Tellus (1996), 48A, 693–707
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TELLUS
ISSN 0280–6495

# An investigation of water and energy budgets for the BALTEX region based on short-range numerical weather predictions

By ERDMANN HEISE*, *Deutscher Wetterdienst, Postfach 100465, D-63004 Offenbach am Main, Germany*

(Manuscript received 12 October 1995; in final form 1 April 1996)

ABSTRACT

The Baltic Sea Experiment (BALTEX) aims at understanding the water and energy budget of the Baltic Sea region and of the catchment area of its tributaries. Some of the budget components are investigated using results of short-range numerical weather predictions. Comparing these modelling results with climatological estimates of the respective budget components provides a valuable tool for model validation. At the same time, budget components which are not likely to be determined from observations, as, e.g., area mean evaporation, are available from model results. Thus, complete and consistent water and energy budgets can, at least in principle, be gained from model simulations. This study indicates the overall ability of the model to simulate the gross features of the water and energy budgets of the BALTEX region. Some model deficiencies are also clearly recognizable. They require further attention and instigate model improvement.

## 1. Introduction

The Baltic Sea Experiment (BALTEX), a regional contribution to the Global Energy and Water Cycle Experiment (GEWEX), will (i) explore, model, and quantify the various mechanisms determining the space and time variability of energy and water budgets of the BALTEX region and its interactions with surrounding regions, and (ii) relate them to the large-scale circulation systems in the atmosphere and oceans over the globe (Raschke, 1994). Key objectives of BALTEX are the improvement of atmospheric, oceanographic, and hydrological models, and the development of coupled models for the region under investigation, which includes the Baltic Sea region and the catchment area of its tributaries.

An important task to be accomplished during BALTEX is the determination of reliable atmospheric water and energy budgets for the region. These budgets will not only provide material for a better understanding of the climate system of the study area but, what is even more important, they will form the basis for the validation and improvement of numerical weather prediction models and climate models. Therefore, a measurement strategy will be used in BALTEX to determine as many of the budget components as possible from meteorological observations. But not all the budget components are likely to be determined from meteorological observations. These components include, e.g., the area mean values of vertical fluxes of water and energy at the surface of the earth. BALTEX intends to initiate a close research cooperation in the fields of meteorology, hydrology, and oceanography. This cooperation will lead to mutual use and intercomparison of measurements in all the three dis-

* email: heise@f4.za-offenbach.dwd.d400.de

ciplines, providing indirect estimates or at least constraints for the range of likely values for some of the aforementioned area mean fluxes.

In addition to the measurement strategy a modelling strategy will be used for BALTEX. Numerical models of the atmosphere are in principle able to provide complete and consistent water and energy budgets for the BALTEX region. But as the determination of budgets from measurements suffers from the incompleteness of observations and from observational errors, the models suffer from not being able to perfectly simulate the atmospheric behaviour. Therefore, both strategies should be combined. The measurements will provide some of the budget components and the models have to be validated using these data. Then the models will provide the components which are not likely to be determined from measurements.

The present study aims at determining (i) the feasibility of using model results for water and energy budget studies for a limited region and (ii) the feasibility of model validation by comparing independently computed budget components with model results. The use of observed water and energy budget components for model validation started with the advance of sophisticated general circulation models (GCMs; Smagorinsky et al., 1965; Manabe, 1969). Because of the very low horizontal resolution of these GCMs, the use of global or zonal averages was sufficient. Nowadays, the increased resolution and the refinement of the model physics require a much more detailed validation. Garrett et al. (1993) described the validation of some GCMs with surface energy budget components from observations. Their study was restricted to five areas distributed globally. The five areas were defined by latitudinal and zonal boundaries. The present study follows this method. However, the investigation is extended to additionally take into account the atmospheric energy budget and the surface and atmospheric water budgets. The budgets will be computed for the BALTEX region from short range (6 h to 30 h) numerical weather predictions of the Europa-Modell (EM) of the Deutscher Wetterdienst. (See Section 2 for a short description of the most recent version of EM.) Three years of data (October 1992 to September 1995) will be used. A drawback of using an operational weather prediction model is the model changes which lead to non-homogeneous time series. Major changes in the period are: (1) introduction of the Ritter and Geleyn (1992) radiation code (January 18, 1993); (2) Reformulation of the transpiration by plants and of the runoff generation process (March 11, 1994). In addition, the maximum rooting depth of plants during the vegetation period was changed several times in order to adjust the Bowen ratio.

In the present state, no attempt has been made to compare the simulated budgets with observations from the same period. Instead, this study is restricted to the use of existing climatological estimates of some budget components. All budgets are computed separately for the Baltic Sea region and for the catchment area of its tributaries.

In Section 2, a sketch of EM is given. Results of climatological estimates of water and energy budget components are summarized in Section 3. After a presentation of the budget equations used in the present study (Section 4), the results are detailed in Section 5. Here the climatological estimates are used to assess the quality of the model results and at least for some budget components the urgent need for temporally collocated verification material will be shown.

## 2. The model

The Europa-Modell of the Deutscher Wetterdienst is described by Cress et al. (1995). Therefore, only its main features will be given here. The model area covers Europe, the northernmost part of Africa, and most of the North Atlantic Ocean including the Norwegian Sea. A rotated latitude/longitude grid is used with 0.5° resolution. The vertical structure of the model atmosphere is resolved by a total of 20 layers, 8 layers being placed in the lowest 2 km to reproduce the structure of the boundary layer sufficiently well. The prognostic variables are surface pressure, horizontal wind components, total heat, defined as the sum of enthalpy and latent heat, and total water content, which is the sum of specific humidity and specific cloud water content. Assuming water saturation in clouds, temperature, specific humidity, and specific cloud water content can be diagnosed from total heat and total water content. The physics package includes the Ritter and Geleyn (1992) radiation code ($\delta$-two-stream approximation, three solar and five thermal spectral intervals, respectively) and a turbulence parameterization following Mellor and Yamada (1974), 2nd order, level 2. The Prandtl-layer parameterization is based on Louis' (1979) formulation of the Dyer-Businger relations. The soil model for heat and water transfer at the surface of the earth comprises two layers. The surface temperature is predicted using the extended force-restore-method (Jacobsen and Heise, 1982). Bare soil evaporation and plant transpiration are computed using the simple bucket method (Manabe, 1969). In the case of snow cover a one-layer model for heat and water content of the snow package is added. Grid-scale rain and snow are diagnosed from cloud water content using parameterized cloud microphysics, convective rain and snow is given by a mass flux convection scheme (Tiedtke, 1989).

