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Sensitivity Studies with the Regional Climate Model REMO

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With 12 Figures

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Summary

A new regional atmospheric model was set up in a joint effort by DKRZ (Deutsches Klimarechenzentrum), DWD (Deutscher Wetterdienst), GKSS (Forschungszentrum Geesthacht) at the MPI (Max-Planck-Institut fuer Meteorologie). This model, called REMO (REgional MOdel) can be used in the weather forecast mode as well as in the climate mode. It is based on the Europa-Model (EM), the main weather forecast model of the new numerical weather prediction system of the Deutscher Wetterdienst. In addition to the physical parameterizations implemented in the EM, REMO has the possibility of using the same physics as the global climate model (MPI) into which it is nested to assess the scale dependence of physical parameterizations within the same dynamical framework.

This paper gives an overview over different case studies investigating the dependence of model results on simulation domain size, horizontal resolution, initial conditions and lateral boundaries especially for long term calculations. A sample of one month long integrations for an arbitrary July month, a four year long run for the Baltic Sea and its drainage basin and two summer seasons of the Indian Monsoon will be used to demonstrate the sensitivity of regional climate model results to different environments.

The sensitivity studies show that it is very important to use realistic large scale driving fields at the lateral boundaries. The regional model results are strongly influenced by the driving fields. The domain size and the simulation length are also influencing the results.

1. Introduction

Determination of sensitivity of the regional model to domain size, horizontal resolution, initial conditions and the influence of lateral boundary conditions of the driving model onto the regional model results is necessary for a meaningfull interpretation of simulated regional features. Case studies are carefully chosen for this purpose and cover a variety of physical and numerical scenarios. For all simulations, time-varying meteorological fields of the MPI climate model ECHAM3/T42 were used as lateral boundary fields. The global climate model as well as the regional climate model were driven by observed sea surface temperatures (SST) updated on a daily base.

First, the flow domain covered by the regional model was varied to study the influence of the computation domain on the simulated climate. Second, the sensitivity of regional climate simulations to small changes in initial conditions was analysed. Third, the horizontal resolution was changed from 0.5° to 0.16° to investigate the scale dependence of results. Fourth, REMO has been applied to the Baltic Sea area to assess the annual cycle of precipitation and evaporation in an extratropical environment in a four year long run. Finally an eighteen month long integration covering two Indian summer monsoon events was done as an example for a tropical area of interest.

Global modelling of the present climate requires a good understanding of energy and water cycles in the climate system. Within the GEWEX (Global Energy and Water Cycle EXperiment) programe, regional experiments are now starting. One of these is the BALTEX (the BALTic Sea EXperiment), in which numerical experimentation as well as validation of numerical models are essential components.

2. Model Designs and Numerical Procedures

2.1 The Global Climate Model ECHAM

The global climate model ECHAM3 is the third generation GCM used for global climate modelling investigations (DKRZ, 1994) in Germany. The prognostic variables include vorticity, divergence, temperature, log surface pressure, water vapour and cloud water. The model equations are solved on 19 vertical levels in a hybrid sigma-pressure system by using the spectral transform method with triangular truncation at wavenumber 42. Nonlinear terms and physical processes, however, are evaluated at grid points of a Gaussian grid providing a nominal resolution of 5.625° in latitude and longitude.

The radiation scheme is a two-stream approximation of the radiative transfer equations with six spectral intervals in the infrared and four in the solar spectrum (Rockel et al., 1991). Gaseous absorption due to water vapour, carbon dioxide and ozone is taken into account as well as scattering and absorption due to aerosols and clouds. The cloud optical properties are parameterized in terms of cloud water content.

The parameterization of cumulus convection is based on the concept of mass flux scheme of Tiedke (Tiedke, 1989) and comprises of effect of deep, shallow as well as mid-level convection on the heat, water vapour and momentum budgets. Cumulus clouds are represented by a bulk model including the effect of entrainment and deterainment on the updraft and downdraft convective mass fluxes. Stratiform clouds are predicted per se in accordance with a cloud water equation including sources and sinks due to condensation/evaporation.

The vertical turbulent transfer of momentum, heat and water vapour is based upon the Monin-Obukhov similarity theory for the surface layer and eddy diffusivity approach above the surface layer (Louis, 1979). The effect of orographically excited gravity waves on the momentum budget is parameterized on the basis of linear theory and dimensional considerations. The land surface scheme considers the heat and water budgets in the soil, snow cover and land and the heat budget of the permanent land and sea ice. The integration is performed following a semi-implicit scheme with a leap frog time filter at every 24 min intervals.

2.2 The Regional Climate Model REMO

The dynamical structure of REMO is similar to the EM/DM system (Majewski, 1991). It is based on the primitive equations in a terrain-following hybrid coordinate system. The finite-difference equations are written in advective form on an Arakawa C-grid. Second order central differences in space are used and the vertical finite difference formulation follows Simmons and Burridge (1981) to conserve energy and angular momentum. To avoid numerical instabilities the vertical advection as well as the vertical turbulent fluxes are treated implicitly. The time-stepping is leap-frog with semi-implicit correction and Asselin-filter; the time step is 5 min.

