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Energy and water balance of the Baltic Sea derived from merchant ship observations

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Individual merchant ship observations from COADS (Comprehensive Ocean Atmosphere Data Set) were used to determine the energy and water budget of the Baltic Sea for the period 1980 to 1995. On a monthly time scale these ship reports provide reasonable estimates for the radiative and turbulent fluxes and the precipitation despite their concentration on narrow shipping routes, because of the large correlation lengths for monthly means. In order to take into account the effects of sea ice on evaporation and albedo, the ice-covered parts of the Baltic Sea are treated separately, where we applied a simple thermodynamic ice model using ice information from the GISST (Global sea Ice coverage and Sea Surface Temperature) data set. As the overall result we found a small surplus of rain compared to evaporation (5 mm per month) and a quasi-balanced energy budget (1 W m^{-2} energy loss of the sea surface).

Introduction

The investigation of the water and energy cycle of the Baltic Sea and its catchment belongs to the major aims of BALTEX (Baltic Sea Experiment). Raschke *et al*. (2001) give a comprehensive overview about the main results achieved up to now and outline the future activities. Due to the long scientific tradition of the countries bordering the Baltic Sea, this region is characterized by an extraordinary high density of meteorological, hydrological and oceanographic observations which is additionally enhanced by the numerous observation campaigns carried out especially for BALTEX. However, it is generally assumed that a comprehensive understanding of the energy and water cycle is only attainable if we are able to model the complex interactions between land, water and air. In this aspect the observations are no end in themselves but still indispensable to validate the used models. Bengtsson (2001) summarizes the numerical modelling work associated with BALTEX and Jacob *et al*. (2001) presented detailed results for the water budget within a comprehensive model intercomparison.

Not only the high data density available but also the quasi-closed area of the Baltic Sea are excellent preconditions for the use of the region as a validation area. Through the narrow, shallow Danish Straits only a small amount of energy can be exchanged with the world ocean so that the net longtime energy flux between the sea and the overlying atmosphere must be in a near-balanced

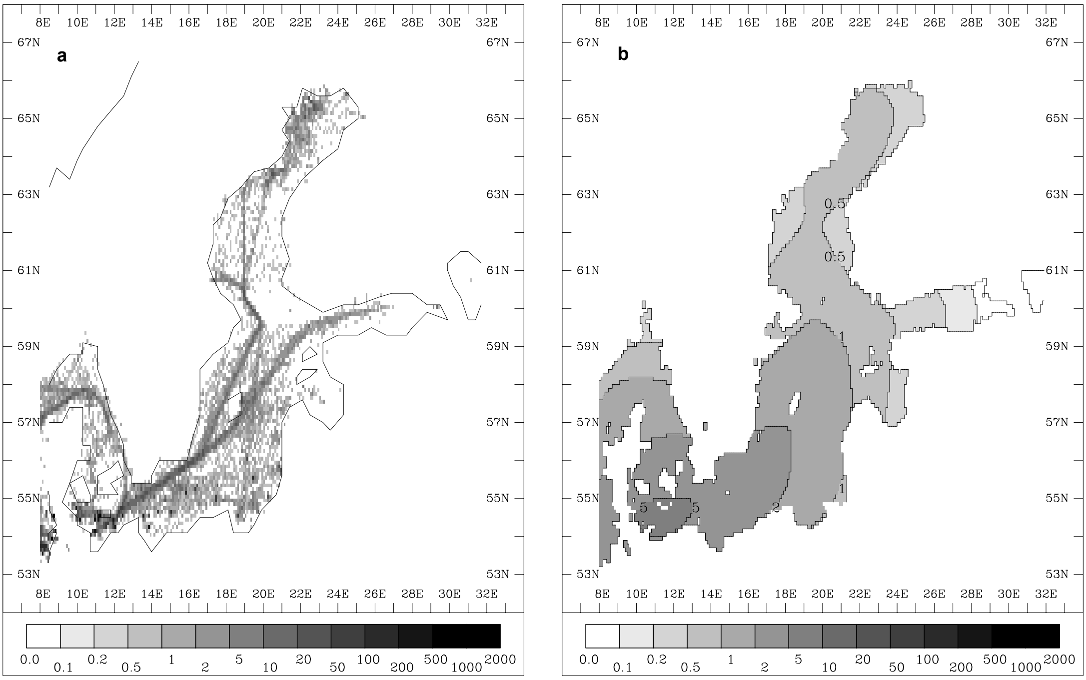

Fig. 1. — **a**: Raw observation density of COADS in January for the period 1980 to 1995. Values are given in observations per 0.1° by 0.1° grid field; — **b**: The observation density obtained after distributing the information into the surrounding by an exponential function (Eq. 1). The constant x_0, which governs the extent of information spreading, is set to 111 km, much smaller than the correlation length for monthly means.