A 6-h intermittent data assimilation scheme provides the three-dimensional atmospheric mass, wind, and humidity fields at 00, 06, 12, and 18 UTC, using the most recent six hour model forecast as first guess fields for the respective variables. Sea surface temperature (SST) is analysed once per day at 00 UTC using ship and buoy data of the last seven days. The SST is held constant during the forecast. Snow depth analyses are performed at 00, 06, 12, and 18 UTC, with the last analysis taken as a first guess. Until now there is no analysis of soil temperature and soil water content. Instead, the most recent six hour predictions are used as initial analyses for the next forecast.

## 3. A short review of climatological estimates of water and energy budget components for the BALTEX region

Compiling water and energy budget components from different sources and for different purposes poses the problem which dimensions should be used. The precipitation for a certain area, e. g., can be given as a specific quantity (mass/(area time)) or as an area mean quantity (mass/time or volume/time). In the following text, the values are given as specific quantities. All conversions between the different dimensions use the areas given in HELCOM (1986), Main Table 1:

| | |
|---|---|
| Baltic Sea: | 415,266 $km^2$ |
| Baltic Sea excluding Kattegat: | 392,979 $km^2$ |
| Catchment area of the Baltic Sea: | 1,721,233 $km^2$ |

This results in the following conversion factors:

1 mm/d $\leftrightarrow$ 151.6 $km^3$/a (Baltic Sea)
1 mm/d $\leftrightarrow$ 143.4 $km^3$/a (Baltic Sea excluding Kattegat)
1 mm/d $\leftrightarrow$ 628.3 $km^3$/a (catchment area)

### 3.1. *Water budget*

There is a long tradition in water budget calculations for the Baltic Sea. Spethmann (1912) seems to be the first who presented a complete water budget for the Baltic Sea region. Using only coastal measurements he estimated a total precipitation amount of 1.08 mm/d. From different sources he compiled the river runoff to be 3.08 mm/d (467 $km^3$/a). In 1912, no measurements or parameterizations were available for the determination of evaporation. He used 3 different rough estimates, the average being 0.53 mm/d. During the next decades a large amount of surface observations became available and, additionally, simple parameterizations to determine evaporation from these observations were developed. Using these data and methods, Brogmus (1952) was able to present a revised water budget of the Baltic Sea (excluding Kattegat). His results are: precipitation 1.27 mm/d, evaporation 1.21 mm/d, runoff 3.34 mm/d (479 $km^3$/a). In view of the large uncertainties in the evaporation determination he used water balance considerations to compute a second evaporation value, resulting in 1.30 mm/d. The average 1.25 mm/d was assumed by Brogmus (1952) to be the most likely evaporation value. But he wondered about the result that precipitation and evaporation are in balance although the Baltic Sea is part of a large region of humid climate where precipitation should exceed evaporation.

After routine aerological measurements had been established, a new method for water budget computations was developed. Benton and Estoque (1954) introduced the "aerological method" for the determination of the difference between evaporation and precipitation. In essence this method is based on a hydrological budget equation for the atmosphere:

$$\Delta S_{W,A} = E - P + Cv_{W,A}. \quad (1)$$

$\Delta S_{W,A}$ is the change of atmospheric water content, $E$ is evaporation from the surface of the earth, $P$

is precipitation and $Cv_{W,A}$ is the net convergence of atmospheric water vapour transport in the area under consideration. $\Delta S_{W,A}$ and $Cv_{W,A}$ can be computed from aerological observations. Adding surface observations of precipitation $P$, the area mean value of evaporation can be determined. Palmèn and Söderman (1966) were the first to make use of this method to compute the evaporation for a large part of the Baltic Sea. They used 6 aerological stations representing the border of the Baltic Proper and the Gulf of Riga and 27 stations with precipitation observations in the same region. The computations were extended over the time period from 1 October 1961 to 30 September 1962. The results obtained by Palmén and Söderman (1966) are: precipitation 1.56 mm/d and evaporation 1.45 mm/d. According to HELCOM (1986) the corresponding values for the total area of the Baltic Sea are smaller by a factor of 0.9808 and 0.9185, respectively, than the values for the region investigated by Palmén and Söderman (1966). Using these results one can estimate the amount of precipitation and evaporation for the Baltic Sea region to be 1.53 mm/d and 1.33 mm/d, respectively. Although they used observations for a direct computation of $S_{W,A}$ and $Cv_{W,A}$, Palmén and Söderman (1966) unfortunately did not show the results. Assuming $\Delta S_{W,A} = 0$ there should be a net convergence of the atmospheric water vapour transport of 0.20 mm/d. In their computations the authors had to take into account evaporation from land areas included in their area under investigation. They estimated a value of 1.06 mm/d. Alestalo (1983) used a three years (1974 to 1976) dataset of rawinsonde observations over most of Europe to compute the net flux convergence of atmospheric water vapour transport. For this region his result was $0.68 \pm 0.05$ mm/d. Assuming a uniform distribution of the convergence, this value will be used as an estimate for both the Baltic Sea region and the catchment area.

In the frame of the International Hydrological Programme/Operational Hydrological Programme Defant (in IHP/OHP, 1985) computed the net atmospheric convergence of the water vapour transport for the Baltic Sea region from rawinsonde observations. The average for the investigated period May 1976 to November 1977 was 0.41 mm/d. Independently, for the same period evaporation was determined by Henning (in IHP/OHP, 1985) and precipitation by Dahlström (in IHP/OHP, 1985), the results being 1.35 mm/d and 1.68 mm/d, respectively. This requires a net convergence of the atmospheric water vapour transport of 0.33 mm/d, roughly in accordance with Defant's value. Jacobsen (in IHP/OHP, 1985) determined the net outflow from the Baltic Sea (excluding Kattegat). Here a value of 2.31 mm/d (314 $km^3$/a) was computed from current measurements.

