and relative humidity (d). The figure depicts yearly means calculated over the Baltic Sea surface region (the Belt Sea and the Kattegat excluded) based on the SMHI meteorological data base. The dashed lines indicate the linear trends and the BALTEX/*BRIDGE* period is marked.

Validation of model simulations of sea ice (not shown) indicates that the model realistically simulates sea ice with mean and rms errors of 10 and 41 $\times$ 10^3 km^3, respectively. With a mean error of 10 $\times$ 10^3 km^3 the relative error becomes about 5%. This is close to the estimated accuracy of the observed maximum ice extent data based on modern ice mapping techniques using satellite data.

4. Baltic Sea mean meteorology conditions

Before analysing the various components of the water and heat cycles, we first examine the meteorological mean parameters (horizontally averaged over the Baltic Sea inside the Danish Straits) during the study period. The meteorological data were extracted from the SMHI gridded data base and horizontal mean fields were calculated over the Baltic Sea area.

The horizontal Baltic Sea mean geostrophic wind speed is depicted in Fig. 6a, where we can observe how the annual mean wind speed varies and note that the wind speed has tended to increase over the studied period. Examining this in more detail (not shown) reveals that the annual westerly wind component has increased, while the annual southerly wind component has decreased. The results are in accordance with studies of trends in near-surface flow over the Baltic Sea by Pryor and Barthelmie (2003). From National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis fields over the Baltic region, they found that the wind had increased during the study period, with the largest annual increase in the south-west of the Baltic Sea (+0.025 m s^{-1} yr^{-1}). Increased frequency of storms during the second half of the 20th century has been observed on the coast of Estonia (Orviku et al., 2003). Trends of storms (1880–1998) derived from pressure data have been examined by Alexandersson et al. (2000). They found that the stormy period centred around 1990 had been broken.

Observation of the horizontal Baltic Sea mean air temperature (Fig. 6b) indicates an increasing annual temperature. Temperatures during the BALTEX/*BRIDGE* period were warm, almost similar to temperatures around 1990. Mean cloudiness (Fig. 6c) decreased slightly, with particularly low values occurring in 2002. Relative humidity (Fig. 6d) also indicated a slight decreasing trend.

Analysis of the Baltic Sea horizontal annual mean meteorological forcing parameters indicates that the BALTEX/*BRIDGE* period did not stand out from the range of variation of the last 30 yr, but showed warm annual means with reduced geostrophic wind speeds. In 2002, the mean cloudiness and relative humidity were also reduced. For long-term climate change statistics over the Baltic Sea region, the reader is referred to Omstedt et al. (2004), where the Baltic Sea climate conditions over the past 200 yr are analysed.

5. Results

5.1. Water balance

The water balance involves many processes related to the hydrological cycle in the atmosphere, the land and the ocean climate systems. Starting from the volume conservation principle, we can write the Baltic Sea water balance as follows (Omstedt and Rutgersson, 2000; Stigebrandt, 2001):

$$A_s \frac{dz_s}{dt} = Q_i - Q_o + (P - E)A_s + Q_r + Q_{ice} + Q_{rise} + Q_T + Q_S + Q_g. \tag{3}$$

Here, A_s is the surface area of the Baltic Sea, z_s is the water level of the Baltic Sea, Q_i and Q_o are the inflows and outflows through the Baltic entrance area, P and E are the precipitation and evaporation rates, Q_r is the river runoff, Q_{ice} is the volume change due to ice advection from the Baltic Sea, Q_{rise} is the volume change due to land uplift, Q_T and Q_S are the volume changes due to thermal expansion and salt contraction, and Q_g is the ground-water inflow.

In the following discussion, we neglect contributions from Q_{ice} (of the order of 10^2 m^3 s^{-1}; Omstedt and Rutgersson, 2000), Q_{rise} (of the order of 10^1 m^3 s^{-1}; Omstedt and Rutgersson, 2000), Q_T, Q_S (small on annual time-scales) and Q_g (of the order of 10^2 m^3 s^{-1}; Peltonen, 2002).

An estimate of Q_S can be derived by considering that a change of 1 in salinity corresponds to about a 1-cm change in sea level (the slope from Bothnian Bay to Skagerrak drops about 35 cm as the salinity increases from zero to almost 35). Winsor et al. (2001, 2003) indicate that Baltic Sea salinity varies about 1 per 30 yr. We estimate then that the volume change due to salt contraction on an annual basis is about $1/15$ cm or of the order of 10^1 m^3 s^{-1} (Baltic Sea surface area inside the entrance sills is about 370 000 km^2). Thermal expansion due to heating and cooling may cause seasonal variation in volume flow of the order of 10^3 m^3 s^{-1} (Stigebrandt, 2001), but on an annual scale the volume flow is at least one order of magnitude less. The left term in eq. (3) is the change in water storage (positive for volume increase) and is important for short-term estimations of the water balance (Lehmann and Hinrichsen, 2001). See Table 1 for estimates of the various terms.