state, thus providing a constraint for the four air–sea heat fluxes. Concerning the water budget of the Baltic Sea, the circumstances are more complicated. In this case, gains and losses are no longer dominated by the air–sea exchange. Precipitation and evaporation are known to be even smaller than both the river runoff into the Baltic and the net outflow through the Danish Straits (Dietrich and Schott 1974). The river runoff is measured with relative high accuracy being a freshwater gain for the Baltic Sea of about 450 km^3 per year (Raschke *et al*. 2001). The net longterm outflow through the Danish Straits is, in contrast, difficult to determine (Sayin and Krauss, 1996). In general, light surface water of low salinity is flowing out whereas the heavier salty water from the North Sea is flowing in at the bottom.

The special nature of semi-enclosed seas has been utilised in several studies to check the consistency of the used flux parameterisations. Bunker *et al*. (1982) investigated the Mediterranean and Red Sea and found a strong surplus of energy which is not consistent with the import through the Strait of Gibraltar. Gilman and Garrett (1994) were able to close the Mediterranean heat budget by taking into account the effect of aerosols, which tend to decrease the incoming solar radiation. In contrast to the Mediterranean, the Baltic Sea is covered by ice over a considerable part of the area during long periods of the year which complicates the heat flux calculations. Therefore, the energy exchange over sea ice is treated separately in this paper.

In general, satellite observations are a promising data source to calculate air–sea fluxes (Grassl *et al*. 2000). However, near the coast the signal is strongly influenced by perturbations from the surrounding land (Lindau and Ruprecht, 2000). For the present satellite resolution, land effects would dominate within the entire Baltic Sea. Ship observations, on the other hand, provide in the Baltic Sea more information than one has in general in the open ocean. In the following, such ship reports of the basic meteorological observations from COADS (Comprehensive

Ocean Atmosphere Data Set) are used to calculate the air–sea fluxes of energy and water at sea surface for the period 1980 to 1995. Maps of the climatological state are presented as well as the interannual variability of basinwide averages.

Data

COADS contains the basic meteorological observations routinely reported from merchant ships, which are often referred to as Voluntary Observing Ships (VOS). The entire data set is global and covers the last one and a half centuries. However, this study is restricted to the period 1980 to 1995, and, as a matter of course to the Baltic Sea. In general, the data distribution is very inhomogeneous, reflecting the major shipping lines in the world ocean, and in this sense, the Baltic Sea is no exception. Figure 1a shows the totally available data in the Baltic Sea for the considered period in January, when sea ice may reduce shipping, expressed in observations per 0.1° by 0.1° grid box. In January, the total number of observations containing wind, temperature and cloud informations is 27 039 with a maximum value of 1281 per tenth degree grid box near the German coast. Due to this inhomogeneous data coverage a simple average of all available observations does not necessarily represent the mean conditions in the Baltic Sea. Therefore, a spatial analysis of the calculated flux fields is performed before averaging, which is discussed later on in this paper.

Methods

COADS provides individual ship observations which were used to calculate the air–sea fluxes via the parameterisations and bias corrections given in Lindau (2000). However, some changes compared to that work are necessary. In Lindau (2000) only the precipitation frequency was used instead of the explicit rain amount. But for the purpose of this paper a quantitative estimate of the precipitation is essential. Therefore, a rain algorithm which is able to estimate the monthly rainfall from standard ship observations is presented here in more detail.

A further extension was made concerning the sea ice, which cannot be neglected in the Baltic Sea. Over ice covered areas the heat fluxes were computed separately so that a special section is attended to the sea ice treatment. The additionally needed ice information is taken from the GISST data set (Parker *et al.* 1995), which provides the monthly mean ice concentration with a spatial resolution of 1° by 1°.