The prognostic variables are surface pressure, horizontal wind components, temperature, specific humidity and cloud water. The vertical structure is the same as in the EM model with 20 model levels. The boundary conditions are specified at the top and the bottom of the model atmosphere, where the vertical velocity vanishes. At the lateral boundaries, time-dependent values for all prognostic variables are specified from the global climate model ECHAM3 at T42 resolution. It is also possible to use model output from different models with different resolutions and to bring in data from analyses. A relaxation scheme according to Davies (1976) is used to adjust the prognostic variables in a zone of 8 grid rows towards the prescribed boundary fields.

The horizontal diffusion of momentum, temperature and moisture is fourth order with a space-dependent diffusion coefficient proportional to the total deformation of the horizontal wind field. The diffusion is performed on hybrid levels but correction terms are added in the temperature and moisture equation to account for the slope of the model layers.

For the sensitivity studies presented here, REMO has been run with EM physics: The vertical turbulent fluxes in the Prandtl layer are formulated following the Dyer-Businger relation modified by Louis (1979). In the Ekman layer and the free atmosphere a so-called level 2 closure of Mellor and Yamada (1974) is used. The exchange coefficients depend on the vertical temperature profile and the wind shear.

The soil model predicts the temporal evolution of the temperature and the water contents of the soil using two layers for temperature and three layers for moisture in the soil and a variable storage at the surface for the interception of water and snow. The depth of the layers are different for heat and water budgets. At the lower boundary the climatological deep soil temperature is specified whereas the vertical moisture flux is set to zero. The heat budget is formulated according to the extended force-restore method (Jacobsen and Heise, 1982). For sea points ice extent, sea surface temperature and ice temperature are specified as boundary conditions.

The grid-scale precipitation is based on a Kessler type perameterization of the cloud microphysics which allows an interaction between water vapor, cloud water, rain and ice. A formation of precipitation via the ice phase is included by emphasizing the Bergeron-Findeisen process. The moist convection is parametrized by a mass flux scheme (Tiedtke, 1989). The radiation scheme of Ritter and Geleyn (1992) for short- and longwave fluxes is used every 1.5 hours. It allows a full cloud-radiation feedback.

3. Sensitivity Studies

Three different flow domains covered by the regional model were used for sensitivity tests. The large area covers the North Atlantic and Europe with a mesh of 181×129 grid points. The small area is fully embedded into the large one and covers Europe with a mesh of 81 × 91 grid points. Both meshs have a size of 0.5° in rotated spherical coordinates (position of the North Pole for all domains: 170° West, 32.5° North). For the studies with respect to changes in the horizontal resolution a third simulation domain (Baltic Sea domain) was created with 121×181 grid points and 0.16° resolution.

For all applications, besides the horizontal resolution case, REMO used the ECHAM3/T42 time-varying fields of surface pressure, horizontal velocities, temperature and moisture as lateral boundary fields updated every 6 hours. Figure 1 shows the coastlines and the resolution of the small and the Baltic Sea domain. For the large

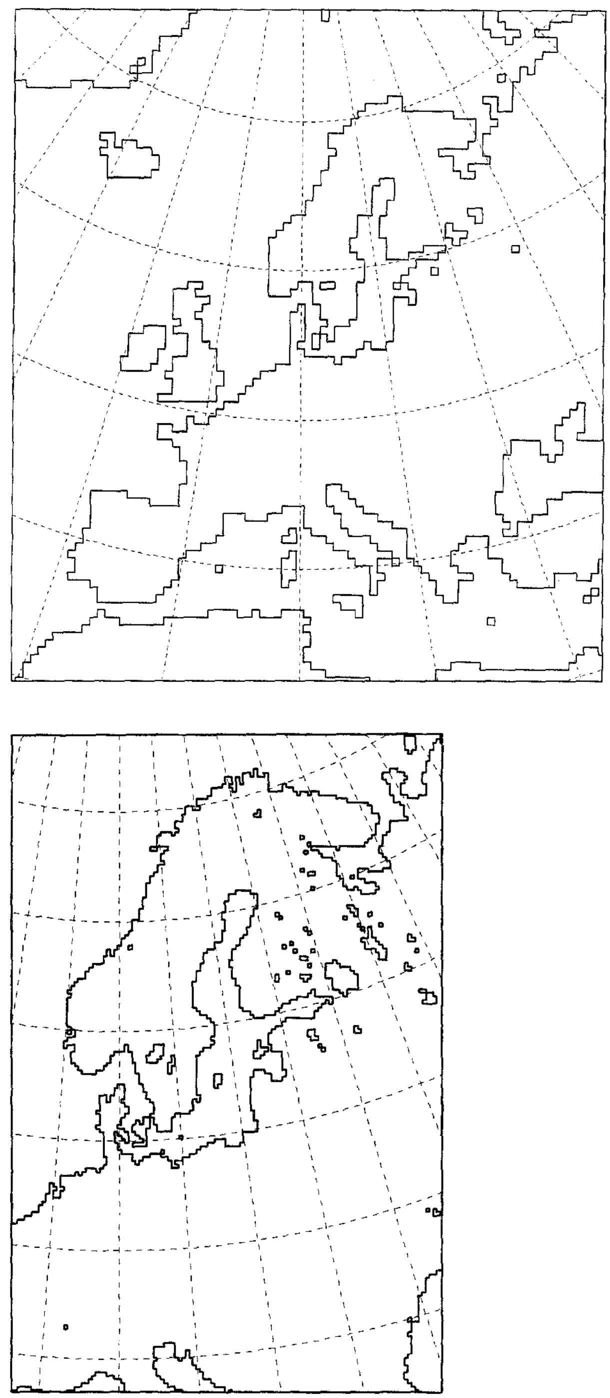

Fig. 1. Coastlines of the small domain and the Baltic Sea domain

domain this information is given in Figs. 3, 4 and 5.