The calculated long-term means of the various components of the water balance are presented in Table 2. In the table we distinguish between the BALTEX/*BRIDGE* period, defined as

Table 1. Estimated annual mean volume flows for the Baltic Sea (order of magnitude). The flows are denoted by: inflow (Q_i), outflow (Q_o), net precipitation ($P - E$), river runoff (Q_r), the volume change due to ice advection from the Baltic Sea (Q_{ice}), the volume change due to land uplift (Q_{rise}), the ground-water inflow (Q_g), the volume changes due to thermal expansion (Q_T) and salt contraction (Q_S). A_s denotes the Baltic Sea surface area

Q_i (m^3 s^{-1})	Q_o (m^3 s^{-1})	$Q_o - Q_i$ (m^3 s^{-1})	$(P - E)A_S$ (m^3 s^{-1})	Q_r (m^3 s^{-1})	Q_{ice} (m^3 s^{-1})	Q_{rise} (m^3 s^{-1})	Q_g (m^3 s^{-1})	Q_T (m^3 s^{-1})	Q_S (m^3 s^{-1})
10^5	-10^5	-10^4	10^3	10^4	-10^2	-10^1	10^2	$\pm10^2$	$\pm10^1$

Table 2. Mean water balance for the Baltic Sea (the Belt Sea and the Kattegat excluded) average (in units of 10^3 m^3 s^{-1}). The flows are denoted as river runoff (Q_r), net precipitation ($P - E$), inflow (Q_i), outflow (Q_o), and storage change. A_s denotes the Baltic Sea surface area

Author	Q_i (m^3 s^{-1})	Q_o (m^3 s^{-1})	$Q_o - Q_i$ (m^3 s^{-1})	Q_r (m^3 s^{-1})	$A_s (P - E)$ (m^3 s^{-1})	Storage change (m^3 s^{-1})	Period
Present	38.44	56.32	17.88	14.88	2.05	−0.95	BALTEX/*BRIDGE* 2000–2002
Present	42.75	59.41	16.76	14.96	1.70	−0.11	1979–2002

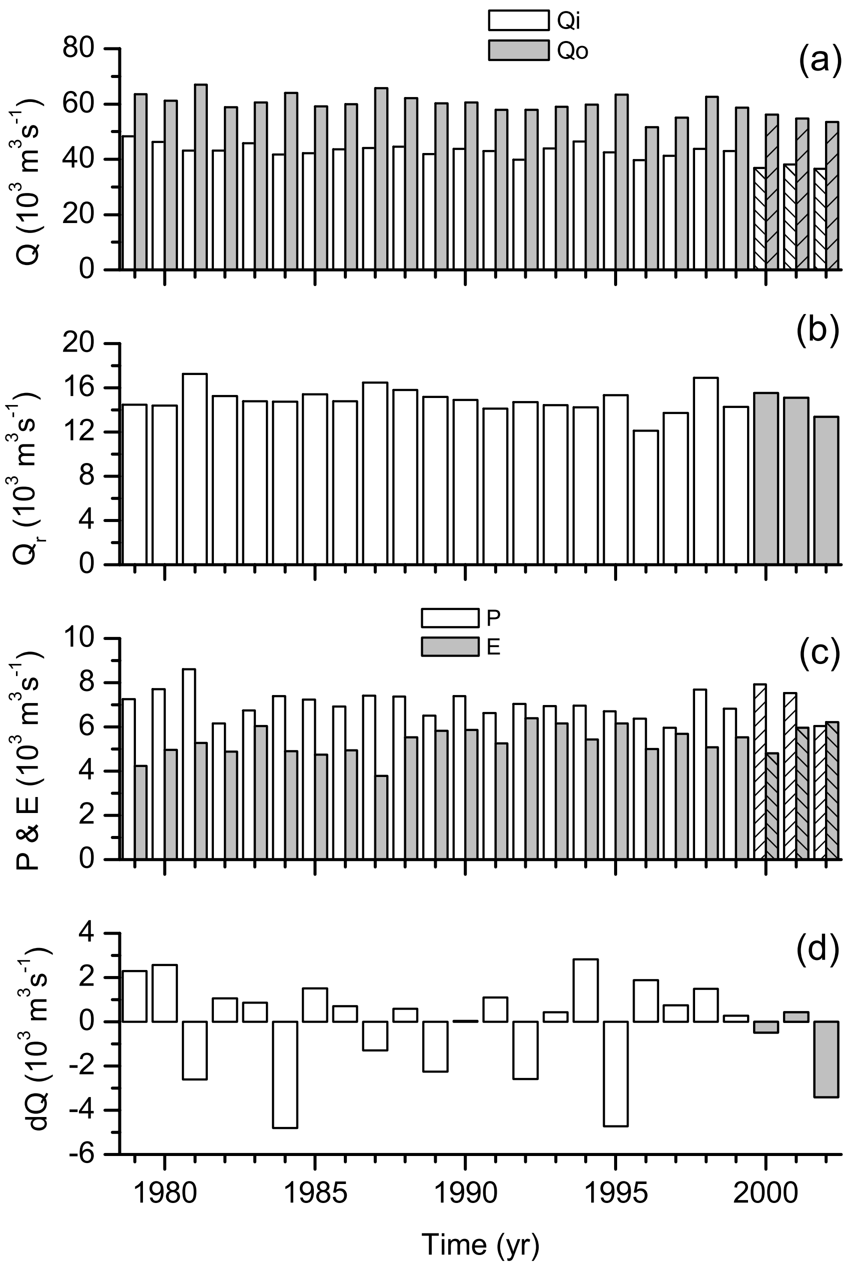

Fig 7. Baltic Sea (excluding the Kattegat and the Belt Sea) annual means of inflows and outflows (a), river runoff (b), precipitation and evaporation (c), and net volume change (d). The BALTEX/*BRIDGE* period is marked.

the three years from 2000 to the end of 2002, and the reference period, illustrated by the period 1979–2002. The annual means are presented in Fig. 7, and the monthly means of the major water balance components are given in Appendix A.