The most comprehensive review of the water budget of the Baltic Sea region was presented by the Baltic Marine Environment Protection Commission (HELCOM, 1986). Using data of the period 1951 to 1970 the results are: precipitation 1.68 mm/d, evaporation 1.37 mm/d, runoff 3.12 mm/d (472.9 $km^3$/a). The difference of precipitation minus evaporation requires a net convergence of atmospheric water vapour transport of 0.31 mm/d. According to this investigation the net outflow from the Baltic Sea amounts to 3.43 mm/d (471 $km^3$/a).

Legates and Willmott (1990) presented a global climatology of monthly mean precipitation distribution, which is compiled from different sources based on different reference periods. From their data the precipitation is 1.99 mm/d for the catchment area and 1.87 mm/d for the Baltic Sea. Bergström and Carlsson (1993) determined a new value for the runoff as 3.19 mm/d (483 $km^3$ /a) for the period 1950 to 1990.

Stigebrandt (1983) presented results of model calculations for the water and salt transport through the Danish Straits which show a very strong dependence of the mean salinity of the Baltic Sea on the assumed value of the mean freshwater surplus. The typical observed salinities (7 to 8‰) of the homohaline surface layer of the Baltic Sea are in equilibrium with a net freshwater surplus of 3.33 mm/d (8‰) to 3.73 mm/d (7‰). Using the river inflow given by Bergström and Carlsson (1993), this constrains the difference of precipitation minus evaporation to fall into the range 0.15 mm/d to 0.55 mm/d for long-term mean values.

Table 1 compiles all the climatological estimates of water budget components for the BALTEX region. Runoff values are presented separately for the catchment area and the region of the Baltic Sea, because due to the different size of the areas an amount given in $km^3$/a results in different

Table 1. *Water budget components of the atmosphere, the soil, and the Baltic Sea from observations*

| | Catchment area | | | | Baltic Sea region | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Reference | $P$ | $E$ | $Cv_{W,A}$ | $R_{CA}$ | $R_{BS}$ | $P$ | $E$ | $Cv_{W,A}$ | $OF_{DS}$ |
| Spethmann (1912) | | | | 0.74 | 3.08 | 1.08 | 0.53 | 0.55* | 3.63* |
| Brogmus (1952) | | | | 0.80 | 3.34 | 1.27 | 1.25 | 0.02* | 3.36* |
| Palmén and Söderman (1966) | | 1.06 | | | | 1.53 | 1.33* | 0.20 | |
| Budyko (1974) | | 1.14 | | | | | 1.74 | | |
| Alestalo (1983) | | | 0.68 | | | | | 0.68 | |
| IHP/OHP (1985) | | | | | | 1.68 | 1.35 | 0.41 | 2.31 |
| HELCOM (1986) | | | | 0.75 | 3.12 | 1.68 | 1.37 | 0.31* | 3.43 |
| Henning (1989) | | 0.83 | | | | | | | |
| Legates and Willmott (1990) | 1.99 | | | | | 1.87 | | | |
| Bergström and Carlsson (1993) | | | | 0.77 | 3.19 | | | | |

Unit: mm/d. Values marked by * are computed as a residuum. $P$: precipitation, $E$: evaporation, $Cv_{W,A}$: net convergence of atmospheric water vapour transport, $R$: runoff (the runoff values are given separately for the catchment area, $R_{CA}$, and for the Baltic Sea region, $R_{BS}$), $OF_{DS}$: outflow from the Baltic Sea.

values in mm/d. Some values not given by the respective authors have been added. They are computed using equation (1) or a corresponding equation for the soil or the Baltic Sea (eqs. (3) and (4), see below) by assuming vanishing temporal change of atmospheric water vapour, of water in soil and snow, and of the water level of the Baltic Sea. The values in the columns of Table 1 have to be compared with caution as they are computed for quite different time periods the length of which varies considerably, too. Additionally, there is a large variety of methods to determine the budget components. Nevertheless, Table 1 shows consensus about the order of magnitude of the budget components. The most recent combined estimates of precipitation and evaporation for the Baltic Sea region (HELCOM, 1986; Henning, 1988) are in accord with the oceanographical constraint for the difference of precipitation minus evaporation (Stigebrandt, 1983). In order to later compare the model results with observations, the last values of each column will be used.

### *3.2. Energy budget*

A lot of studies deal with the determination of components of the global energy budgets of the atmosphere and of the surface of the earth using different methods (e. g. Budyko, 1974; Savijärvi, 1988; Kyle et al., 1990; Fortelius and Holopainen, 1990; Fortelius, 1995). From Budyko's (1974) maps some estimates for the BALTEX region can be gathered. But in contrast to water budget calculations, there are only few studies with estimations of energy budget components especially for the BALTEX region. Normally, the Baltic Sea is not considered in global investigations of the heat balance of the oceans, either (Hsiung, 1986).

An early attempt to provide energy budget components for the Baltic Sea was made by Hankimo (1964), but he mainly considered data for the Bothnian Sea. Behr and Speth (1977) used aerological data of the period September 1963 to December 1970 in the region of the Baltic Sea and some surrounding areas to compute the net convergence of atmospheric transports of enthalpy and potential energy, the vertical turbulent flux of sensible heat at the ground, and the atmospheric divergence of the flux of longwave radiation. Additionally, they estimated the latent heat released by condensation from climatological distributions of precipitation. Their main result was a very large convergence of the atmospheric transport of enthalpy amounting to 126 W/m$^2$ in the annual mean. This value is much larger than the corresponding result of Alestalo (1981), who arrived at 55 W/m$^2$ using aerological data for the three year period of 1974 to 1976 and an area covering central and northern Europe. Alestalo (1981) could show that his result for the convergence of the atmospheric transport of total energy (sensible plus potential plus latent plus kinetic energy), which incidentally also amounts to 55 $W/m^2$, compares rather well with estimates of the net radiation balance at the top of the atmosphere (TOA) of roughly $-64$ $W/m^2$. These two values should compensate exactly if the storage of energy and oceanic heat transports are negligible (Holopainen, 1996). The convergence of the oceanic heat transport was estimated to be 2 $W/m^2$ by Alestalo (1981) using the maps presented by Bunker and Worthington (1976). But as the maps cover the North Atlantic Ocean (including the North Sea) only, Alestalo's (1981) results in this respect are not applicable to the Baltic Sea.

