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Calculation of the water budget over the Baltic Sea catchment area using the regional forecast model REMO for June 1993

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ABSTRACT

The atmospheric components of the water cycle over the Baltic Sea and its catchment area are calculated using the regional numerical weather prediction model REMO. Daily as well as monthly mean values of precipitation, evapotranspiration, horizontal water transport, and change of atmospheric water content are presented. As a first attempt of validation, precipitation data provided by several national meteorological services (5898 stations) are compared with the model results. The areal averages of daily precipitation over the whole catchment area agree well with the measurements but on some days there is a mismatch in the geographical distribution between observations and model results. A comparison of evaporation and precipitation with measured data of June 1993 as well as with climatological values shows that the model reflects the relatively wet character of this month.

1. Introduction

The determination of the water and energy budgets over the Baltic Sea and its catchment area is one of the major components of the Baltic Sea Experiment (BALTEX). Several studies investigated the mean monthly atmospheric water budget over the Baltic Sea using observations from aerological stations in combination with precipitation measurements. The budget calculations were based on the "aerological method" in which the divergence of the water transport and the change of water content are determined from atmospheric soundings, and the difference between evaporation and precipitation is computed as the residuum of the budget. Palmén and Söderman (1966) computed the evaporation from the central part of the Baltic Sea for the time period October 1961–September 1962 using the aerological method. Alestalo (1983) presented the seasonal variation of the water budget over Europe based on radiosonde data for July 1969–June 1977 in comparison with longterm averages of precipitation and evaporation. The most comprehensive study of the water budget of the Baltic Sea was initiated by the Baltic Marine Environment Protection Commission-Helsinki Commission-(HELCOM, 1986). Long-term averages (1951–1970) of precipitation and evaporation as well as river inflow and sea volume changes were presented there. For increasing spatial and temporal resolution of water and energy transport investigations, one could think of more and more advanced physically based interpolations of measurements in space and time. This eventually leads to models already in use for numerical weather prediction. They can provide a tool for obtaining

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estimates of all components of the atmospheric part of the energy and water cycle with high spatial and temporal resolution. However, comparison with measurements is needed to confirm the reliability of the results and to improve model parameterizations in turn. For the BALTEX region, results from 3 years' numerical simulation with the Europa-Modell (EM) of the German Weather Service (DWD) have been reported by Heise (1995). He calculated the components of energy and water cycles over the Baltic Sea catchment area from consecutive daily operational forecasts. Especially for research within BALTEX a REgional scale MOdel REMO has been implemented in a joint effort of the DWD, the Max-Planck-Institute for Meteorology (MPI) in Hamburg, the Deutsches Klimarechenzentrum (DKRZ) in Hamburg, and the GKSS-Research Centre Geesthacht to cover a region including the Baltic Sea catchment area. REMO is operated in two different modes at MPI and GKSS: a "climate mode" at MPI and a "forecast mode" at GKSS. In "climate mode" initial and boundary conditions are obtained from climate model runs. Results of these investigations are reported by Jacob and Claussen (1995). "Forecast mode" means that results of consecutive short range weather forecasts (30 hours) are used to analyse a time span of the order of months, here June 1993. Initial and boundary conditions are derived from analyses, and the model is restarted with new initial conditions every day. This paper presents results of the forecast mode approach. Section 2 includes details of the model and the initial and boundary conditions. In section 3 results for all components of the atmospheric water budget over the Baltic Sea catchment area for June 1993 are presented. Section 4 shows a comparison of the calculated precipitation with measured data of the same time period and also with climatological values. Conclusions are given in section 5.