The values calculated for the various water balance components are in good accordance with earlier studies (e.g. Omstedt and Rutgersson 2000; Omstedt and Axell, 2003). The major component comprises inflows and outflows through the Baltic Sea entrance area. The largest inflow was 48 268 m^3 s^{-1} in 1979, while the largest outflow was 67 008 m^3 s^{-1} in 1981. The latter year corresponded to the maximum freshwater inflow, with 17 242 and 3329 m^3 s^{-1} being contributed by river runoff and net precipitation, respectively. The wettest year was 1981, when the sum of net precipitation and river runoff was 20 571 m^3 s^{-1}, while the driest year was 1996, when total freshwater inflow was 13 493 m^3 s^{-1}. The years 1981 and 1996 were also the years with the largest and smallest annual mean net outflows, calculated as 23 902 and 11 928 m^3 s^{-1}, respectively.

The water balance values for the BALTEX/*BRIDGE* period are in line with those of the longer time period with one important exception. The net precipitation was calculated as negative during 2002. This clearly deviates from the findings of earlier studies which have analysed net precipitation over other recent periods. This is due to the unusually warm year, 2002, as

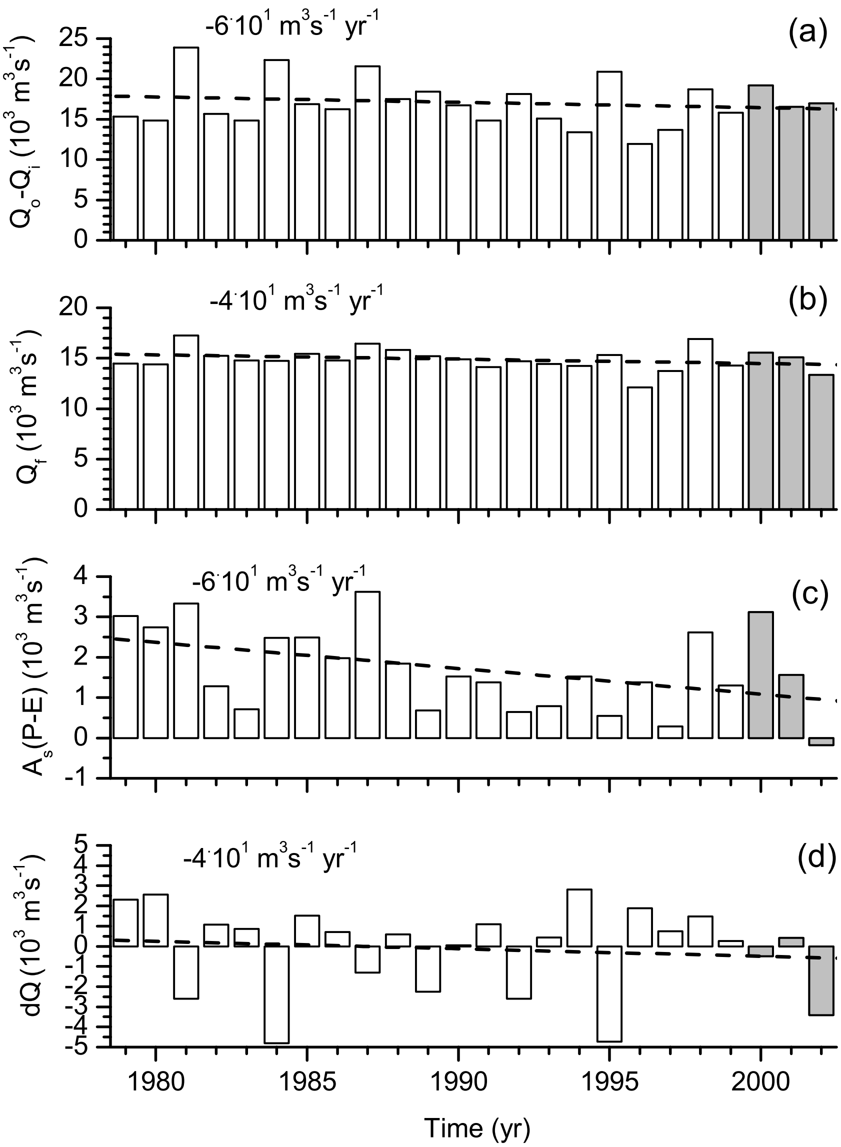

Fig 8. Baltic Sea (excluding the Kattegat and the Belt Sea) annual means of the water balance components: difference between outflows and inflows (a), river runoff (b), net precipitation (c), and net volume change (d). The dashed lines indicate the linear trends and the BALTEX/*BRIDGE* period is marked.

indicated in Section 4, which had a particularly warm and dry autumn with low winds. The autumn of 2002 also witnessed an unusual inflow event, when warm, saline bottom water flowed into the Baltic Sea (Piechura and Beszczynska-Möller, 2003).

The trends in the different water balance components are illustrated in Fig. 8. In general, we can notice a negative trend in the net outflow, the river runoff and the net precipitation. The decreasing net outflow ($Q_\mathrm{o} - Q_\mathrm{i}$) balances the reduction in river runoff, net precipitation, and storage change.