In IHP/OHP (1985), the radiation balance and the sensible heatflux at the surface of the Baltic Sea as well as the latent heat released by condensation were computed by Henning, who later presented a comprehensive discussion of his results (Henning, 1988). Adding the TOA radiation balance given by Alestalo (1981), a value of 38 $W/m^2$ can be estimated for the net convergence of atmospheric enthalpy transport from these results. Henning (1989) computed the components of the surface heat balance for all continents except Antarctica. From his maps some gridpoint values were gathered for the catchment area and areal averages were determined. Rather large differences between the values of Budyko (1974) and Henning(1989) are found both in the net radiation balance and in the latent heatflux. But in both papers the balance of all components is close to zero, i.e., the storage of heat in the soil is negligible. For the Baltic Sea region the same is only true for Budyko's (1974) results. In IHP/OHP (1985) there is a net loss of energy at the surface of the Baltic Sea of 16 $W/m^2$, to be compensated by a net inflow of sensible energy due to either river inflow or transport through the Danish Straits.

Stigebrandt (1995) questioned the ability of warm water inflow to the Baltic Sea to compensate for a deficit in the surface energy budget of some 10 $W/m^2$ by a simple order of magnitude calculation. Following his arguments we take into account three eventual sources of warm water: (1) river inflow (3.19 mm/d), (2) precipitation (1.87 mm/d), and (3) inflow through the Danish Straits driven by sea level differences which may be, according to Stigebrandt (1983), one order of magnitude larger than river inflow (31.90 mm/d). The total water input amounts to 36.96 mm/d or $4.27 \cdot 10^{-4}$ kg/($m^2$ s). On average the same amount has to leave the Baltic Sea by evaporation and by outflow through the Danish Straits. The temperature difference between inflowing and outflowing water might be a net gain of thermal energy to compensate a surface energy budget deficit. We neglect problems like redistribution of warm water, presumable values for the temperature of rain water etc. Using the specific heat of water (4184 J/(kg K)), all inflowing water would on average have to be 5.6 K warmer than the outflowing water to compensate a surface energy budget deficit of 10 $W/m^2$ . As the assumption that all inflowing water can be cooled down is quite unrealistic and as in addition a cooling of 5.6 K on an annual mean basis is not likely to occur, the surface energy budget deficit should be significantly smaller than 10 $W/m^2$.

Holopainen (1996) doubts whether reliable budget components, especially for inferring the atmospheric diabatic heating, can be obtained using the aerological method for the BALTEX region. The smallest scale to which the usefulness of this method extends is not yet known. He stresses the need for independent validation material to assess the accuracy of budget components computed using the aerological method in the context of BALTEX.

The different climatological estimates are compiled in Table 2. Of course, some values for latent heat flux and latent heat released by condensation could be added using the data in Table 1, but these values would not provide independent material for model validation and are therefore omitted.

## 4. Theoretical considerations for the determination of budget components from short- range numerical weather predictions

In principle, all water and energy budget components can be computed from the results of numerical models of the atmosphere. But the present system used in the Europa-Modell was originally not installed for water and energy budget calculations but rather for controlling the model results with the aid of some area integrated values. This system was extended to compute many but not all of the budget components for the BALTEX region. The restrictions of the system are: (1) atmospheric budget components are

Table 2. *Budget components of sensible heat of the atmosphere, the soil, and the Baltic Sea from observations*

| Reference | Budyko (1974) | Behr and Speth (1977) | Alestalo (1981) | IHP/OHP (1985) | Henning (1989) |
|---|---|---|---|---|---|
| Catchment area | | | | | |
| $Rd_{TOA}$ | −50 | | −64 | | |
| $Rd_{surf}$ | 44 | | | | 37 |
| $F_{se}$ | 13 | | | | 12 |
| $F_{la}$ | 36 | | | | 24 |
| $\Delta S_{E,S}$ | −5* | | | | 1* |
| $Cv_{E,A}$ | | | 55 | | |
| Baltic Sea region | | | | | |
| $Rd_{TOA}$ | −50 | | −64 | | |
| $Rd_{surf}$ | 66 | | | 41 | |
| $F_{se}$ | 13 | 8 | | 18 | |
| $F_{la}$ | 50 | | | 39 | |
| $LP$ | | 46 | | 49 | |
| $Cv_{E,A}$ | | 126 | 55 | | |
| $Cv_{E,O}$ | −3* | | | 16* | |

Unit: $W/m^2$. Values marked by * are computed as a residuum. $Rd_{TOA}$, $Rd_{surf}$: downward directed net radiation fluxes at the top of the atmosphere (TOA) and at the surface of the earth (surf), respectively, $F_{se}$, $F_{la}$: sensible (se) and latent (la) heatflux, positive upwards, $LP$: latent heat released by condensation, $Cv_{E,A}$: net convergence of atmospheric transport of sensible heat, $\Delta S_{E,S}$: temporal change of heat storage in the soil, $Cv_{E,O}$: net convergence of horizontal transport of thermal energy in the Baltic Sea.

computed for the water and sensible heat budgets only; (2) the conversion term between sensible heat and kinetic energy is neglected; (3) transports of water and sensible heat across the lateral boundaries of the area under investigation are not computed directly. They are determined as residua in the respective budget equations, this may be called a "reversed aerological method"; (4) the latent heat released by condensation is computed from precipitation using the latent heat of vaporization (i.e., in the case of snowfall at the ground the latent heat of fusion is neglected in the atmospheric budget of sensible heat). Likewise evaporation is computed from the latent heatflux (neglecting the latent heat of fusion if temperatures at the ground are below 0°C); (5) the effect of horizontal diffusion is neglected. This leads to the following simplified budget equations, in which all terms are to be considered as area mean values:

### *(a) Water budget of the atmosphere*

Eq. (1) is used with

$$\Delta S_{W,A} = \frac{\partial}{\partial t} \int_0^{p_s} q \, \frac{dp}{g}. \qquad (2)$$

Here $p$ is pressure, $p_s$ surface pressure, $t$ time, $q$ specific humidity, and $g$ acceleration of gravity. The net convergence $Cv_{W,A}$ of atmospheric water vapour transport is computed as a residuum in the budget equation.