2. Description of the model

The regional model REMO as used here is essentially the same code as the regional weather forecast model "Europa-Modell" (EM, version 2.11) of the German Weather Service (Majewski, 1991). The model uses the hydrostatic approximation with 20 vertical levels in a hybrid coordinate system. The horizontal resolution is 1/6° in a rotated spherical coordinate system whose equator is almost in the centre of the computational domain. This results in a horizontal grid size of approximately 18×18 km^2. The EM grid refers to the same coordinate system but with 1/2° horizontal resolution. Thus every third REMO grid point coincides with an EM grid point. The Baltic Sea and its catchment area are located in the centre of REMO's computational domain, covering about 29% of it. In contrast to earlier EM versions, REMO has water vapour q_v, cloud water q_c, and temperature T among its prognostic variables, not total water content $q = q_v + q_c$ and total heat $h = c_p T + Lq$ (with c_p heat capacity at constant pressure and L latent heat of condensation). For details see Jacob et al. (1995). In REMO the same parameterizations of the physical processes as in EM are used. The parameterization of microphysical processes in stratiform clouds follows in general the scheme of Kessler (1969), but the importance of the ice phase for the precipitation formation is enhanced. Moist convective processes are parameterized using a mass flux scheme (Tiedtke, 1989). Evapotranspiration from land surfaces is determined in a soil model which predicts temperature and water content in the soil. It has two layers and an interception storage for water and snow at the surface. The heat budget is formulated according to an extended force-restore method (Jacobsen and Heise, 1982). Evaporation over sea surfaces is calculated with a bulk formula, assuming water vapour saturation at the surface and using Charnock's formula for the roughness length.

Both REMO and EM are started for each day of June 1993 at 00 UTC using analyses on the EM grid obtained from DWD as initial conditions. Sea surface temperature is analysed daily using ship and buoy data and is kept constant during each forecast. No analysis of the prognostic variables of the soil model (temperature and moisture) is performed. Their values are taken from the 6 h first guess of the EM data assimilation procedure (Majewki, 1991). A 30 h forecast is computed by both models. EM uses analyses of 00, 06, 12, 18 UTC as boundary conditions. REMO's boundary conditions are provided by hourly data from the EM run. To account for a spin up time, only REMO results obtained after the first 6 hours of the forecast are shown in this paper. This spin up time has been shown to be sufficient for EM and Deutschland-Modell (DM) and is therefore taken also in the present study. By restarting the model every day with analyses the model state is forced to stay close to the real weather situation. This facilitates a comparison with measurements with high spatiotemporal resolution. However, small scale features which develop during the forecast period are destroyed at the next restart, because the initial conditions are interpolated from a coarser grid. The influence of the length of the forecast time on the spatiotemporal structures of the water balance and on the integrated balance components has not been investigated in this study.

All components of the atmospheric water cycle (precipitation, evapotranspiration, horizontal transport, and change of water content in the atmosphere) are computed explicitely and time integrated during the model run. Thus the conservation of atmospheric water in the model can be verified. The water balance components of the vertical soil model are also computed.

3. Results

The total atmospheric water storage W changes due to precipitation P, evapotranspiration E, and horizontal water transport convergence C. These components of the atmospheric water budget are calculated for the atmospheric columns above each grid point. The present model implementation allows for an easy access to all of them in a prescribed time interval during the calculated period. To obtain results for a region, the values for all columns inside the region are summed up. Results are presented either in kg m^{-2} or equivalently in mm. The water budget components are defined as follows.

The total atmospheric water storage W expressed as water mass per unit area is calculated as vertical integral over each atmospheric column:

$$W=\int_0^{p_s} \frac{\mathrm{d}p}{g}\, q. \qquad (1)$$

.Here p_s denotes surface pressure, g gravitational acceleration, and q is the mass fraction of water in the atmosphere. Total precipitation P and evapotranspiration E are computed as time integrals of the corresponding rates which are calculated by the model at every time step. Horizontal water transport into a vertical column B of grid boxes between the times t_1 and t_2 is given by

$$C(B, t_1, t_2)=-\int_{t_1}^{t_2} \mathrm{d}t \int_{\partial B_H} \mathrm{d}n \int_0^{p_s} \frac{\mathrm{d}p}{g}\, q\mathbf{v}_H, \qquad (2)$$

.where $\mathbf{v}_H$ is the horizontal wind, ∂B_H is the horizontal boundary of the column and d$\mathbf{n}$ its outward normal. Thus the convergence of atmospheric water transport is calculated explicitely from model variables.