5.2. Heat balance

From the heat conservation principles, we can write the heat balance equation (Omstedt and Rutgersson 2000) for the Baltic Sea according to

$$\frac{\mathrm{d}H}{\mathrm{d}t} = (F_\mathrm{i} - F_\mathrm{o} - F_\mathrm{loss})A_\mathrm{s}, \tag{4}$$

where $H = \int\int \rho c_\mathrm{p} T \,\mathrm{d}z\,\mathrm{d}A$ is the total heat content of the Baltic Sea, F_i and F_o are the heat fluxes associated with inflows and outflows, and F_loss is the total heat loss to the atmosphere (note that the fluxes are positive when going from the water to the atmosphere). F_loss reads

$$F_\mathrm{loss} = (1 - A_\mathrm{i})\left(F_\mathrm{n} + F_\mathrm{s}^\mathrm{o}\right) + A_\mathrm{i}\left(F_\mathrm{w}^\mathrm{i} + F_\mathrm{s}^\mathrm{i}\right) - F_\mathrm{ice} + F_\mathrm{r} + F_\mathrm{g} \tag{5}$$

where

$$F_\mathrm{n} = F_\mathrm{h} + F_\mathrm{e} + F_\mathrm{l} + F_\mathrm{prec} + F_\mathrm{snow}. \tag{6}$$

Table 3. Estimated annual mean heat fluxes for the Baltic Sea (order of magnitude). The fluxes are denoted as net heat flux ($F_{\rm n}$), sun radiation to the open water surface ($F_{\rm s}^{\rm o}$), heat flow from water to ice ($F_{\rm w}^{\rm i}$), sun radiation through ice ($F_{\rm s}^{\rm i}$), the heat fluxes associated with precipitation in the form of rain ($F_{\rm prec}$) and snow ($F_{\rm snow}$), the heat sink associated with ice advection from the Baltic Sea ($F_{\rm ice}$), heat flows associated with river runoff and ground-water flow $F_{\rm r}$ and $F_{\rm g}$, the heat fluxes associated with inflows ($F_{\rm i}$) and outflows ($F_{\rm o}$), and the total heat loss to the atmosphere ($F_{\rm loss}$). The fluxes are positive when going from the water to the atmosphere

$F_{\rm n}$ (W m^{-2})	$F_{\rm s}^{\rm o}$ (W m^{-2})	$F_{\rm w}^{\rm i}$ (W m^{-2})	$F_{\rm s}^{\rm i}$ (W m^{-2})	$F_{\rm prec}$ (W m^{-2})	$F_{\rm snow}$ (W m^{-2})	$F_{\rm ice}$ (W m^{-2})	$F_{\rm r}$ (W m^{-2})	$F_{\rm g}$ (W m^{-2})	$F_{\rm o} - F_{\rm i}$ (W m^{-2})	$F_{\rm loss}$ (W m^{-2})
10^2	-10^2	10^0	-10^{-1}	10^{-1}	10^{-1}	-10^{-1}	10^{-1}	10^{-1}	10^{-1}	-10^0

Table 4. Mean heat balance of the Baltic Sea (the Belt Sea and the Kattegat excluded). The fluxes are positive when going from the water to the atmosphere. The fluxes are denoted as sensible heat ($F_{\rm h}$), latent heat ($F_{\rm e}$), net long-wave radiation ($F_{\rm l}$), sun radiation to the open water surface ($F_{\rm s}^{\rm o}$), sun radiation through ice ($F_{\rm s}^{\rm i}$), heat flow from water to ice ($F_{\rm w}^{\rm i}$), and net heat loss $F_{\rm loss} = (1 - A_{\rm i})\,(F_{\rm h} + F_{\rm e} + F_{\rm l} + F_{\rm s}^{\rm o}) + A_{\rm i}(F_{\rm s}^{\rm i} + F_{\rm w}^{\rm i})$, where $A_{\rm i}$ is the ice concentration

Author	$F_{\rm h}$ (W m^{-2})	$F_{\rm e}$ (W m^{-2})	$F_{\rm l}$ (W m^{-2})	$F_{\rm s}^{\rm o}$ (W m^{-2})	$F_{\rm w}^{\rm i}$ (W m^{-2})	$F_{\rm s}^{\rm i}$ (W m^{-2})	$F_{\rm loss}$ (W m^{-2})	Period
Present	10	37	37	−88	3	−0	−0	BALTEX/*BRIDGE* 2000–2002
Present	9	35	36	−85	4	−0	−1	1970–2002

The various terms in eqs. (5) and (6) are denoted as follows. $A_{\rm i}$ is ice concentration, $F_{\rm h}$ is the sensible heat flux, $F_{\rm e}$ is the latent heat flux, $F_{\rm l}$ is the net long-wave radiation, $F_{\rm prec}$ and $F_{\rm snow}$ are the heat fluxes associated with precipitation in the form of rain and snow, respectively, $F_{\rm s}^{\rm o}$ is the short-wave radiation to the open water surface, $F_{\rm w}^{\rm i}$ is the water flux to the ice, $F_{\rm s}^{\rm i}$ is sun radiation through the ice, $F_{\rm ice}$ is the heat sink associated with ice advection out from the Baltic Sea, and $F_{\rm r}$ and $F_{\rm g}$ are heat flows associated with river runoff and ground-water flow, respectively. The orders of magnitude of the different terms are given in Table 3; $F_{\rm prec}$, $F_{\rm snow}$, $F_{\rm ice}$, $F_{\rm r}$ and $F_{\rm g}$ are neglected in the present analysis.

The calculated long-term means of the various components of the heat balance appear in Table 4, while the annual means appear in Fig. 9 and the monthly means of the major heat balance components are given in Appendix A. The estimated net heat loss during the BALTEX/*BRIDGE* period was zero, while for the whole period it was -1 W m^{-2}. This is in good accordance with earlier results (Omstedt and Rutgersson, 2000; Meier and Döscher, 2002), and is important as it illustrates that the Baltic Sea is almost in local balance with the atmosphere over long time-scales. The inter-annual variations in net heat loss, Fig. 9d, indicate an inter-annual variability of ± 10 W m^{-2}.