### *(b) Water budget of the upper soil layers*

The budget is computed for the catchment area

$$\Delta S_{W,S} = \frac{\partial W}{\partial t} = P - E - R. \qquad (3)$$

W is the water content of the hydrologically active soil layers (of a thickness of 1 m in EM) plus the water content of the snow package, $\Delta S_{W,S}$ is the temporal change of $W$, and $R$ is runoff generation.

### *(c) Water budget of the Baltic Sea*

A vanishing change of the total water content of the Baltic Sea is assumed. On an annual mean basis, this assumption is justified by the results of Samuelsson and Stigebrandt (1996), showing annual variations of the mean sea level of the order of 0.03 mm/d in accordance with the

HELCOM (1986) results. This variation is small compared to the other water budget terms.

$$0 = P - E + R - OF_{DS} \tag{4}$$

Instead of a convergence term the net outflow $OF_{DS}$ of water from the Baltic Sea is computed as a residuum.

*(d) Atmospheric budget of sensible heat*

$$\Delta S_{E,A} = \frac{\partial}{\partial t} \int_0^{p_s} c_p T \frac{dp}{g} = Rd_{TOA} - Rd_{surf} + LP + F_{se} + Cv_{E,A}. \tag{5}$$

$T$ is atmospheric temperature, $c_p$ specific heat at constant pressure, $\Delta S_{E,A}$ temporal change of atmospheric sensible heat, $Rd_{TOA}$ and $Rd_{surf}$ are net radiation fluxes (positive downwards) at the top of the atmosphere (TOA) and at the surface of the earth (surf), respectively, $L$ is latent heat of vaporization, and $F_{se}$ is the sensible heatflux at the surface of the earth (positive upwards). The net convergence $Cv_{E,A}$ of atmospheric transport of sensible heat is computed as a residuum.

*(e) Heat budget of the upper soil layers*

The budget of heat transfer is computed for the active soil layers of a thickness of about 0.3 m for the catchment area. The heat flux through the lower boundary of the active soil layers is neglected and the temporal change $\Delta S_{E,S}$ of the storage term computed as a residuum:

$$\Delta S_{E,S} = Rd_{surf} - F_{se} - F_{la}. \tag{6}$$

$F_{la}$ is the latent heatflux (positive upwards).

*(f) Heat budget of the Baltic Sea*

A vanishing change in the total thermal energy of the Baltic Sea is assumed. The net convergence $Cv_{E,O}$ of horizontal transport of thermal energy in the Baltic Sea is computed as a residuum.

$$0 = Rd_{surf} - F_{se} - F_{la} + Cv_{E,O} \tag{7}$$

## 5. Budget components for water and sensible heat from model results

### *5.1. Data base*

First computations for the BALTEX region considering only part of the budget components started in February 1992. The complete system described above became operational in April 1992. The computations are performed for all forecasts of the Europa-Modell starting at 00 UTC, the time period 6 h to 30 h is used. Only monthly mean values of the budget components are saved for further processing. In addition to the area mean budget components, monthly mean horizontal distributions for the whole model area are computed and saved for some variables, e.g., precipitation, evaporation, radiation fluxes.

Three years of data (October 1992 to September 1995) will be used for the present study. Annual means are computed for the years 1993, 1994, and for the one year period October 1994 to September 1995. Annual cycles are computed from the whole 3 years period. Due to computer problems horizontal distributions at present are only available for the period June 1994 to May 1995.

### *5.2. Annual mean budgets*

*5.2.1. Water budget.* Table 3 shows the atmospheric water budget, complete with runoff and net outflow from the Baltic Sea. In both the subregions (Baltic Sea region and catchment area, respectively) precipitation compares well with the climatological estimates. In view of the difficulties in estimating area mean evaporation from observations, the agreement of model results with climatology seems satisfactory, but there is a tendency for modelled evaporation values being too large. The difference of precipitation minus evaporation in this region, nearly vanishing in 1993, amounts to some 0.5 mm/d in the two following periods. This is very close to the upper limit for long term mean values according to the oceanographical constraint presented by Stigebrandt (1983). Although this constraint does not strictly apply to annual mean values but rather to longer time periods, modifications of the evaporation and precipitation parameterization have to take account of it.

Despite these rather promising results the storage term $S_W$ both in the atmosphere and in the

Table 3. *Water budget components of the atmosphere, the soil, and the Baltic Sea from model results*

| Period: | Jan.–Dec. 1993 | Jan.–Dec. 1994 | Oct. 1994–Sept. 1995 | Climatolg. |
|---|---|---|---|---|
| Catchment area | | | | |
| $P$ | 1.97 | 1.93 | 2.23 | 1.99 |
| $E$ | 1.08 | 1.01 | 1.16 | 0.83 |
| $\Delta S_{W,A}$ | 0.07 | −0.26 | −0.30 | |
| $Cv_{W,A}$ | 0.96* | 0.66* | 0.77* | 0.68 |
| $\Delta S_{W,S}$ | 0.62 | 0.37 | 0.40 | |
| $R_{CA}$ | 0.27 | 0.55 | 0.67 | 0.77 |
| Baltic Sea region | | | | |
| $R_{BS}$ | 1.13 | 2.29 | 2.79 | 3.19 |
| $P$ | 1.97 | 2.10 | 2.20 | 1.87 |
| $E$ | 2.00 | 1.56 | 1.65 | 1.37 |
| $\Delta S_{W,A}$ | 0.26 | −0.05 | −0.18 | |
| $Cv_{W,A}$ | 0.23* | 0.49* | 0.37* | 0.68 |
| $OF_{DS}$ | 1.10* | 2.83* | 3.34* | 3.40 |