3.1 Month long Integrations

In order to check how strongly the results depend on the flow domain covered by the regional model, REMO has been integrated for two months using the large (run1) and the small (run2) area. Striking differences can be seen in the July monthly mean precipitation on the Norwegian West Coast and the Gulf of Bothnia (Figs. 2 and 3). The high level of precipitation on the Gulf of Bothnia is caused by a relatively small low which developed in the Mediterranian area and moved to the North East, reaching the Baltic Sea after a few days. This feature develops only in the large area. It does not occur in the driving model, which has a much coarser resolution. This mesoscale feature needs the high resolution and the large domain to develop. The strong forcing of the boundaries prevents this development in the small area. Small changes in the initial conditions for a simulation of a climatological July, using the large area, result in similar climate for the Baltic Sea, but differ in precipitation pattern and amount for the Baltic drainage basin. These studies have been done by starting the 3 integrations with an offset of 24 hours (Figs. 3 (run1), 4 (run3) and 5 (run4)).

For the third sensitivity study the Baltic Sea domain was driven by lateral boundaries from the small domain run (run2). Comparison of the total July precipitation obtained with the 0.5° resolution run (run2) on the small domain (Fig. 6) with the results (run5) on the Baltic Sea domain with 0.16° resolution (Fig. 7) shows that the high resolution gives a much more detailed information of the spatial distribution for precipitation.

Since the above mentioned experiments were driven with flow fields from a climate run, it would only be possible to compare the precipitation with climatologies. For this purpose an ensemble of integrations is needed, which has not been done yet. During BALTEX an intense collection of observations for the Baltic Sea will be done. Simulations using analyses fields as forcing fields for the time period of data collection are planed. They will be verified against observations.

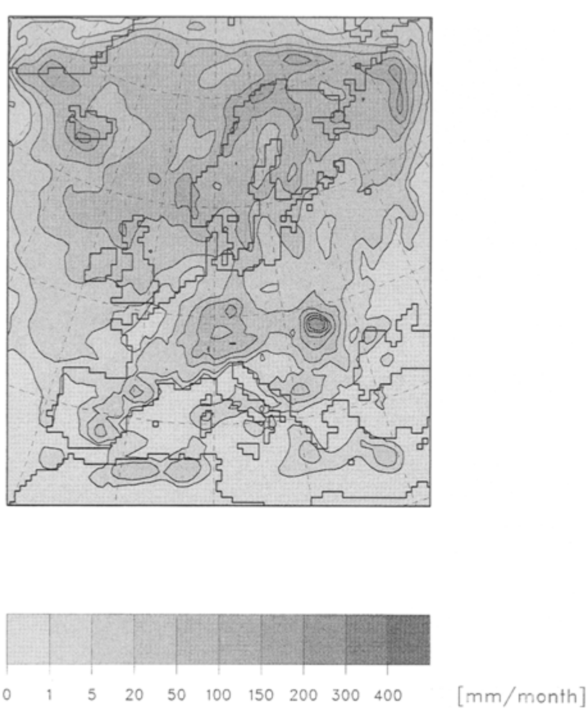

Fig. 2. Total precipitation for one climatological July computed from a regional model covering the small flow domain (mm/month)

3.2 Long term Integrations

3.2.1 Baltic Sea

Approximately 80 million inhabitants living adjacent to the Baltic Sea are affected by changes in the water resources. Therefore a detailed knowledge of changes in the water balance of the Baltic Sea is necessary to manage long term environmental deterioration of the system and the resulting economic and recreational impact. The inflow of fresh water with different contamination levels varies on different time scales.

A combination of advanced atmospheric and hydrological models may be used to increase the understanding of energy and water fluxes over high latitude regions of the Northern Hemisphere. Inside BALTEX, the interaction with a huge inland sea (the largest brackish water body of the world with a total surface of 377400 km^2 and 21200 km^3 volume (Sjoeberg, 1992) and surrounding land areas is explored, including intense small-scale weather systems.