The used COADS raw data are available in the form of individual observations. In the first step, the fluxes are calculated individually. In the second step, a spatial analysis is applied to the flux fields in order to obtain fully covered maps for each month of the considered 16-year period. However, these fields are still an intermediate product because the data base within one month is considered to be too small to provide both a high temporal and a high spatial resolution. Consequently, these fields are in the third step either averaged basinwide in order to yield time series with a 30-days resolution or they are averaged temporally to obtain maps of climatological monthly means where the high spatial resolution is retained.

Thus, in principle, the fluxes are analysed and averaged, not the basic meteorological variables. Only one exception is made. For the specific humidity individual monthly analyses are produced according to the above described step two. If a ship report does not contain the air humidity this information is taken from the spatial analysis, otherwise the reported value is preferred.

Spatial analysis

In order to obtain fully covered fields we distributed the information of each ship report with an exponential distance-dependent function into the area, reaching a weight reduction of e^{-1} at x_0 = 111 km.

$$w = w_0 e^{-\frac{x}{x_0}} \quad (1)$$

This proceeding is admissible since we are dealing with monthly means. On this time scale the correlation lengths of the considered parameters are lying in the order of 500 km, thus being much greater than the used value of x_0. The

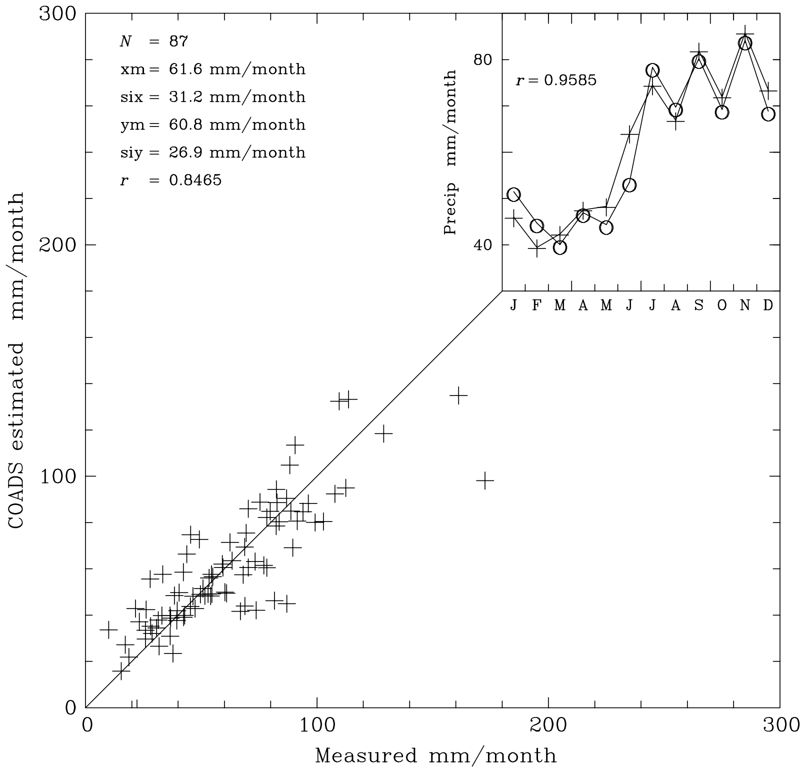

Fig. 2. Quality control of the derived precipitation algorithm (Eq. 2) by comparing rain estimates from COADS derived by the algorithm against precipitation measurements on light vessels. In the upper right corner the mean annual cycle measured by light vessels (+) is compared to the COADS estimate (o).

autocorrelation function of the parameter relative humidity shows e.g. a correlation of 0.55 for zero distance, revealing that nearly half of the variance is caused by random observation errors. However, these errors reduce the correlation for each distance by a constant factor. At 511 km, the correlation is decreased to 0.20, which is equal to a fraction of e^{-1} of the original value for vanishing distance, so that 511 km can be inferred as the correlation length.

Thus, using the relatively small value $x_0 = 111$ km in Eq. 1, the smoothing effects of the applied technique remain limited. Nevertheless, fully covered fields are obtained as shown in Fig 1b. After this procedure the data density e.g. in January ranges between 6 observations per tenth degree grid box in the southern Baltic Proper and 0.5 observations in the Gulf of Bothnia.