The largest inter-annual variability was found in short-wave radiation, which ranged between -74.1 and -93.3 W m^{-2}. The inter-annual variabilities of the sensible ($F_{\rm h}$), the latent ($F_{\rm e}$) heat flux, the net long-wave radiation ($F_{\rm l}$) and the heat flux from water to ice ($F_{\rm w}^{\rm i}$) were in the range of ± 5, ± 8, ± 8 and ± 3 W m^{-2}, respectively. It is interesting to note that the inter-annual variation in net heat loss was largest during the BALTEX/*BRIDGE* period.

Trends in some of the major heat balance components are illustrated in Fig. 10. The increase in net heat flux ($F_{\rm n} = F_{\rm h} + F_{\rm e} + F_{\rm l}$) to the open water surface balances the increase in sun radiation ($F_{\rm s}^{\rm o}$). The net Baltic Sea heat loss ($F_{\rm loss}$) indicates no trend. This is also indicated in the observed Baltic Sea mean temperature, Fig. 5, where no trend can be noticed. The study thus shows that even if we have had an increasing air temperature of about 1°C during the studied 30-yr period, we cannot notice any changes in the annual Baltic Sea mean temperature. The result indicates that the Baltic Sea climate is influenced by negative feedback mechanisms that stabilize trends in the annual mean air temperature.

6. Comparison between ocean and atmospheric calculated heat fluxes

The scientific objectives in BALTEX include the determination of the water and energy cycles in the Baltic Sea region by combined data and modelling exercises, and the development of coupled, high-resolution forecasting systems for a better handling of the complex weather and climate processes. It is well known today that the weather forecasting of precipitation (and evaporation) provides the largest problems in weather predictions. This is also true for meteorological reanalysis such as the NCEP/NCAR data (Ruprecht and Kahl, 2003).

During the BALTEX/*BRIDGE* period, the coupled HIRLAM–BALTEX system was run for 1 yr (September 1999 to the end of October 2000) in a delayed data assimilation mode (Fortelius et al., 2002). The coupled model system was claimed to simulate the essential features of the water and energy cycles. To examine

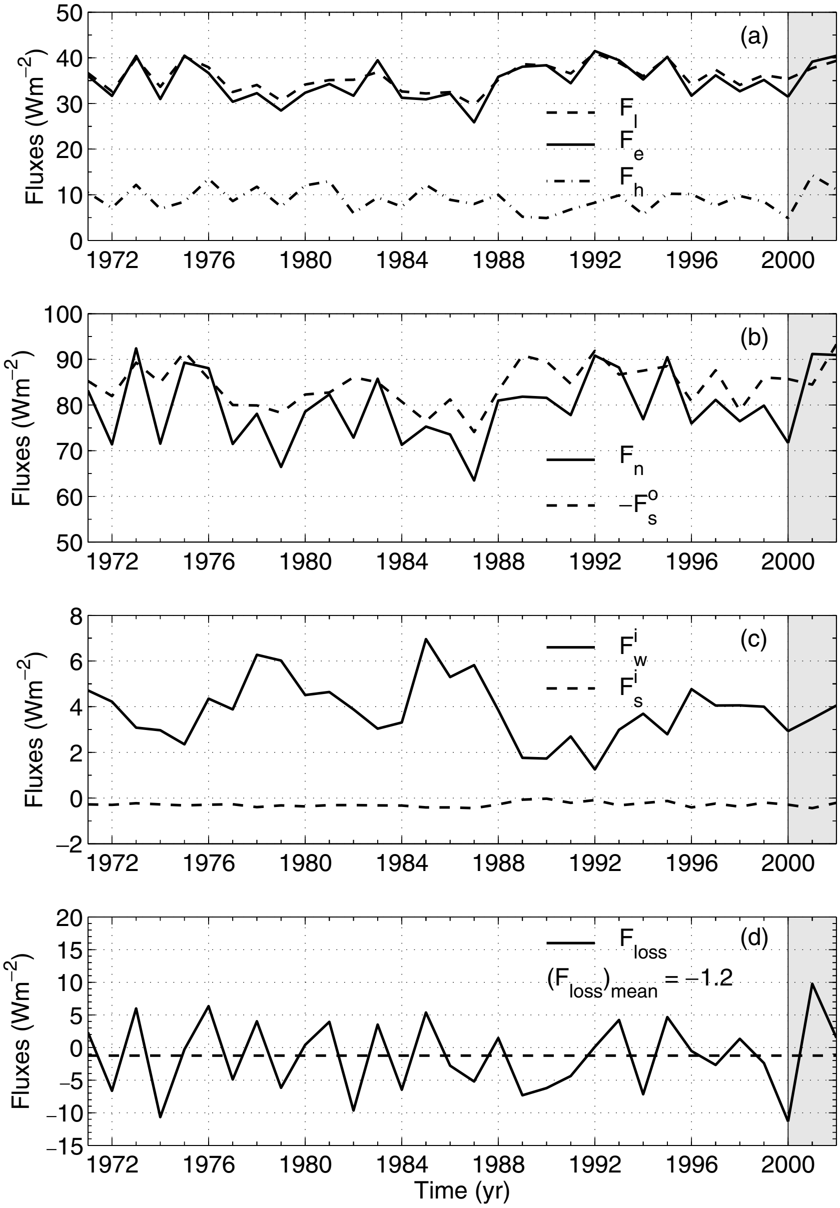

Fig 9. Annual means of sensible heat (F_h), latent heat (F_e), net long-wave radiation (F_l), net heat flux ($F_n = F_h + F_e + F_l$), sun radiation to the open water surface (F_s^o), sun radiation through ice (F_s^i), heat flow from water to ice (F_w^i), and net Baltic Sea heat loss $F_{loss} = (1 - A_i)(F_s^o + F_h + F_e + F_l) + A_i(F_s^i + F_w^i)$, where A_i is the ice concentration.