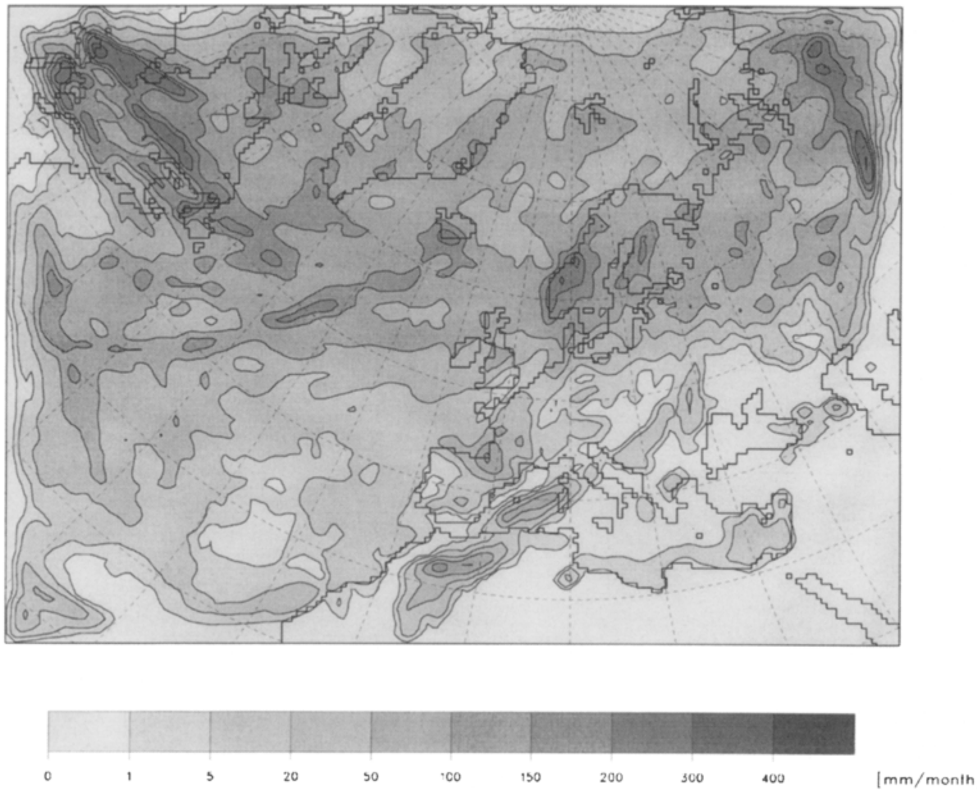

Fig. 3. Total precipitation for one climatological July computed from a regional model covering the large flow domain (mm/month)

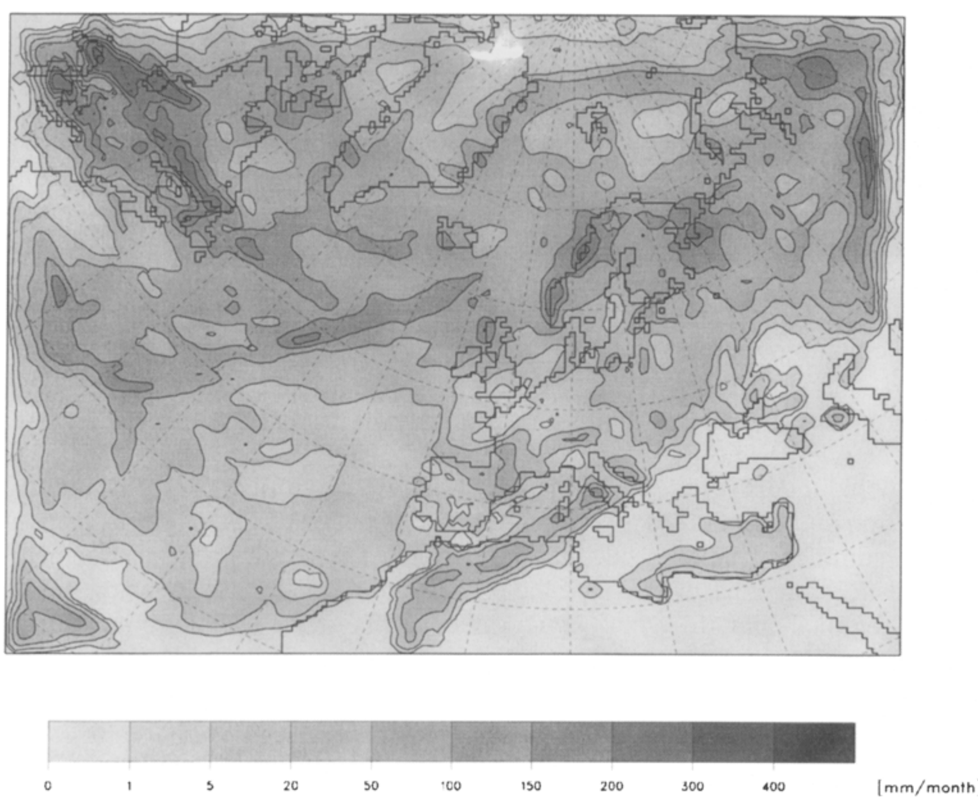

Fig. 4. Same as Fig. 2 with slightly different initial conditions (offset 24 h)