Precipitation

Following the basic ideas of Tucker (1961), we derived a simple rain algorithm which needs as input not more than the present weather code 'ww' and the specific humidity, both observed routinely on merchant ships.

$$\mathrm{RR} = c\, n_{\mathrm{ww}}\, s \qquad (2)$$

with $c = 2079.5$ mm d^{-1}; $n_{\mathrm{ww}} = 0$ if ww < 50, $n_{\mathrm{ww}} = 1$ if $50 \le$ ww < 80, and $n_{\mathrm{ww}} = 2$ if ww ≥ 80; s is specific humidity in kg/kg

For the decision whether it rains at all, the present weather code is very reliable, whereas rain intensity is estimated by the additional humidity information. For the derivation of the algorithm we calibrated the weather and humidity observations of 24 years from four light vessels in the German Bight against the wind corrected daily rain measurements carried out aboard these ships. In a second step the quality of the obtained rain algorithm is checked by its application on independent COADS data. Merchant ship observations within a 2° by 3° surrounding of the light vessels are used. For monthly means a correlation of 0.85 is obtained, for the climatic annual

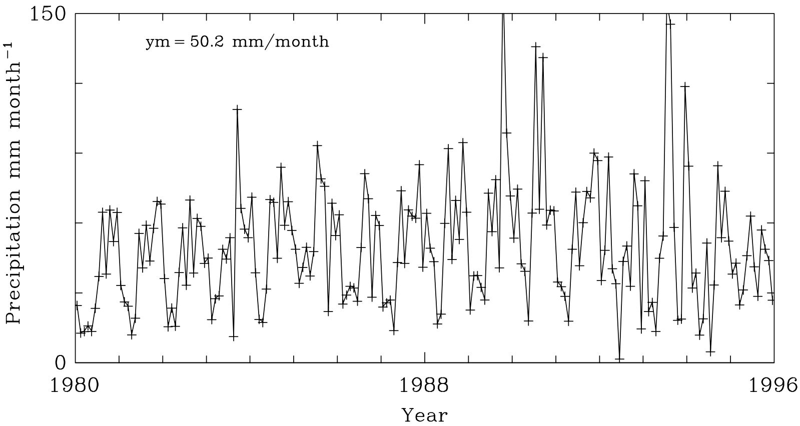

Fig. 3. Time series of the spatially averaged precipitation over the Baltic Sea as obtained from COADS.

cycle even one of 0.96 (Fig 2).

However, rain observations are difficult to validate, since available measurements themselves are not beyond any question. Thus, before using the rain algorithm in the Baltic Sea, we tested it with global data. Together with the evaporation a near-balanced state was obtained for this longtime global application, which enhances the confidence into the algorithm.

After this encouraging test the rain algorithm is used to estimate the precipitation over the Baltic Sea. The longtime spatial distribution is characterized by high precipitation at the German coast and a minimum in the central Baltic Sea (not shown). The overall mean of the considered 16-year period amounts to 50 mm per month. The temporal evolution of the spatially averaged precipitation is given in Fig. 3, showing an increase of the variability in the second half of the considered period.

Effects of sea ice on heat fluxes

Concerning the energy fluxes, problems occur in the Baltic Sea due to sea ice which changes albedo and surface temperature and influences in this way the air–sea fluxes. Using the ice information of the GISST data set we calculated the energy fluxes separately for those parts of the Baltic Sea which are ice covered.

For this purpose we applied a model of seven ice thickness classes (Maykut and Untersteiner 1971) covered by a possible snow layer. The model considers the energy balance at both surfaces of the ice, at the top and the bottom side. The key parameter for the upper, atmospheric fluxes is the temperature of the ice surface, which is calculated by the model, whereas air temperature and humidity, wind and cloud information are available from COADS. In the original model, the ice thickness is a prognostic variable. However, here it is estimated by an empirical function of the sea surface temperature.

The basic idea of the model is to find an equilibrium temperature of the ice surface, so that the four atmospheric fluxes and the conductive heat flux through the ice are in balance. If that is not possible at temperatures below 0 °C, the surplus of surface energy is used for melting. Applying this procedure to the individual COADS observations, we found e.g. for January a mean ice temperature of –6.3 °C whereas the mean reported air temperature for that month is –6.6°C. The mean condition over ice covered sea areas is shown in detail in Fig. 4. Considering first the atmospheric fluxes, only the shortwave radiation SWR heats the ice surface by 3.13 W m^{-2}. Due to longwave radiation LWR, latent heat flux LHF and sensible heat flux SHF the ice surface loses energy as indicated by the respective values, so that the atmosphere cools the ice surface by totally 47.72 W m^{-2}. However, together with the conductive heat flux CHF of 52.60 W m^{-2} through the ice, the net surface flux NSF amounts to 4.88 W m^{-2}, which is used for melting at the surface. On the other hand the bottom of the ice is cooled by the CHF which cannot be compensated by the small oceanic flux OF, estimated by a constant input of 5 W m^{-2}. Consequently, the