The components have been calculated for every day of June 1993 over the catchment area of the Baltic Sea. The results are shown in Fig. 1, where points have been connected by straight lines. Also shown is the small residuum in the water balance which arises if only the above defined components are regarded:

$$R=\Delta W-(E-P+C). \qquad (3)$$

Here, ΔW denotes the change of atmospheric water content W during the considered time interval. The residuum R is not exactly zero because of the neglect of horizontal turbulent diffusion of water in the budget calculation and numerical errors. The fact that R is small is a necessary condition for the capability of the model to give reliable estimates of the atmospheric part of the water cycle. There is, however, another source of error which has to be considered. Due to the daily reinitialization of the model, all variables are discontinuous in time at 6 UTC on every day but the first. Thus adding water storage changes which occur during each day of the month is not equivalent to calculating the storage change as difference of the two contents at the beginning and at the end of the month.

In the daily balance plot Fig. 1 it can be seen that the first 10 days of June 1993 were comparatively dry over the BALTEX region. Major precipitation events of about 4 kg m^{-2} d^{-1} occur later on June 12, 17, 20 and 25. Daily mean evapotranspiration remains nearly constant near its mean value of 1.5 kg m^{-2} d^{-1} during the month. From day 3 to 8 the change in water content is mainly determined by horizontal transport. Precipitation and evapotranspiration approximately balance each other. In contrast to this, water storage and horizontal transport follow the strong precipitation in the period from day 17 to 20. For a more detailed analysis the synoptic weather situation has to be considered. As an example, on 12 June

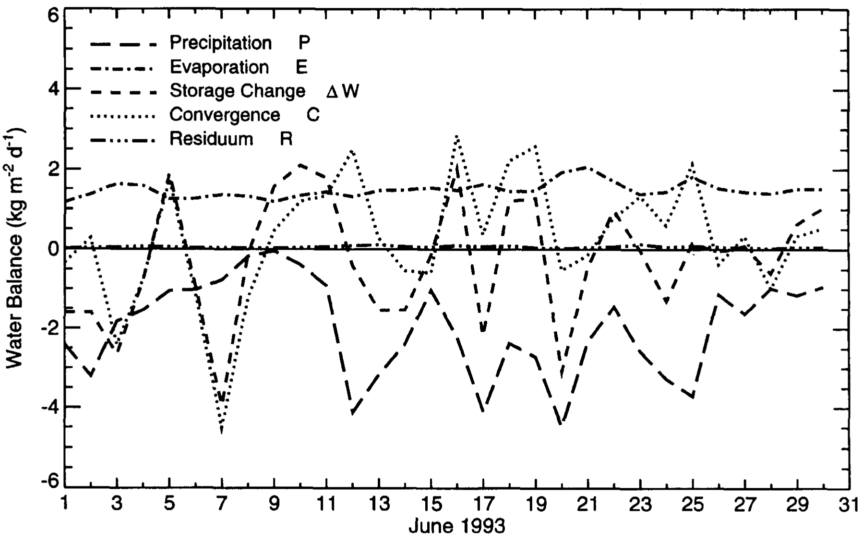

Fig. 1. Atmospheric components of the water cycle over the catchment area of the Baltic Sea for June 1993. The daily values refer to the time span from 06 UTC to 06 UTC on the following day, corresponding to hours 6 to 30 after model start at 00 UTC.

the high precipitation values in a frontal zone reaching from Southern Norway to the Black Sea are almost balanced by a decrease of atmospheric water content and a convergence of water transport. In other areas, convergence prevails. On the monthly time scale precipitation and evaporation are the dominant components of the water budget. In June 1993 the excess of precipitiation over evapotranspiration is balanced by a transport of water into the region and a decrease of water content (see Table 1).