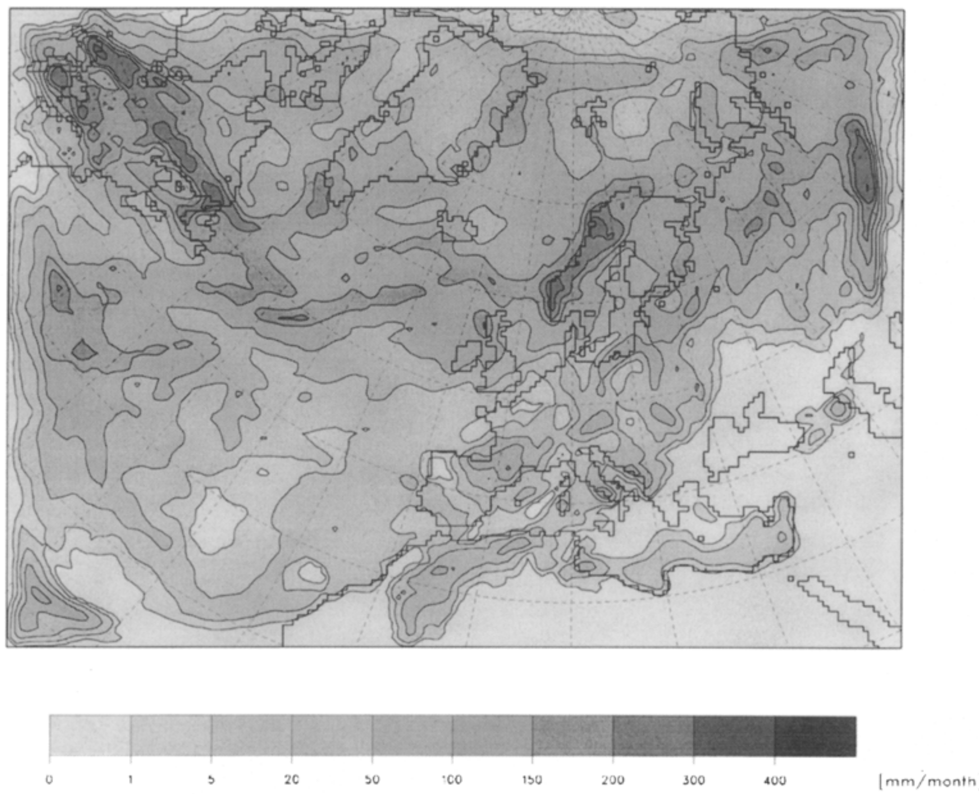

Fig. 5. Same as Fig. 3 with slightly different initial conditions (offset 48 h)

The following study is designed to prepare long term climate simulations over Northern Europe. REMO has simulated a 4-year climatology (run6) driven by ECHAM3/T42 using observed SSTs for the years 79 to 82. The area of interest was the Baltic Sea and its drainage basin, therefore the small domain with 0.5° resolution was used. The annual cycles of precipitation and evaporation – a four year mean climatology over the catchment area – simulated with the global model and the regional model are compared. It is noted that the regional model basically follows the annual cycle of the driving global model (Fig. 8). Monthly means of precipitation and evaporation differ mainly during the summer. Spatial patterns differ due to more realistic orography in the regional model. Both the regional and the global model overestimate the runoff into the Baltic Sea by some 60 km^3/y (Observations: 520 km^3/y, ECHAM3/T42: 588 km^3/y, REMO: 580 km^3/y).

The four year mean of the surface water balance of the catchment area (Fig. 9) shows that the precipitation rate is in good agreement with LEGATES value of 1.99 mm/day, whereas the runoff generation is a little higher than the measured value of 0.77 (Bergstroem and Carlsson, 1993). The interannual variability can be seen in the following values (mm/day):

Year	1	2	3	4	
Precipitation	1.84,	2.02,	1.89,	1.93	(mean 1.92)
Evaporation	– 0.92,	– 0.98,	– 0.99,	– 0.99	
Runoff	0.71,	1.01	0.87,	0.94	(mean 0.75)
Balance	0.21,	0.03,	0.02,	– 0.01	

The mean annual cycle of evaporation minus precipitation (not shown separatly) gives positive values in July only. This is not in good agreement with the estimate of Alestalo (1981), who reports positive values in May for a long-term mean calculation of evaporation minus precipitation. The shift in our simulations has to be investigated in detail.

The simulated mean surface energy balance (Fig. 10) for the catchment shows the large annual cycle of net surface radiation, followed by

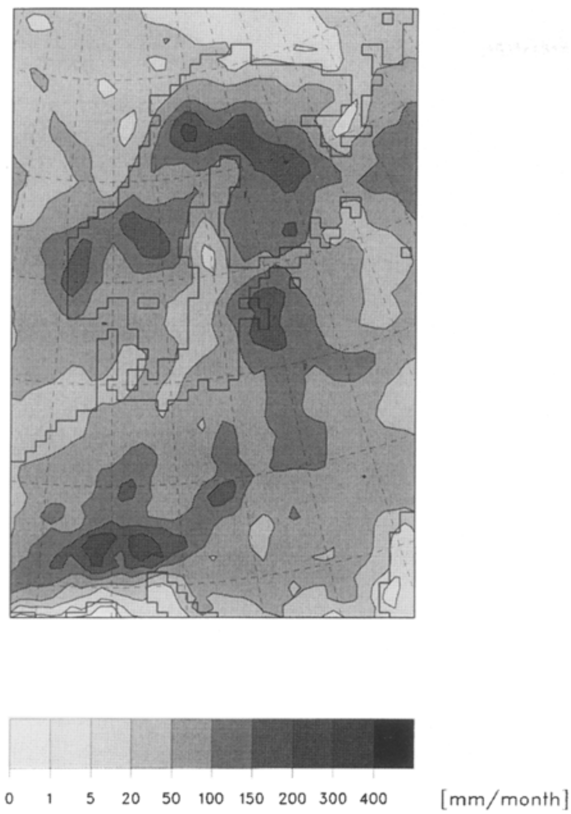

Fig. 6. Total precipitation for one climatological July covering the small flow domain (mm/month, only the area of interest is shown)