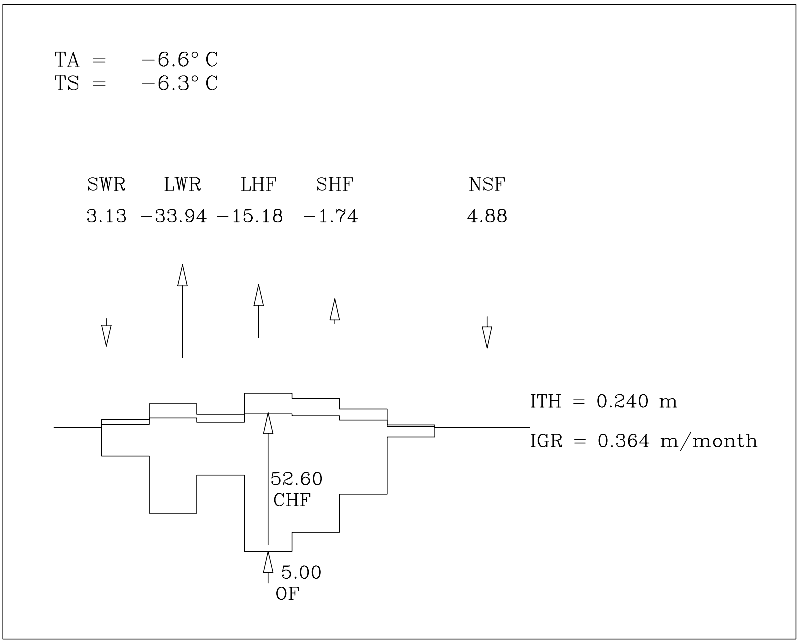

Fig. 4. Illustration of the applied ice correction by a schematic vertical section through the ice. The example shows the mean condition in January found over ice-covered sea areas, for the air and ice temperature TA and TS, the short and longwave radiation SWR and LWR, and the latent and sensible heat flux LHF and SHF. Further, CHF denotes the conductive flux and NSF = SWR + LWR + LHF + SHF the net surface flux. OF denotes the oceanic flux, IGR and ITH the ice growth and thickness, respectively.

ice growth IGR is 36.4 cm per month while the mean ice thickness ITH is 24 cm.

Results

Using the above described ice correction scheme, an annual mean evaporation of about 45 mm per month is calculated, strongest in the south-eastern part and decreasing to the north-west (not shown). Together with precipitation it shows that the Baltic Sea gains water from the atmosphere in its northern and its southern part and loses water in the central part (Fig. 5a). The total average is 5 mm per month, approximately 10% of both components.

The annual cycle (Fig. 5b) shows an increase of both components during the year from spring to autumn. Precipitation minus evaporation ($P - E$) remains nearly balanced almost throughout the year. It attains considerable positive values only in spring and early summer, when rain is already increasing but evaporation is still low due to the relative low sea temperature. As for precipitation, the individual monthly means of $P - E$ show an increase of variability since 1980.

The derived net energy flux for the entire Baltic Sea, consisting of the ice corrected radiative and turbulent fluxes at sea surface, is about –1 W m^{-2}. Thus, the energy balance is nearly closed. Spatial distribution shows, not surprisingly, an energy gain in the south-western part, while the north-eastern parts, especially the Gulf of Bothnia, lose energy in the annual mean (Fig. 6a). The mean annual cycle (Fig. 6b) shows the commonly known variation in shortwave radiation, while the variability of the other three fluxes remains subdominant. Consequently, strong differences in the net energy flux between summer and winter of more than 300 W m^{-2} occur.