Unit: mm/d. Values marked by * are computed as a residuum. $\Delta S_{W,A}$: temporal change of atmospheric water content, $\Delta S_{W,S}$: temporal change of the water content of soil and snow. Other symbols as in Table 1.

soil of the catchment area exhibits significant model problems. The mean decrease of atmospheric water content is well known from diagnostics of the Europa-Modell. It might be due to precipitation values being too large and/or evaporation values being too small. The third possibility is too high a first guess of atmospheric moisture values during the assimilation cycle of the model. The first two possibilities are not supported by comparison with the climatological estimates. However, firm conclusions can be drawn only after temporally collocated precipitation and evaporation determinations from observations become available during BALTEX. The mean increase of soil moisture content during the 6 h to 30 h forecast period used for the budget calculations again might be due to precipitation values being too large and/or evaporation values being too small, but more likely, the initial soil moisture distribution on average seems to have too low values. In view of the large impact of initial soil moisture values on short- and long-range forecasts (Rind, 1982; Delworth and Manabe, 1989; Viterbo and Illari, 1994), this seems to be a serious problem to be solved by the development of soil moisture assimilation methods. A first attempt was presented by Mahfouf (1991).

*5.2.2. Sensible heat budget.* The simulated sensible heat budget of the atmosphere (Table 4) shows the BALTEX region to be a sink region for sensible heat in accordance with the climatological estimates. The magnitude of the compensating convergence of atmospheric horizontal transports of sensible heat is slightly smaller than the value given by Alestalo (1981) and significantly smaller than that given by Behr and Speth (1977). The net divergence of atmospheric radiation compares rather well with Budyko's (1974) estimate, but the sensible heatflux at the surface seems to be too small in the catchment area. In contrast to the water budget the storage term of enthalpy both in the catchment area and in the Baltic Sea region is small compared to the other terms (except the small sensible heatflux). The budget of sensible heat is in reasonable equilibrium during the forecasts.

Considering the heat budget of the soil (Table 4) for the catchment area, the net radiation is in accordance with the climatological estimates, whereas the sensible heatflux seems to be too small and the latent heatflux too large. However, the net effect of the heatfluxes over this region is very small, showing a good balance at the surface of the earth. Concerning the Baltic Sea region there are rather large differences between the two climatological estimates. The model is in accord with the IHP/OHP (1985) results except for the latent heatflux which seems to be too large. In contrast to the catchment area there is a consider-

Table 4. *Budget components of sensible heat of the atmosphere, the soil, and the Baltic Sea from model results*

| Period: | Jan.–Dec. 1993 | Jan.–Dec. 1994 | Oct. 1994–Sept. 1995 | Climatolg. |
|---|---|---|---|---|
| Catchment area | | | | |
| $Rd_{TOA}$ | −79.4 | −75.4 | −77.0 | −57 |
| $Rd_{surf}$ | 33.0 | 38.5 | 38.3 | 37 |
| $F_{se}$ | −0.4 | 6.3 | 1.8 | 12 |
| $F_{la}$ | 31.4 | 29.3 | 33.4 | 24 |
| $LP$ | 57.1 | 55.8 | 64.4 | |
| $Cv_{E,A}$ | 45.5* | 47.8* | 45.7* | 55 |
| $\Delta S_{E,A}$ | −10.2 | −4.0 | −3.4 | |
| $\Delta S_{E,S}$ | 2.0* | 2.9* | 3.1* | 1* |
| Baltic Sea region | | | | |
| $Rd_{TOA}$ | −69.7 | −65.3 | −64.6 | −75 |
| $Rd_{surf}$ | 38.8 | 46.2 | 47.9 | 41 |
| $F_{se}$ | 22.4 | 16.9 | 15.8 | 18 |
| $F_{la}$ | 58.0 | 45.0 | 46.3 | 39 |
| $LP$ | 56.9 | 60.4 | 62.2 | |
| $Cv_{E,A}$ | 18.9* | 30.0* | 31.8* | 55 |
| $\Delta S_{E,A}$ | −10.3 | −4.2 | −2.7 | |
| $Cv_{E,O}$ | 41.6* | 15.7 | 14.2* | 16* |

Unit: $W/m^2$. Values marked by * are computed as a residuum. $\Delta S_{E,A}$: temporal change of atmospheric sensible heat. Other symbols as in Table 2.

able deficit in the surface energy budget both in the observations and in the model results. As was mentioned earlier, an energy transport to compensate this deficit can not be accomplished by water transports. Therefore, the problem of the energy budget deficit at the surface of the Baltic Sea has to be solved by a general refinement of the physical parameterizations of the atmospheric model and by the use of temporally collocated validation material.

### *5.3. Annual cycle of water and energy budget components*

For the computations of mean annual cycles of model results, all values from October 1992 to September 1995 are used. Fig. 1 shows the annual cycle of water budget components of the atmosphere for the BALTEX region. The gross features of the annual course of the precipitation rate (a distinct maximum in late summer and a broad minimum during spring and early summer) are covered reasonably well in comparison to the results of Legates and Willmott (1990). The same is true for the sum of the storage term and of the net convergence of atmospheric water vapour transports in comparison with Alestalo's (1983) results. This component exhibits a strong annual variation. But only during summer months this sum is close to zero. The model results indicate a net divergence of atmospheric water vapour transport from June to August (not shown). As the catchment area is much larger than the Baltic Sea region the annual cycle of evaporation is dominated by the catchment area and shows a broad maximum in summer.