4. Comparison with measurements

The validation of the individual components of the water cycle is necessary to assure reliable estimates of the balance. It will also indicate possible deficiencies in the physical parameterizations and their feedbacks in the model. The main objective here is the validation of the precipitation field because this is a critical input parameter for hydrological models. Furthermore a comparison with climatological data is presented.

Table 1. *Atmospheric water budget components over the Baltic Sea computed with REMO and from ECMWF T213 analyses for June 1993, and climatological data for June from Henning and Dahlström as given in (HELCOM, 1986); the two different values for storage change occur because of the daily model restart, see section 3*

Values for June ($kg\ m^{-2}\ month^{-1}$)	Baltic Sea incl. catchment area REMO 1993	Baltic Sea incl. catchment area ECMWF 1993	Baltic Sea REMO 1993	Baltic Sea HELCOM 1951–70	Baltic Proper REMO 1993	Baltic Proper HELCOM 1951–70
Precipitation	59.1	71.4	40.2	40.8	39.9	43.0
Evaporation	44.3	86.1	34.5	13.9	39.6	13.7
Convergence	8.1	—	0.2	—	−2.9	—
Sum of daily storage changes	−8.4	—	−5.5	—	−3.2	—
Overall storage change	−0.55	—	−1.3	—	−0.09	—

REMO model precipitation is compared with measurements from the operational rain gauge network of several meteorological services within the Baltic Sea region, as far as they were available to the authors (data collection of the International BALTEX Secretariat). Observations from 5898 stations were used. The measurements are converted to the model grid by taking the average of the values of all stations situated in a grid box. Fig. 2 shows accumulated measured and calculated precipitation for June 1993 at those grid boxes where measurements were available. In some regions the model underestimates the amount of precipitation significantly. The differences are mainly due to a mismatch in location of the precipitation regions, and only to a lesser extent to a general underestimation. This is also confirmed by the daily sums of precipitation in Fig. 3. Even on days when the areal averages over the whole catchment area are quite close to the observed values, the large RMS of the difference reflects errors in the geographical distribution. The largest errors occur when also precipitation amount is high.

As a first step in comparing also the other components of the water balance with measurements, Table 1 shows REMO results for June 1993 together with values obtained from ECMWF T213 analyses, and climatological June values (HELCOM, 1986). The latter refer to the Baltic Sea itself, not to the whole catchment area. While the mean precipitation agrees with the climatological value (note, however, that the first 10 days are relatively dry), evaporation in June 1993 is much stronger than its long time average. Bumke (personal communication) obtained 36.3 kg m^{-2} evaporation over the Baltic Sea for June 1993 from ship based measurements. This value is very close to the REMO result. Over the Baltic Proper Isemer (personal communication) obtained from ship based measurements an evaporation of 27.3 kg m^{-2} for June 1993, REMO calculated 39.6 kg m^{-2} evaporation, and Henning (HELCOM, 1986) reports 13.7 kg m^{-2} over this region. Precipitation and evapotranspiration have been calculated using data from the ECMWF archive (surface forecast fields 6–30 h), resulting in 71.4 kg m^{-2} and 86.1 kg m^{-2} over the whole Baltic Sea catchment area, respectively. This evapotranspiration value is about twice as high as the results from REMO calculations. This is mainly due to two reasons. Firstly, the ECMWF T213 produces more precipitation than REMO which provides a higher water supply at ground for evaporation. Secondly, the different parameterizations of cloudiness give less cloud cover in the ECMWF T213 than in REMO. Mean values are 38.7% and 61.3%, respectively. Because cloud cover is a main factor determining solar radiation at ground, this leads to higher solar radiation at ground in the ECMWF T213 (approximately 12% higher than in REMO) and thus to a higher energy supply for the evaporation process.