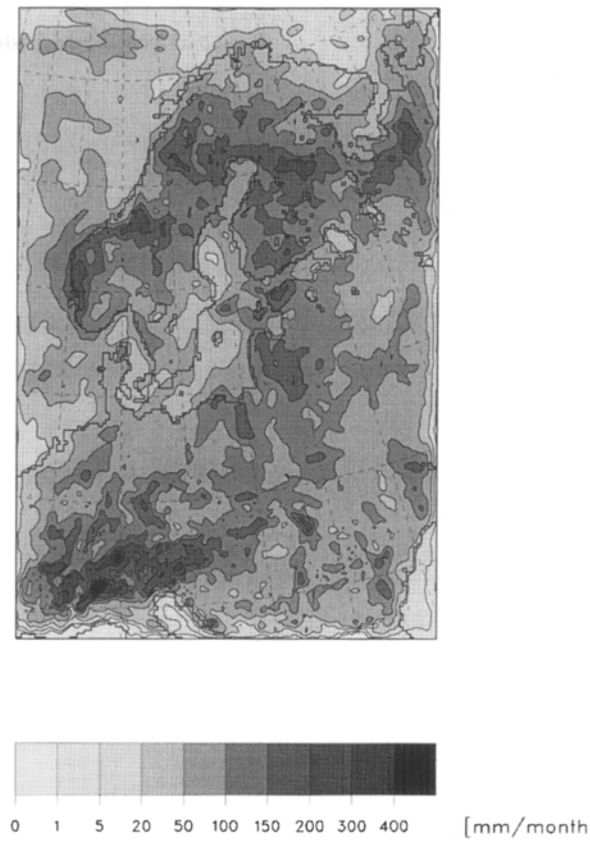

Fig. 7. Total precipitation for one climatological July covering the Baltic Sea domain with 0.16 degree horizontal resolution (mm/month)

sensible and latent heat flux. The positive balance describes a mean heat flux into the ground, heating the uppermost soil layers by about 1 W/m^2. Again the interannual variability is given by the following values (W/m^2):

Year	1	2	3	4
Net surface radiation	36.72,	32.74,	34.22,	35.14
Latent heat flux	−26.80,	−28.42,	−28.82,	−28.93
Sensible heat flux	−9.03,	−2.92,	−4.84,	−4.77
Balance	0.88,	1.40,	0.55,	1.43

3.2.2 Asian Monsoon

The Asian summer monsoon constitutes the most spectacular manifestation of regional anomalies in the general circulation of the atmosphere resulting from land-sea thermal contrasts and orographic features. Regional differences play a dominant role with respect to the monsoonal features over India and its neighbourhood. The thermal structure of the adjoining sea areas – the Arabian Sea, the Bay of Bengal and the South Indian Ocean – and its temporal variations appears to have a modulating influence on the monsoon activity. The summer monsoon circulation over the Indian subcontinent gets established towards the end of May and continues till end of September. It accounts for over 75% of the annual rainfall over most of India. Much of the monsoon rainfall over the central plains of India is associated with the low pressure systems which develop over the Head Bay of Bengal and move on to the subcontinent along a northwesterly track. In a coarse mesh global model, it is not possible to replicate the origin and movement of these low pressure systems and associated interannual and intraseasonal variabilities in monsoon rainfall.

A GCM with uniform resolution of about 50 km or less would require vast computing

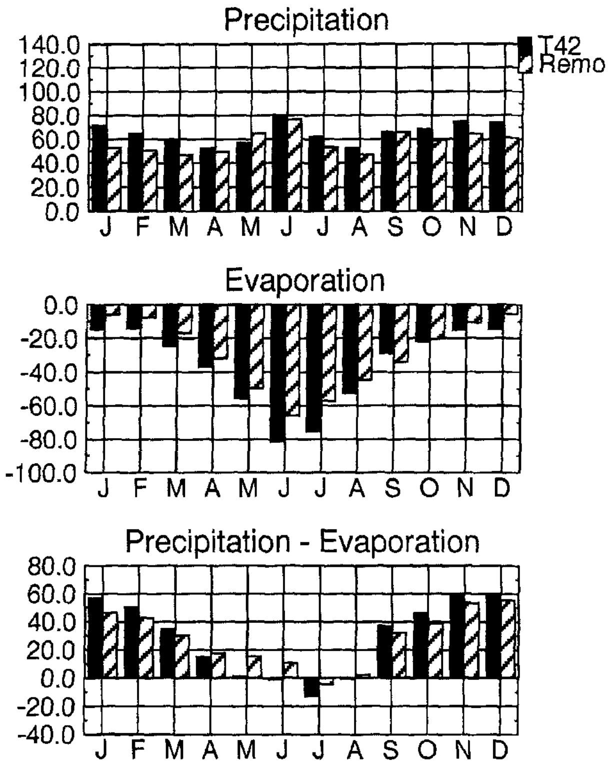

Fig. 8. Annual cycle of precipitation P, evaporation E and P-E (mm / month) of a four year climatology computed over the catchment area of the Baltic Sea from a global model (black bars) and a regional model (grey bars) nested into the global model

resources. An alternative approach to realistically simulate the regional climate which seems more practical at present is the use of a regional climate model nested within a global climate model. From theoretical point of view, the artificial lateral boundaries of the regional model form the most critical disadvantage of such models.

We have performed an eighteen month long climate simulation using SSTs for the years 1987/1988 with REMO nested into ECHAM3/T42 for a more realistic simulation of monsoon climate on regional scales. The basic strategy of the approach is that while the GCM simulates the response of the general circulation to large scale forcings, the high resolution REMO embedded in the GCM captures the effect of local sub-GCM grid scale forcings, e.g., coastlines, surface vegetation characteristics and complex topography.