As there is not yet reliable observational material on the annual course of the atmospheric sensible heat budget, only the components of the thermal energy budget at the surface of the Baltic Sea are presented in Fig. 2. The model values are compared with the IHP/OHP (1985) results. The model results generally show values of the net radiation some 10 $W/m^2$ higher than IHP/OHP (1985) in spring and values slightly smaller in autumn. But in general the agreement is very good. Keeping in mind the difficulty of parameterizing turbulent fluxes (sensible plus latent heatflux) the same can be stated for this budget component. Only in October—and to a lesser

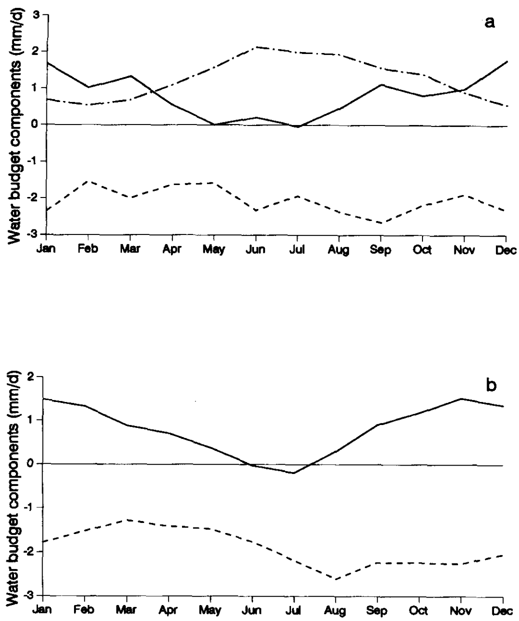


*Fig. 1.* Annual cycle of water budget components of the atmosphere for the BALTEX region: net convergence of atmospheric horizontal water transport plus temporal change of atmospheric water content (solid), evaporation (dash-dotted), precipitation (dashed). Positive values denote a gain of water for the atmosphere: (a) model results (October 1992 to September 1995); (b) observations after Alestalo (1983) and after Legates and Willmott (1990).

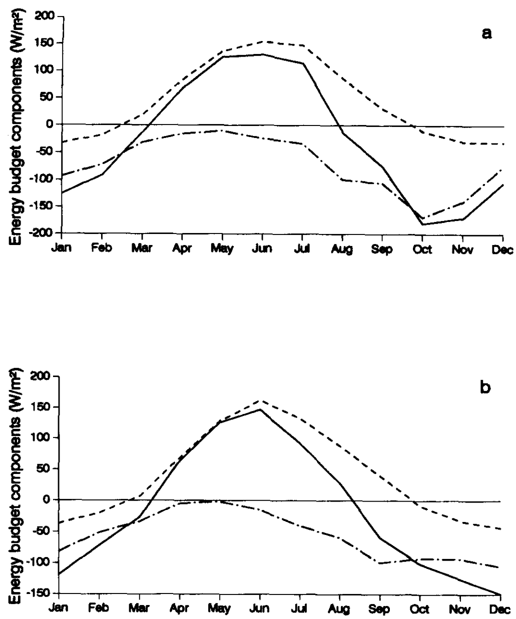


*Fig. 2.* Annual cycle of budget components of thermal energy at the surface of the Baltic Sea: net radiation flux (dashed), sensible plus latent heatflux (dash-dotted), heat budget (solid). Positive values denote a gain of thermal energy for the Baltic Sea: (a) model results (October 1992 to September 1995); (b) observations after IHP/OHP (1985).

degree in November, too—are there large discrepancies between the two curves. These are caused by both the sensible and the latent heatflux being twice as large as the IHP/OHP (1985) results in October. The factor is roughly 1.5 in November and both model values are smaller than the climatological estimates in December. Inspection of the data of the three years available shows that these values are biased by extremely large turbulent fluxes in October and November 1992. This suggests either unusually warm sea surface temperatures or unusually cold air temperatures during these two months. The overall accord between these model results and the climatological estimates of the budget components is very good. This also applies to the net gain or loss of energy from the Baltic Sea. From April to July the results show a net gain of energy which is (according to the annual mean values in Table 4) overcompensated by an energy loss from September to March. In August both curves show near zero values being negative for the model results and positive for the climatological estimates.

Fig. 3 depicts the annual course of the atmospheric enthalpy budget for the BALTEX region. At present no observational material is at hand to validate these model results. The atmospheric radiation budget shows the very strong annual cycle of a region extending from the mid latitudes to the polar circle. The sensible heatflux obeys a similarly large annual variation. On the other hand, there is only a comparably small variation in the condensation rate. Because of the approximation in computing the condensation rate from precipitation, the respective values during winter months are in fact higher. Compared to the large annual cycle of the atmospheric radiation budget, the change of the storage term of enthalpy is rather small. Surprisingly, this budget component is positive in November as a result of positive values in both 1993 and 1994. Only in 1992 the model results were negative as is anticipated for

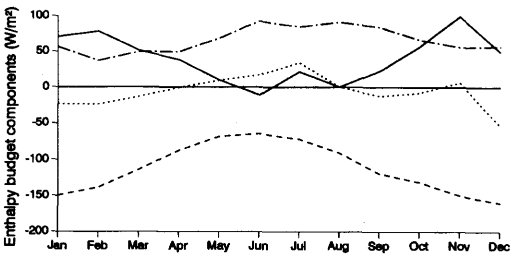


*Fig. 3.* Annual cycle of atmospheric budget components of enthalpy for the BALTEX region, model results (October 1992 to September 1995): net convergence of atmospheric transport of enthalpy (solid), net radiation budget of the atmosphere (dashed), latent heat released by condensation plus sensible heatflux at the surface (dash-dotted), temporal change of enthalpy (dotted). Positive values denote a gain of enthalpy for the atmosphere.

this month. Temporally collocated validation material would be required to distinguish between true but unusual atmospheric behaviour and model problems. The net convergence of atmospheric horizontal transports of enthalpy exhibits much the same variation as the convergence of water vapour transports. Only in summer there are small or even negative contributions to this budget term.

### *5.4. Horizontal distribution of precipitation*

In addition to the area averaged budget components monthly mean distributions of vertical fluxes of water and energy at the surface and at the top of the atmosphere are determined. Fig. 4 presents the annual mean precipitation distribution of the model predictions (June 1994 to May 1995) in comparison with the climatological estimates by Legates and Willmott (1990). This distribution is dominated by the contrast between the extremly large precipitation depth along the Norwegian coast and the much smaller values in most of the other area. But indeed the model results show much finer details as, e.g., (1) the relative precipitation maxima along the west coasts of Denmark, Sweden, and the Baltic States, and (2) the relative precipitation minima over the Baltic Sea and over the Kola peninsula. These features are in good accordance with the climatological precipitation field. This confirms the model's ability to simulate even small scale variations of water budget components.