Table 5. A comparison between fluxes calculated by the PROBE-Baltic model and the HIRLAM–BALTEX model. For details of the nomenclature, see Table 4

Author	F_h (W m^{-2})	F_e (W m^{-2})	F_l (W m^{-2})	F_s^o (W m^{-2})	F_{loss} (W m^{-2})	Period
Fortelius (private communication)	7	44	54	−123	−18	1999–2000
Present	7	38	38	−88	−5	1999–2000

the output from the HIRLAM–BALTEX system, we analyse the heat balance in some more detail and particularly the closure of the Baltic Sea heat balance.

The calculated monthly mean heat fluxes from the HIRLAM–BALTEX system appear in Table 5 and Fig. 11 and are compared with those obtained in the present study. The estimated sensible heat fluxes show good agreement, but the latent heat fluxes estimated using the HIRLAM–BALTEX system are slightly higher than those estimated with PROBE-Baltic system. The main differences are found in the net long-wave and short-wave radiation, where the HIRLAM–BALTEX system calculates unrealistically large net fluxes.

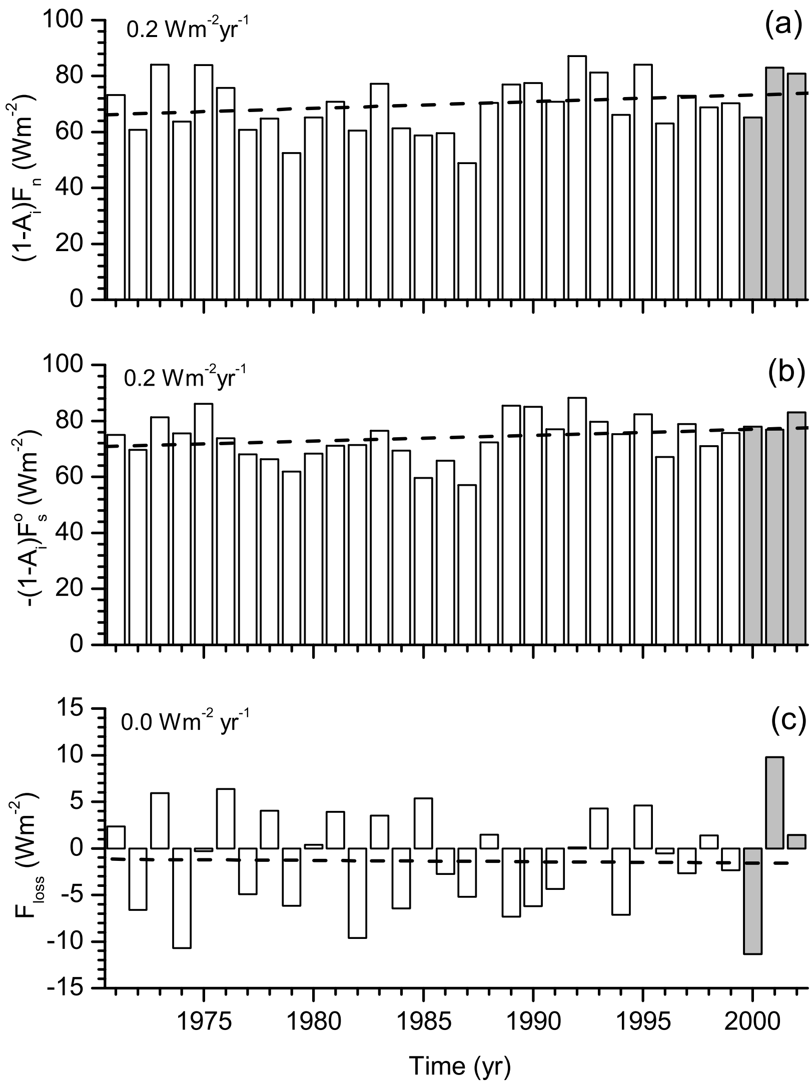

Fig 10. Annual means of some major heat fluxes: net heat flux ($F_{\mathrm{n}} = F_{\mathrm{h}} + F_{\mathrm{e}} + F_{\mathrm{l}}$), sun radiation to the open water surface ($-F_{\mathrm{s}}^{\mathrm{o}}$), and net Baltic Sea heat loss $F_{\mathrm{loss}} = (1 - A_{\mathrm{i}})\,(F_{\mathrm{s}}^{\mathrm{o}} + F_{\mathrm{h}} + F_{\mathrm{e}} + F_{\mathrm{l}}) + A_{\mathrm{i}}\,(F_{\mathrm{s}}^{\mathrm{i}} + F_{\mathrm{w}}^{\mathrm{i}})$, where A_{i} is the ice concentration. The dashed lines indicate the linear trends and the BALTEX/*BRIDGE* period is marked.

From the net heat loss we conclude that HIRLAM–BALTEX system gives an unrealistically high net input. This is probably because the HIRLAM–BALTEX system underestimates the cloud cover over the Baltic Sea (Fortelius, private communication), producing too high values for both short-wave and long-wave radiation.

7. Summary and conclusions

The main BALTEX experiment (*BRIDGE*) was the central element in the BALTEX (Baltic Sea Experiment) Phase I programme, with the aim of improving our understanding of water and energy cycle in the climate system. This work has examined the Baltic Sea water and heat balances for the *BRIDGE* period (2000–2002) in relation to current climatic conditions (1970–2002). The study follows on from earlier work in which Baltic Sea modelling is used as a tool for synthesizing available data. The modelling approach was validated with independent data sets of observations from salinity, temperature and ice extent. Data assimilation methods have therefore not been introduced in the modelling efforts.