5. Conclusions

The atmospheric part of the water cycle over the BALTEX area has been calculated using a regional weather prediction model. Initial and boundary conditions are applied in a way similar to an operational 30 hour forecast, thus forcing the model state to be close to the real weather situation of June 1993. Comparison with measured data shows quantitative agreement for the daily precipitation when summed over the whole catchment region. The wet character of this month is at least qualitatively reproduced by the model precipitation and evaporation. Differences in the geographical distribution, however, lead to comparatively large rms errors especially when the amount of precipitation is high. Therefore, comparison with measured data should help to identify regions and time intervals where the model can be used as a kind of microscope in space and time to analyse the water cycle.

It has to be kept in mind that comparison with point measurements always involves the problem of their relation to grid point values and also of interpolation. In this paper, only the described very special straightforward gridding method is applied to precipitation measurements. It can certainly be refined. Error bars for measured and calculated precipitation values are not available so far. This will hopefully be one of the future results of BALTEX.

6. Acknowledgements

We thank the German Weather Service DWD for providing their model and valuable support,

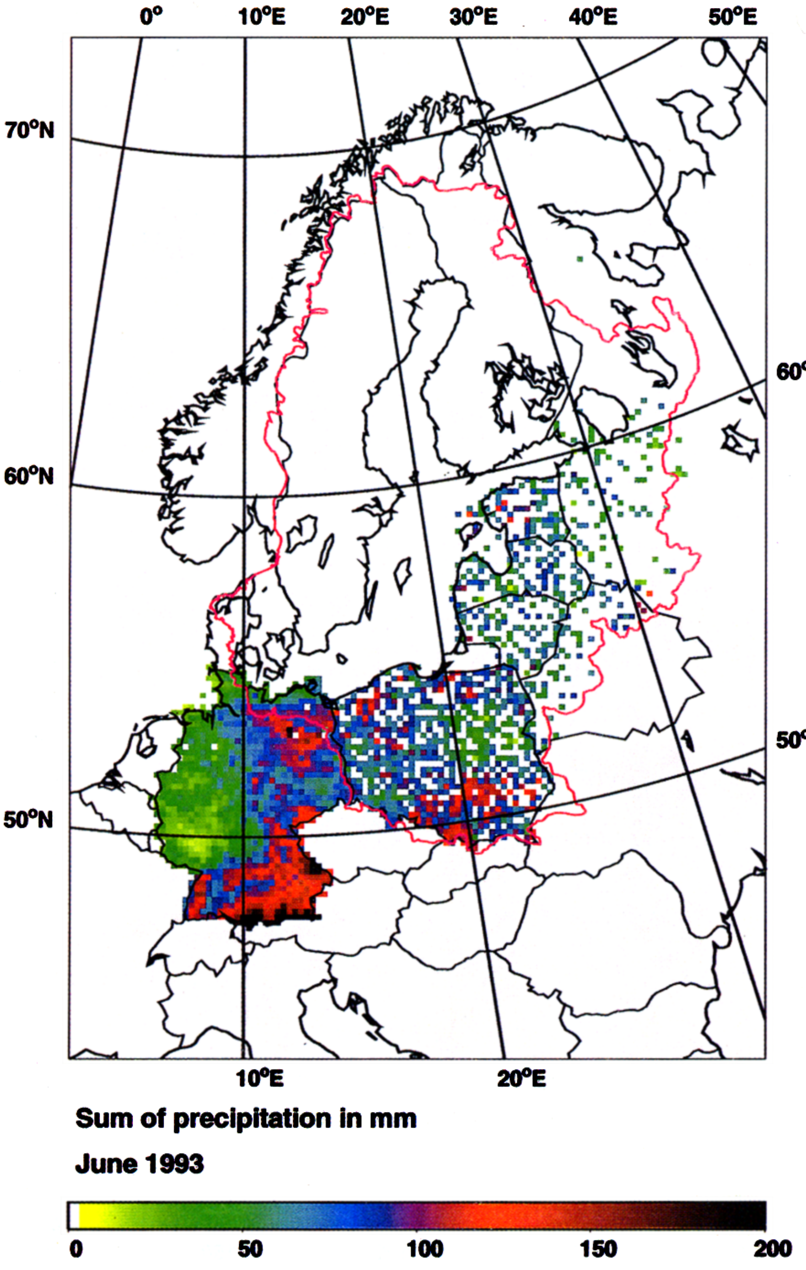

Fig. 2. Measured and calculated precipitation in June 1993. Only grid boxes where measurements were available are coloured, all others are shown in grey. The Baltic Sea catchment area is marked by the pink line.

and also initial and boundary condition data sets for EM. Precipitation measurements were also provided by DWD. The International BALTEX Secretariat collects precipitation data. Special thanks to the following national services and institutions who provided these data: Committee for Hydrometeorology of Belarus, Estonian Meteorological and Hydrological Institute,