The simulation domain covers an area from 30° to 110° East and from 15° South to 40° North with a mesh of 151×109 grid points (grid resolution: 0.5°). Figure 11 shows the total rainfall from June to September for the two summer seasons in our area of interest. The observed monsoon of the year 1987 was unusually dry, whereas the monsoon of year 1988 was relatively moist. REMO is able to reproduce these features quite well and shows generally the same spatial distribution of precipitation as a long term climatology (Fig. 12). A direct validation with observations of the years 1987–1988 is not

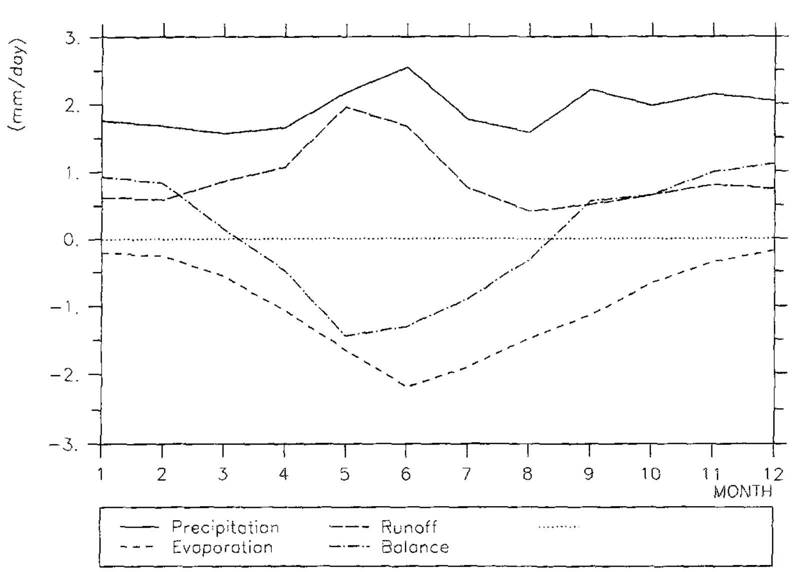

Fig. 9. Four year mean of the surface energy balance for the catchment area of the Baltic Sea tributaries (Wm^{-2})

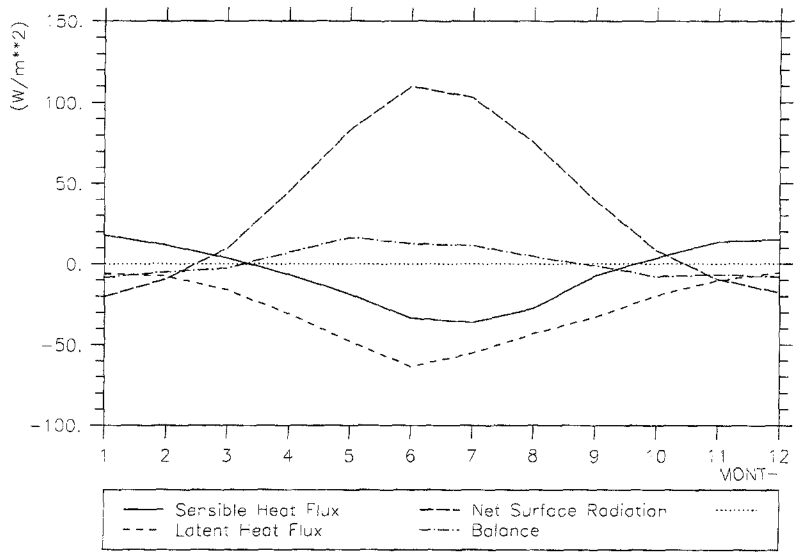

Fig. 10. Four year mean of the surface water balance for the catchment area of the Baltic Sea tributaries (mm/day)

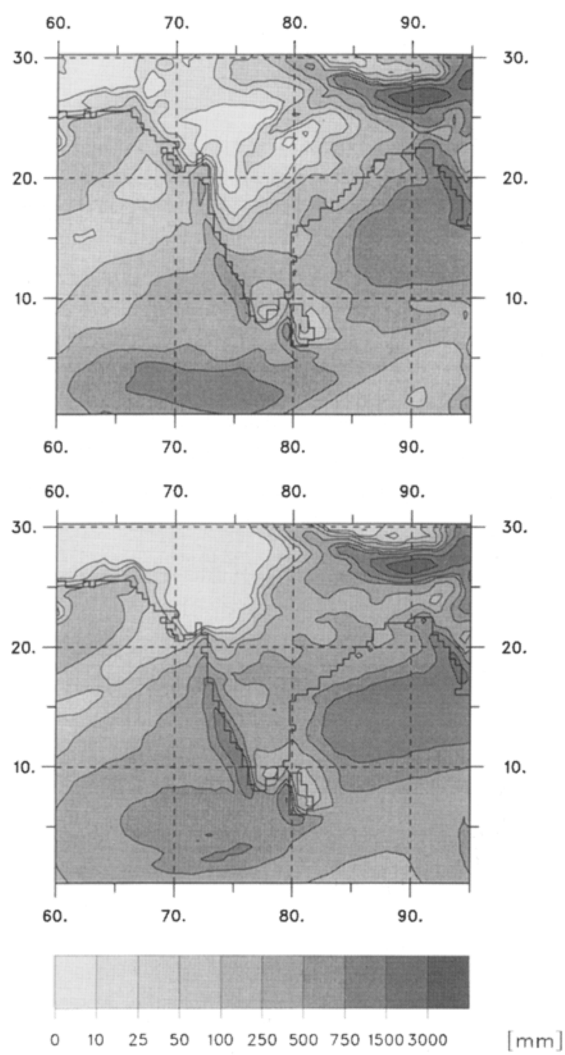

Fig. 11. Total amount of precipitation (mm) for June to September of a dry (top) and a wet (bottom) season simulated by the regional model using observed SSTs for the years 1987 and 1988