Conclusions

We have demonstrated that it is possible to cal-

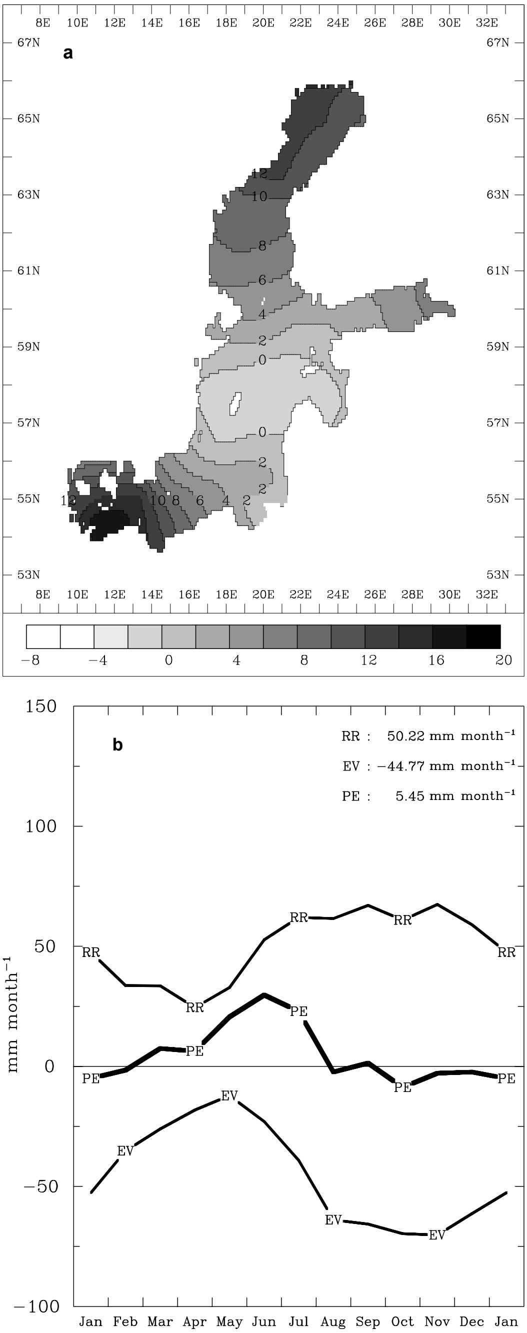

Fig. 5. — **a**: Longtime mean (1980–1995) precipitation minus evaporation (mm per month); — **b**: Longtime mean annual cycle of precipitation RR and evaporation EV over the Baltic Sea and the residuum PE. Averaged over the entire year, RR amounts to 50.22 mm per month, while the evaporation is only 44.77 mm per month, so that $P - E$ is positive with 5.45 mm per month.

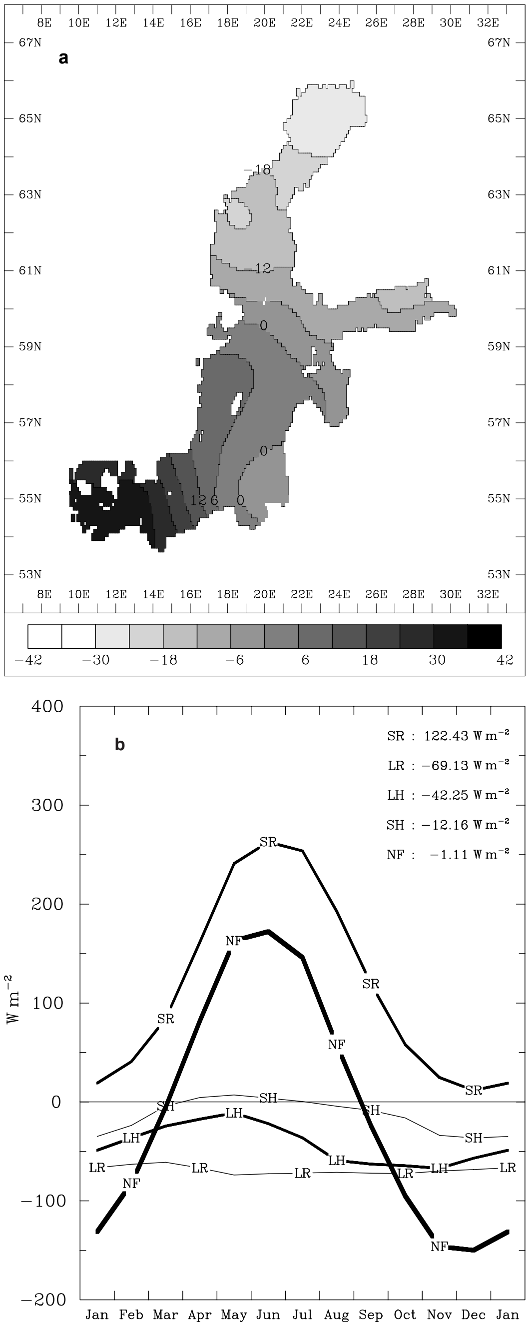

Fig. 6. — **a**: Longtime mean net heat flux (W m^{-2}) over the Baltic Sea; — **b**: Longtime mean annual cycle of the net heat flux NF and its four constituents shortwave radiation (SR), longwave radiation (LR), latent heat flux (LH), and sensible heat flux (SH). The total means, averaged over the entire year, are given in the upper right corner.