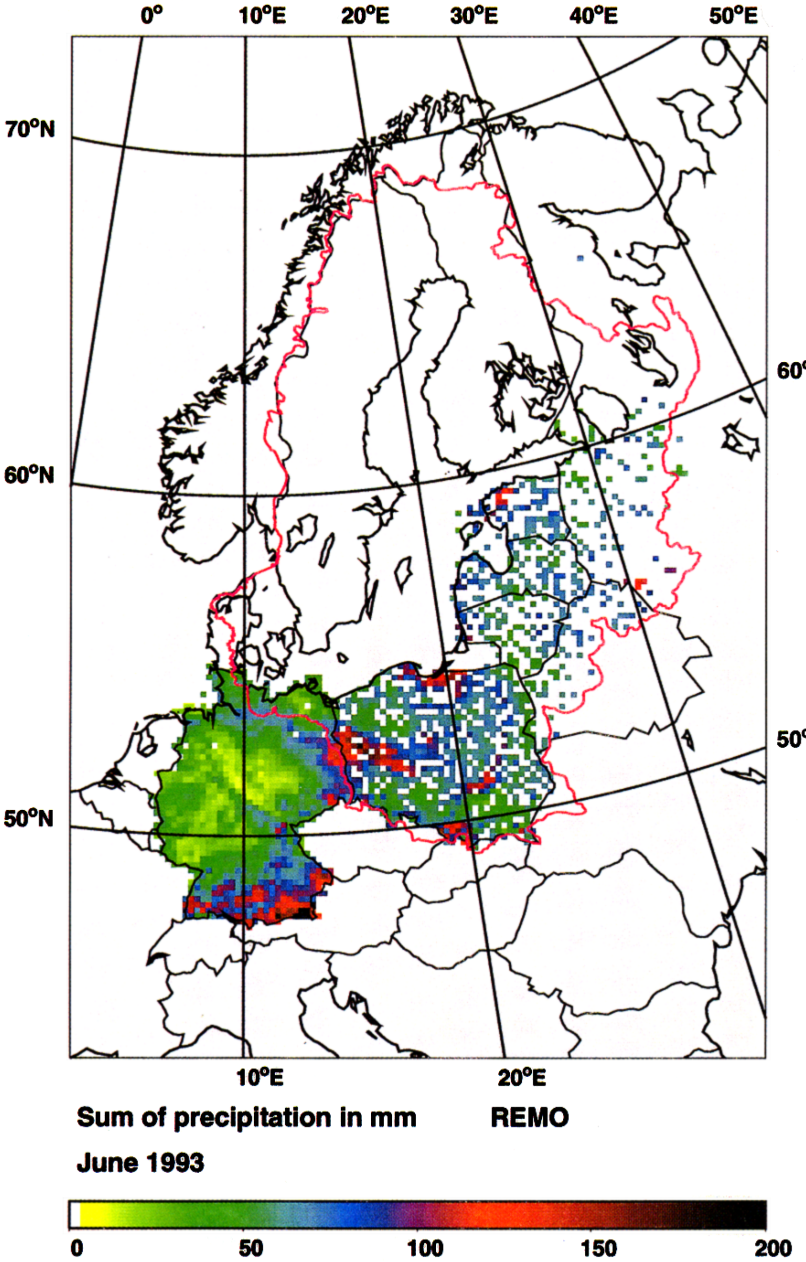

Fig. 2. (Continued).

Hydrometeorological Agency of Latvia, Lithuanian Board for Hydrometeorology, Institute of Meteorology and Water Management in Wroclaw (Poland), and the Russian Federal Service for Hydrometeorology and Environmental Monitoring. We thank the European Centre for Medium Range Weather Forecast (ECMWF) for providing analyses and forecast data of their T213