## 6. Summary and conclusions

The determination of reliable water and energy budgets from both observations and numerical modelling requires large efforts during BALTEX. This paper presented results of water and energy budget calculations from model results. Short-range (6 h to 30 h) predictions with a limited area model (Europa-Modell of the Deutscher Wetterdienst) are used to compute monthly mean budget components.

At present, the validation of the model results has been restricted to climatological estimates of the respective budget components instead of calculations from temporally collocated observations. But even this first attempt presented valuable insight into the capability of the model to provide fairly reliable water and energy budgets.

Oceanographical constraints concerning the difference of precipitation minus evaporation and the surface energy budget deficit in the Baltic Sea region in combination with the climatological estimates indicate that precipitation values are too high and perhaps also, to a lesser degree, evaporation values are too high. Here a refinement of the model parameterizations seems to be necessary which has to take into accout the large influence of evaporation above water areas on precipitation above land areas.

The only major drawback of using these short-range numerical weather prediction results for the computation of water and energy budget components seems to be the spin-up problem of the water content both in the atmosphere and in the soil of the catchment area. On the other hand, no similar problems seem to occur in the atmosphere of the Baltic Sea region. The close to zero annual mean surface energy balance in the catchment area region and the atmospheric storage term of sensible heat being small compared to the other budget terms in both regions are indicators of a good thermal balance of the model. In general these results support the use of short-range numerical predictions for the computation of water and energy budgets.

The use of climatological estimates of water and energy budget components for model validation proved to be valuable. However, for a more detailed tracing of model problems the use of temporally collocated verification material is indispensable. Providing this material will be one of the most challenging tasks for the measuring strategy during BALTEX.

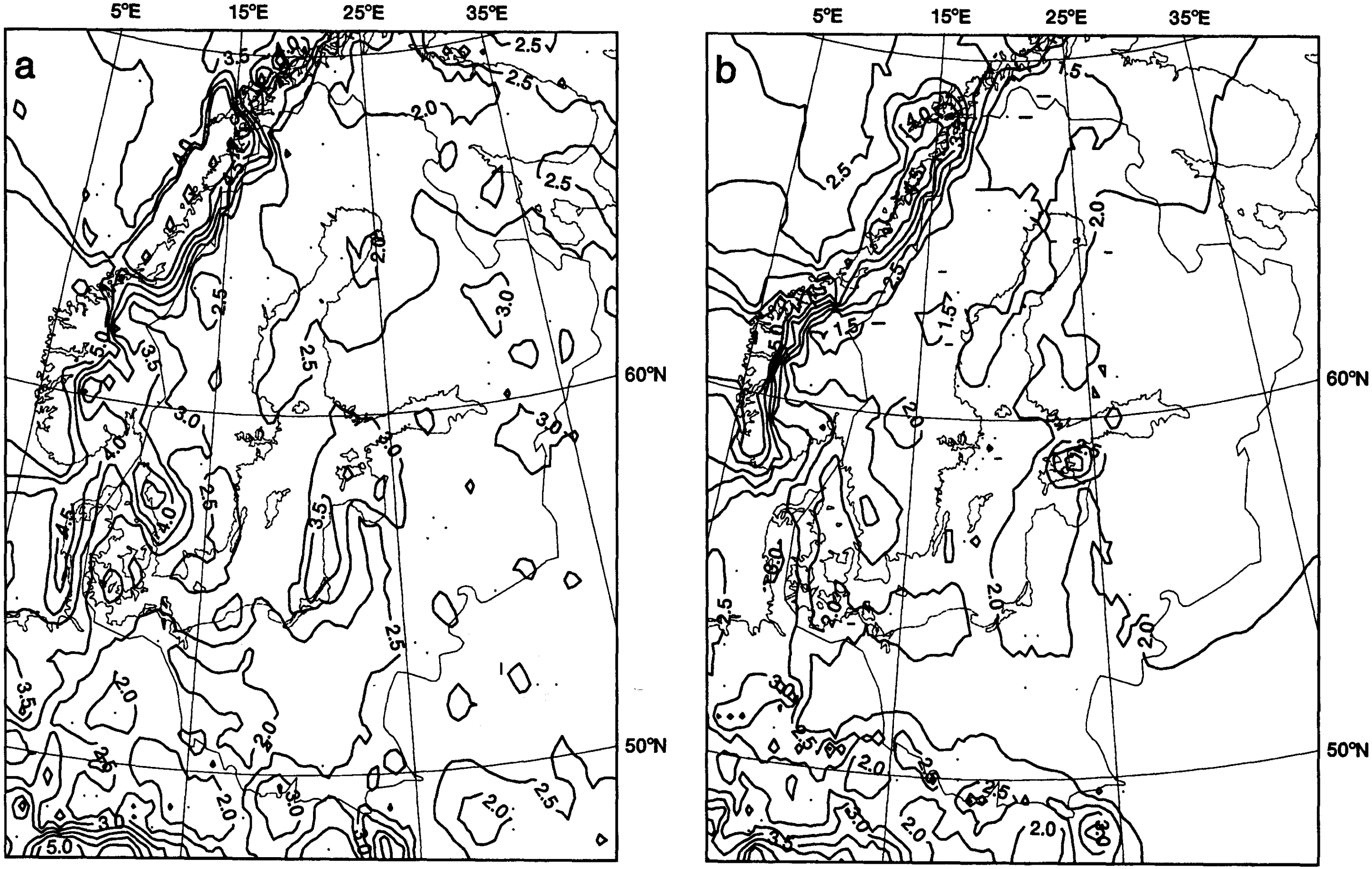


*Fig. 4.* Annual mean precipitation distribution. Unit: mm/d. Up to 5 mm/d isolines are drawn in 0.5 mm/d intervals and for larger values in 2 mm/d intervals. The boundary of the catchment area is shown as a thin line: (a) model results (June 1994 to May 1995); (b) observations after Legates and Willmott (1990).

## 7. Acknowledgements

The author is indepted to D. Majewski, who is responsible for the development of the operational Europa-Modell, and to B. Fay, Dr. H.-J. Herzog, Dr. V. Renner, and B. Ritter for helpful discussions. Technical support was given by M. Anders and E. Fischer.

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