The basic questions raised in the paper were as follows. (1) What are the values of the individual terms of the water and heat balances during the BALTEX/*BRIDGE* period and how do they vary over time? (2) How accurately can these balances be calculated? (3) Can detection of climate change signals be carried out more easily for the water and heat-cycle components compared to standard parameters such as temperature?

The values of the individual terms are illustrated in the figures and given as table values. Monthly mean values for the different terms during the BALTEX/*BRIDGE* period are also given in Appendix A. The calculated values show large seasonal and inter-annual variations in most components and do not reveal any strong climate change trends, except that net precipitation over the Baltic Sea was negative in 2002. This year stands out from the rest of the study period, when net precipitation was

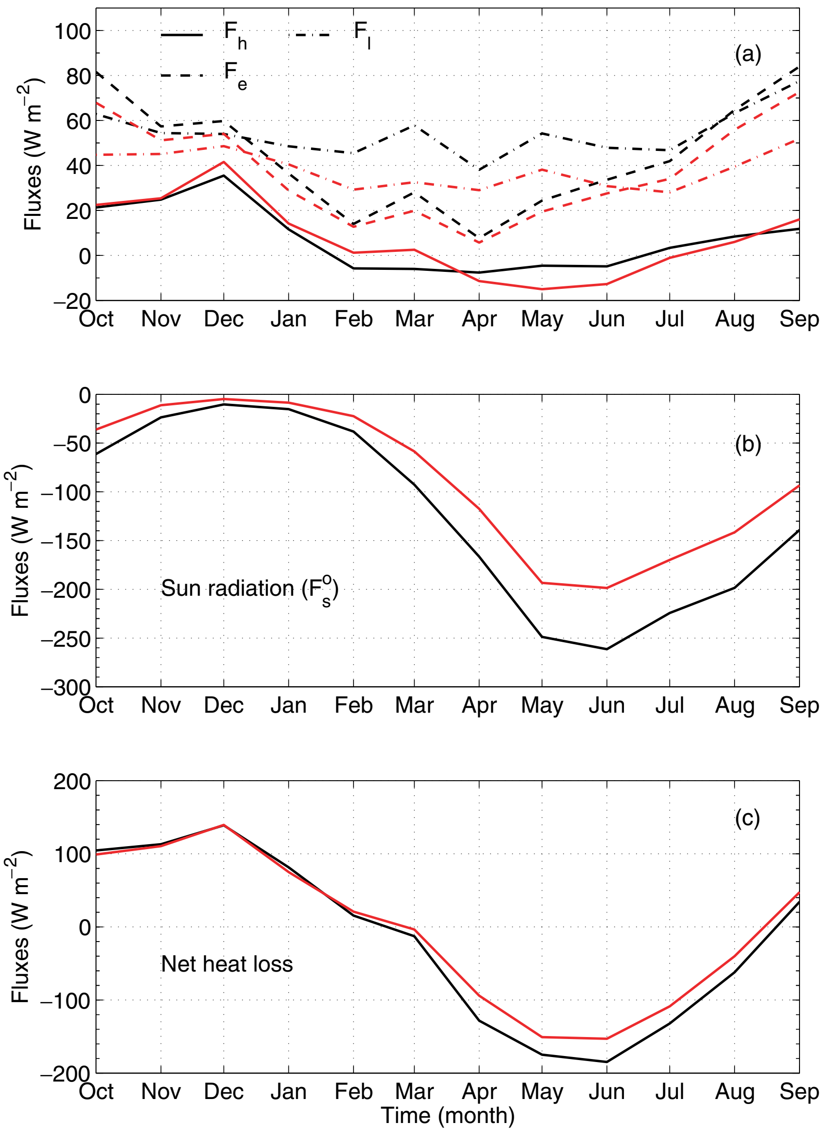

Fig 11. Comparison between flux calculations from the HIRLAM–BALTEX (black) and the PROBE-Baltic (red) model systems. For nomenclature, see caption to Fig. 9.

positive. Also, the inter-annual variability of net heat flux between the atmosphere and the Baltic Sea showed large variations during the *BRIDGE* period.

The errors in the water balance were investigated by comparing calculated and, from observations, estimated mean salinities of the Baltic Sea. The results imply that the mean error in the net water balance is much less than the river runoff (4% of the river runoff). This indicates that the net freshwater balance averaged over decades is quite accurate. The rms error is 10 times as large as the mean error, which implies that water balance studies on time-scales shorter than a decade could have large errors. The corresponding mean and rms errors in the net heat flux, determined by comparing calculated and observed mean temperatures of the Baltic Sea, were estimated as 2 and 3 W m^{-2}, respectively.

Detection of climate change signals can be found in different time series. Here we have examined both time series of mean meteorological conditions over the Baltic Sea and the corresponding calculated water and heat balances. The water and heat balances involve many different processes that may cause positive or negative feedback mechanisms. Despite observed atmospheric warming over the Baltic Sea during the 30-yr study period, no trends were observed in the annual mean water temperature or the net heat loss. The reason was that the increased net heat flux from the open water surface was balanced by an increase in sun radiation. Detection of climate change signals was not easier to observe in the water and heat balance studies, but these studies provide another item of information that can explain more about how the climate system responds to changes in forcing. Water and heat balance studies should therefore be used together with trend analysis on observed time series as tools in climate change studies.