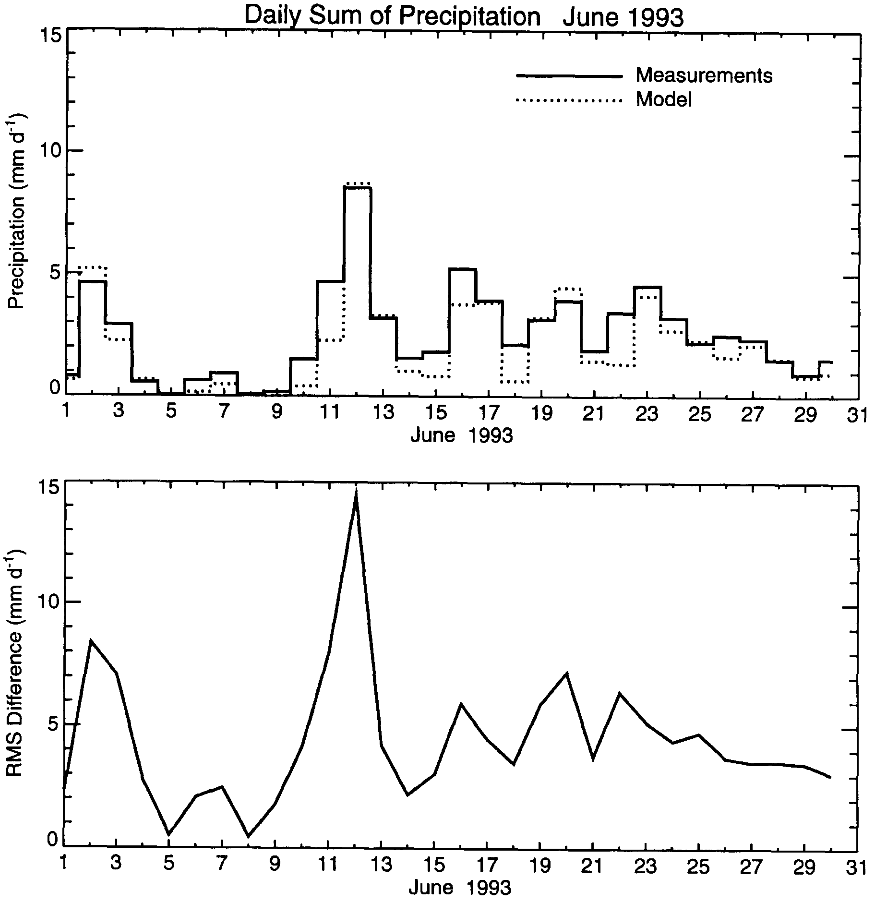

Fig. 3. Daily sums of precipitation, averaged over all REMO grid boxes inside the Baltic Sea catchment area where measurements were available. See Fig. 2 for their geographical distribution. The RMS values refer to the root mean square difference between measurements and model results.

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