possible. Again the forcing fields from a climate model run, which simulated a climate similar to the years 1987–1988, were used. For validation a simulation using analyses of the years 1987 and 1988 would be needed.

The rainfall distribution over Indian subcontinent during monsoon (June–September) season as simulated by REMO has been compared with that simulated by the GCM and the observed climatology. The REMO simulates the observed steep gradient in monsoon rainfall from west coast towards the east (a rainshadow effect in the lee of the western Ghats) more realistically. The striking observed variations in monsoon rainfall in the hilly and mountain ranges of north-east India are also well reproduced by REMO.

The results suggests that large scale summer monsoon circulation simulated by REMO does not substantially differ from that of the driving GCM, this stresses the need for good large scale driving climatology. Owing to a better representation of sub-GCM grid-scale details and orography, however, the limited area model produces more realistic spatial and temporal details of key surface climate elements, e.g., surface pressure, surface air temperature, winds and precipitation over the region of interest as compared to the driving GCM as inferred from a number of objective measures of climate simulation skill.

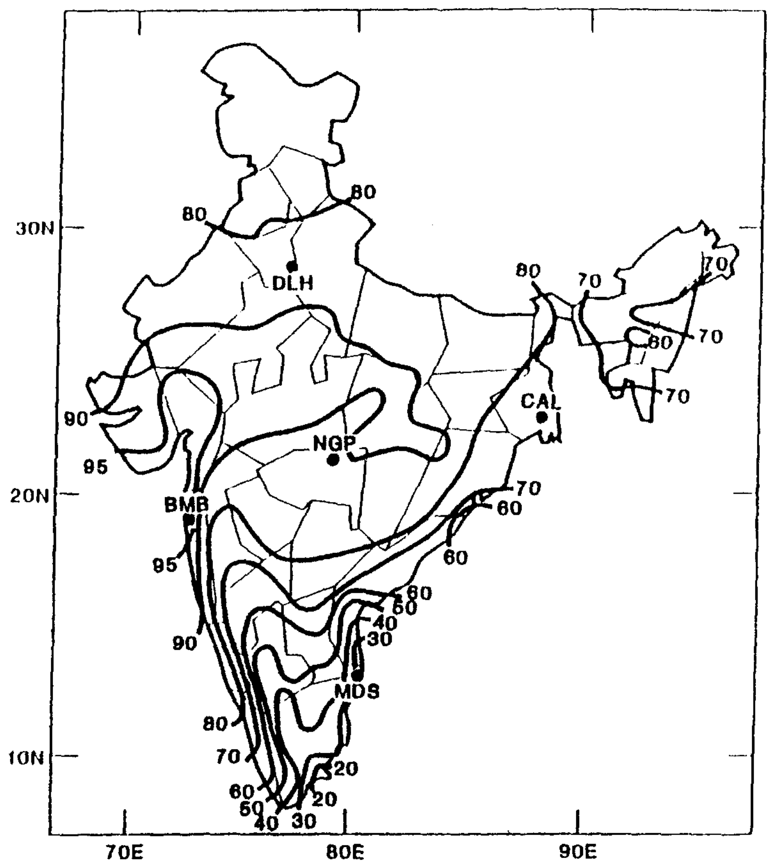

Fig. 12. Geographical distribution of the concentration of rainfall during the Summer Monsoon Season over India (percent of annual), 1871–1984. (Indian Meteorological Department, Rainfall Atlas of India, 1971)

4. Conclusions

A regional model system, called REMO, has been set up which is used for weather forecast and climate simulations. Preliminary studies are presented here which demonstrate the sensitivity of seasonal simulations to changes in flow domain covered by REMO, horizontal resolution and to small changes in initial conditions. Work in progress suggests that these sensitivities become less important when considering long-term simulations. Moreover, the influence on model results due to changing physical parameterizations and model domain seems to be second order in comparison with the influence of boundary conditions from the driving global model. This emphasizes the need for realistic large scale driving climatologies to simulate regional climate. Our findings are in good agreement with Jones et al. (1995), who studied the sensitivity of model results to the location of the lateral boundaries for climate change senarios over Europe. An intense validation of present-day regional climate simulations over Europe has been summarized by Machenhauer et al. (1996). This paper as well as the work by Creß et al. (1995) and Podzun et al. (1995) also emphases the importance of the global large scale fields for regional studies.

A more detailed validation of the model results for the 4 year climatology over the Baltic Sea drainage basin with climatological estimates of energy and water budgets will be done in the future. It is planned to couple the atmospheric regional climate model REMO with an ozeanographic model of the Baltic Sea and a hydrological model for the catchment area.

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