culate a reasonable energy and water budget of the Baltic Sea from COADS's individual merchant ship observations. However, the effects of sea ice have to be taken into account because it changes the fluxes e.g. via reduced evaporation and an increased albedo. For the period 1980 to 1995 both, the energy and the water budget considered at sea surface are nearly closed. We found a small positive value for $P - E$ of about 5 mm per month. For the energy exchange at sea surface a quasi-balanced state is found. Our calculations yield a longtime mean heat gain of the atmosphere of not more than 1 W m^{-2}.

The conviction of the usefulness of ship observations for the aims of the BALTEX research community is not prevalent. However, the energy and water balance of the Baltic Sea is a central issue of BALTEX and the presented results show that COADS gives satisfactory estimates for both, the longterm energy and water exchanges, so that these estimates can be used for the calibration of models.

In this study only a 16-year period of COADS is utilised. The entire COADS comprises an about 10 times larger period reaching back to middle of the nineteenth century. After the encouraging results presented here it will be worth to examine the complete data set, in order to capture also the decadal variability of the Baltic climate.

References

Bengtsson L., 2001. Numerical modelling of the energy and water cycle of the Baltic Sea. *Meteorology and Atmospheric Physics* 77: 9–17.

Bunker A.F., Charnock H. & Goldsmith R.A. 1982. A note on the heat balance of the Mediterranean and the Red Seas. *J. Marine Res.* 40 (Supplement): 73–84.

Dietrich G. & Schott F. 1974. Wasserhaushalt und Strömungen. In: Magaard L. & Rheinheimer G. (eds.), *Meereskunde der Ostsee*, Springer Verlag, 269 pp.

Gilman C. & Garrett C. 1994. Heat flux parameterization for the Mediterranean Sea: The role of atmospheric aerosols and constraints from the water budget. *J. Geophys. Res.* 99: 5119–5134.

Grassl H., Jost V., Kumar R., Schulz J., Bauer P. & Schlüssel P. 2000. The Hamburg Ocean-Atmosphere Parameters and Fluxes from Satellite Data (HOAPS): A climatological atlas of satellite-derived air-sea-interaction parameters over the oceans. *Max-Planck-Report* 312, 130 pp.

Jacob D., van den Hurk B.J.J.M., Andrae U., Elgered G., Fortelius C., Graham L.P., Jackson S.D., Karstens U., Köpken Chr., Lindau R., Podzun R., Rockel B., Rubel F., Sass B.H., Smith R.N.B. & Yang X. 2001. A comprehensive model inter-comparison study investigating the water budget during the BALTEX-PIDCAP period. *Meteorology and Atmospheric Physics* 77: 19–43.

Lindau R. & Ruprecht E. 2000. SSM/I-derived total vapour content over the Baltic Sea compared to independent data, *Met. Zeitschrift* 9: 117–123.

Lindau R. 2000. *Climate atlas of the Atlantic Ocean derived from COADS*, Springer Verlag Heidelberg, 448pp.

Maykut G.A. & Untersteiner N. 1971. Some results from a time-dependent thermodynamical model of sea ice. *J. Geophys. Res.* 76: 1550–1575.

Parker D., Jackson M. & Horton E. 1995. The 1961–1990 GISST 2.2 sea surface temperature and sea-ice climatology. *Hadley Centre Climate Research Tech. Note 63*, Hadley Centre for Climate Prediction and Research, 35 pp.

Raschke E. *et al.* 2001. The Baltic Sea Experiment (BALTEX): A European contribution to the investigation of the energy and water cycle over a large drainage basin. *Bull. American Meteorol. Soc.* 82: 2389–2413.

Sayin E. & Krauss W. 1996. A numerical study of the water exchange through the Danish Straits. *Tellus* A48: 324–341.

Tucker G.B. 1961. Precipitation over the North Atlantic. *Quart. J. Roy. Meteor. Soc.* 87: 147–158.

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