The conclusions from the paper can be summarized as follows.

(i) Current Baltic Sea modelling and the meteorological and hydrological data available from the BALTEX data centres indicate that the net water balance and the net heat flux can be estimated with good accuracy (mean errors over decadal time-scales being about 600 m^3 s^{-1} and 2 W m^{-2} respectively). The accuracy of the individual terms is still unknown.

(ii) Negative net precipitation was calculated for 2002; this year stands out from the rest of the 30-yr period when annual mean net precipitation rates were always positive. The calculated inter-annual variability of the net heat loss between atmosphere and Baltic Sea during the BALTEX/*BRIDGE* period indicated large variations ($\pm$10 W m^{-2}).

(iii) The Baltic Sea annual mean temperature has not increased during the study period despite an atmospheric warming of 1 °C. The reason was explained by the heat balance that indicated no trend in the Baltic Sea net heat loss.

8. Acknowledgments

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Finally we would like to thank all the enthusiastic scientists who have made BALTEX and Baltic Sea basic research possible.

9. Appendix A: Calculated major components in the water and heat balances during the BALTEX/*BRIDGE* period

Table A1. Monthly mean water balance for the Baltic Sea (the Belt Sea and the Kattegat excluded). The flows are denoted as: difference between outflows and inflows ($Q_o - Q_i$), river runoff (Q_r), net precipitation ($P - E$), storage change, and A_s the Baltic Sea surface area

Year	Month	$Q_o - Q_i$ (10^3 m^3 s^{-1})	Q_r (10^3 m^3 s^{-1})	A_s $(P - E)$ (10^3 m^3 s^{-1})	Storage change (10^3 m^3 s^{-1})
1999	10	9.98	10.59	−2.02	−1.41
1999	11	1.53	10.37	−4.96	3.88
1999	12	10.31	10.65	0.29	0.63
2000	1	4.67	10.87	−1.19	5.00
2000	2	24.27	12.48	2.49	−9.30
2000	3	40.99	14.56	1.96	−24.47
2000	4	30.67	19.27	4.68	−6.73
2000	5	−0.57	21.24	1.99	23.80
2000	6	16.50	17.76	5.36	6.62
2000	7	26.25	18.54	8.23	0.52
2000	8	21.66	17.78	−1.93	−5.81
2000	9	36.66	13.74	−8.05	−30.96
2000	10	−15.26	11.37	2.02	28.64
2000	11	26.68	14.47	5.79	−6.42
2000	12	2.22	14.44	0.52	12.74
2001	1	36.31	12.16	−0.45	−24.60
2001	2	4.91	12.01	−0.89	6.21
2001	3	38.54	12.60	0.42	−25.52
2001	4	3.91	17.48	6.31	19.87
2001	5	10.50	21.39	2.13	13.02
2001	6	23.94	16.91	5.89	−1.14
2001	7	8.30	15.26	1.43	8.39
2001	8	11.70	15.76	0.44	4.49
2001	9	37.04	16.56	3.44	−17.03
2001	10	−18.62	14.98	−1.40	32.19
2001	11	17.59	14.11	−6.88	−10.36
2001	12	5.54	11.82	−6.19	0.09
2002	1	−9.57	12.16	4.03	25.76
2002	2	16.89	12.01	5.94	1.06
2002	3	59.75	12.60	2.33	−44.82

Table A2. Monthly mean heat balance of the Baltic Sea (the Belt Sea and the Kattegat excluded). The fluxes are positive when going from the water to the atmosphere. The fluxes are denoted as: sensible heat (F_h), latent heat (F_e), net long-wave radiation (F_l), sun radiation to the open water surface (F_s^o), heat flow from water to ice (F_w^i), net heat loss (F_{loss}), and A_i the calculated Baltic Sea monthly mean ice coverage

Year	Month	F_h (W m^{-2})	F_e (W m^{-2})	F_l (W m^{-2})	F_s^o (W m^{-2})	F_w^i (W m^{-2})	F_{loss} (W m^{-2})	A_i
1999	10	23	70	45	−34	0	104	0
1999	11	26	54	45	−10	0	115	0
1999	12	48	61	51	−4	0	157	0
2000	1	20	36	42	−8	6	97	0.14
2000	2	5	17	32	−22	10	41	0.29
2000	3	5	23	33	−56	9	13	0.30
2000	4	−11	5	28	−112	7	−83	0.17
2000	5	−17	14	36	−189	0	−155	0
2000	6	−18	17	29	−200	0	−170	0
2000	7	−5	25	26	−170	0	−124	0
2000	8	4	50	39	−141	0	−49	0
2000	9	15	73	55	−94	0	49	0
2000	10	10	43	35	−34	0	54	0
2000	11	19	39	32	−9	0	80	0
2000	12	32	43	44	−4	0	115	0
2001	1	31	41	42	−7	0	107	0
2001	2	39	41	45	−24	15	116	0.22
2001	3	9	19	31	−49	11	20	0.38
2001	4	−8	6	26	−100	10	−67	0.18
2001	5	−17	12	37	−190	0	−158	0
2001	6	−16	11	29	−197	0	−173	0
2001	7	−6	38	35	−201	0	−134	0
2001	8	4	56	39	−143	0	−45	0
2001	9	16	62	37	−75	0	40	0
2001	10	13	45	37	−34	0	62	0
2001	11	41	82	53	−11	0	165	0
2001	12	65	65	53	−4	1	180	0.02
2002	1	18	25	29	−6	10	75	0.27
2002	2	5	20	30	−22	9	42	0.28
2002	3	1	17	33	−59	7	−1	0.27

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